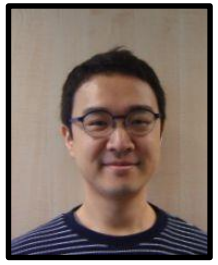
Equal-spin supercurrents and magnetization dynamics in high-temperature superconductor/ferromagnet hybrids

Javier E. Villegas
Unité Mixte de Physique CNRS/Thales, France

Acknowledgements



D. Sanchez, S. J. Carreira, S. Mesoraca, M.-W. Yoo, V. Rouco, X. Palermo, A. Balan, K. Seurre, A. Sander, A. Anane & Javier E. Villegas
Unité Mixte de Physique CNRS, Thales, **FRANCE**

G. Orfila, A. Cuellar, M. Cabero, L. Marcano, M. Rocci, J. Garcia-Barriocanal F. Gallego, J. Tornos, A. Rivera, J. M. Gonzalez-Calbet, C. Leon & J. Santamaria
Universidad Complutense Madrid, **SPAIN**

S. Valencia
Helmholzt-Zentrum Berlin, **GERMANY**

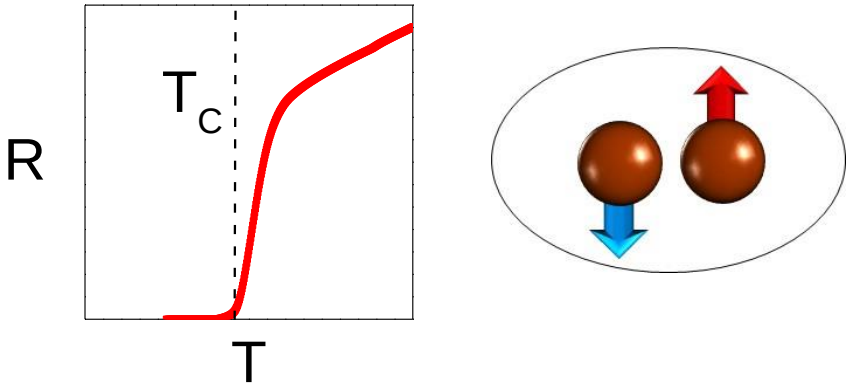
F. Mompean, M. Garcia-Hernandez
ICMM-CSIC, **SPAIN**

C. Feuillet-Palma, N. Bergeal & J. Lesueur
ESPCI-Paris, **FRANCE**

A. I. Buzdin
Université de Bordeaux**, FRANCE**

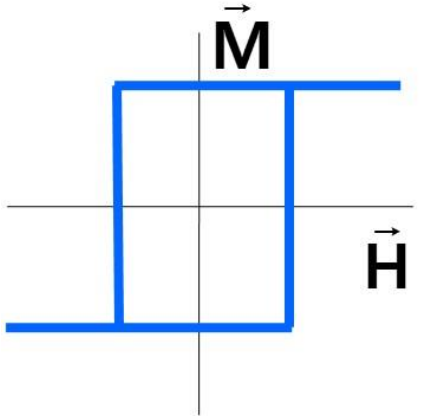
Superconductor/ferromagnet hybrids

Superconductor



Large resistance variation
Coherent transport

Ferromagnet



Memory
Spin-polarized transport

→OPPORTUNITIES FOR SPINTRONICS

Main goals in the area

feature article

Spin-polarized supercurrents for spintronics

Matthias Eschrig **Physics Today, 64 43 (2011)**

A marriage between superconductivity and ferromagnetism is opening the door for new spin-based applications.

nature physics

REVIEW ARTICLES

PUBLISHED ONLINE: 2 APRIL 2015 | DOI: 10.1038/NPHYS3242

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Jacob Linder[1]* and Jason W. A. Robinson[2]*

Mesoscopic magnetism and superconductivity

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MRS Bulletin

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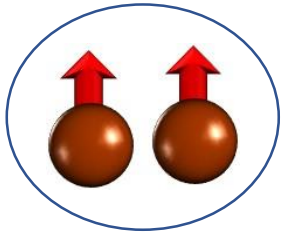
- Equilibrium
- Low-dissipation spin transport
- Spin torques
- Phase coherence effects (Josephson)
- Large spin signals (spin valves)



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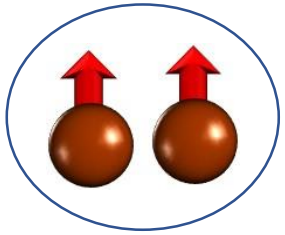
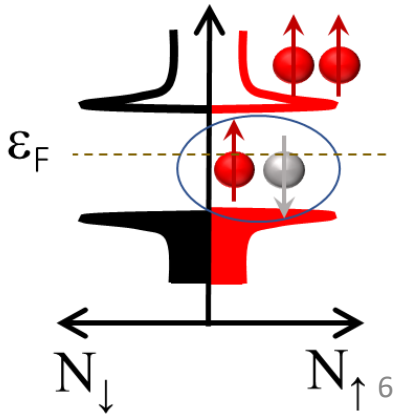


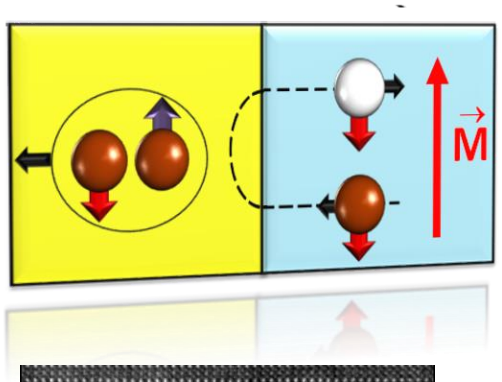
B) SPIN-POLARIZED QUASIPARTICLES

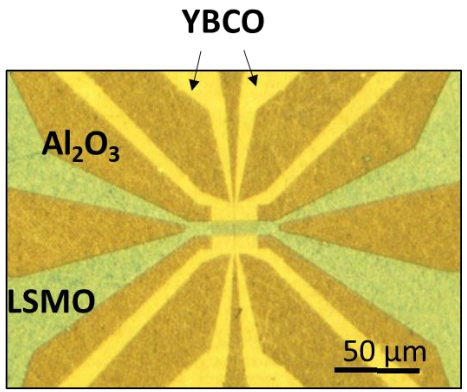
- Non-equilibrium
- Quantum protection
- Enhanced spin lifetimes
- Enhanced spin Hall effects
- Dynamic coupling

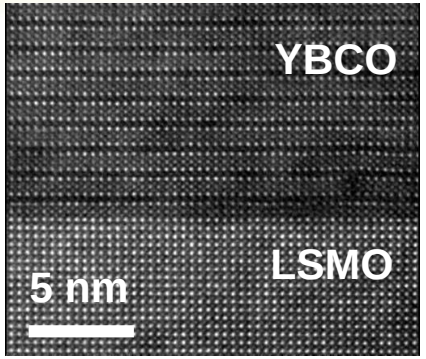


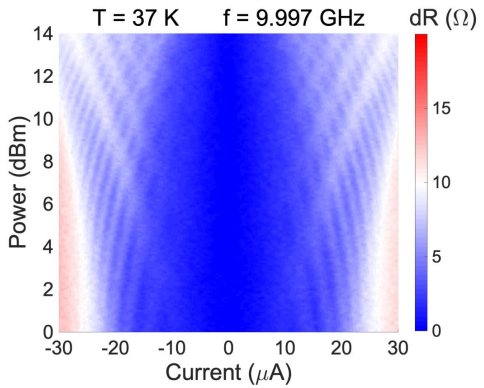
The talk in a nutsell

Proximity effect









Fully spin-polarized, high-T_C Josephson supercurrents
Quantum phase coherence effects

Sanchez-Manzano *et al.* Nature Materials (2022)

The talk in a nutsell

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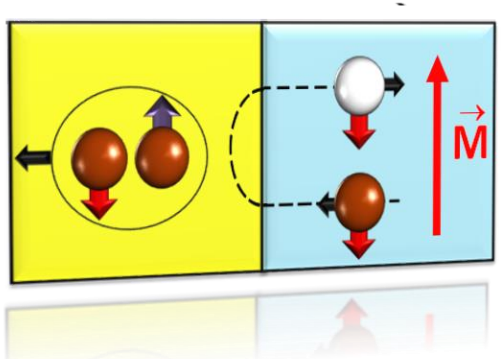

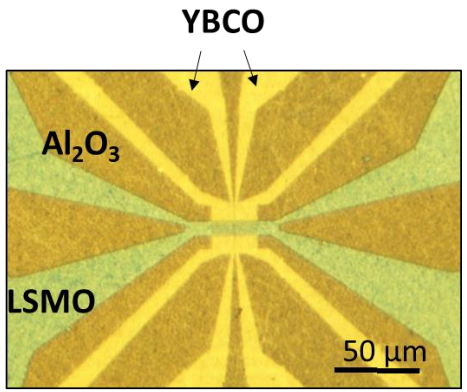

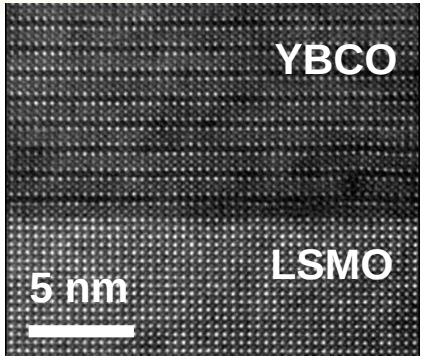

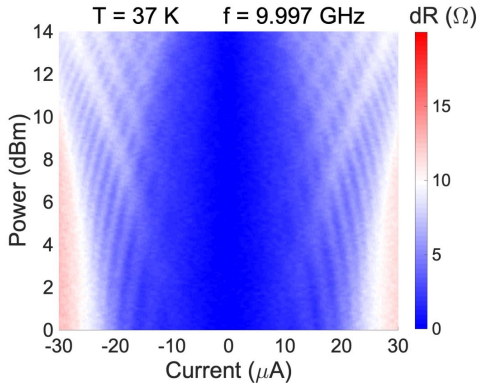

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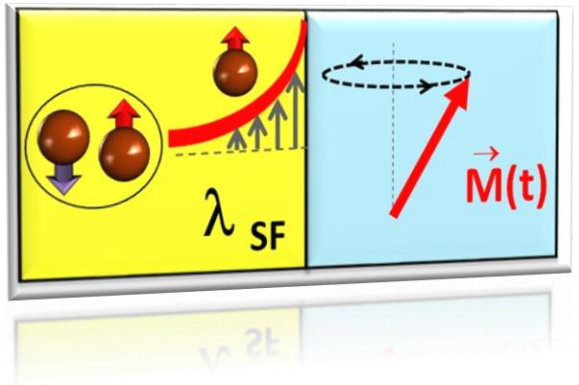
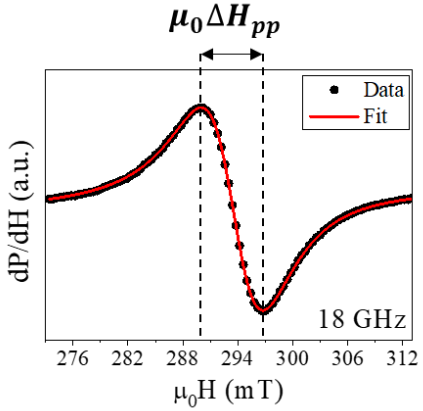
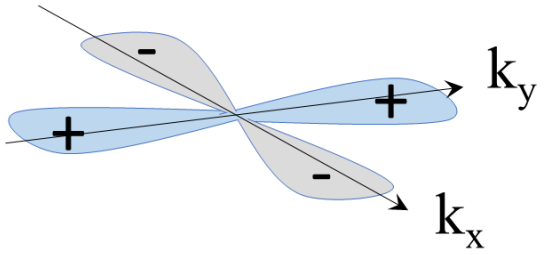
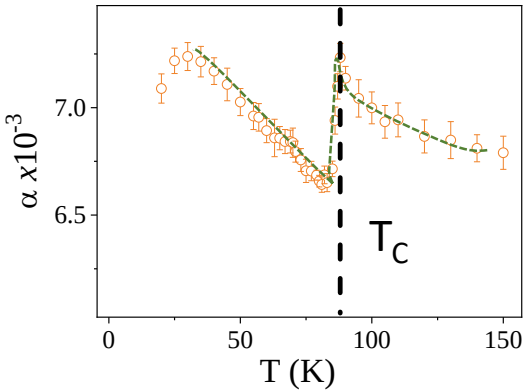
Sanchez-Manzano *et al.* Nature Materials (2022)

Dynamic coupling









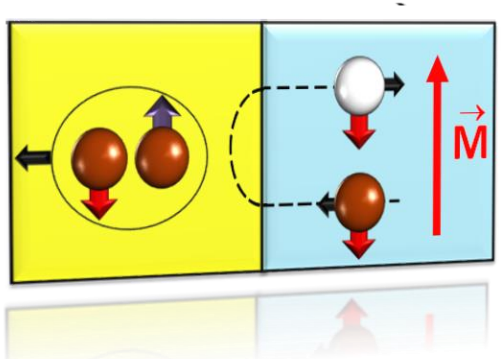
Tunable spin sink
d-wave effects

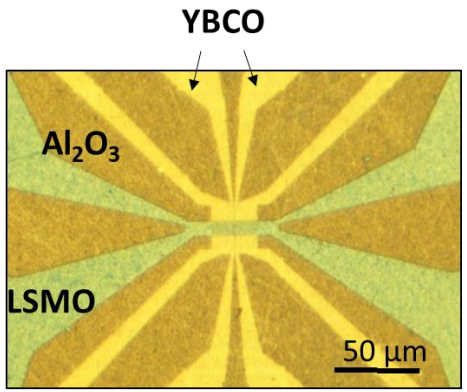
Carreira *et al.* PRB (2021)

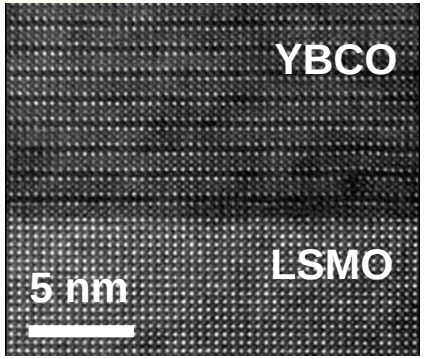
→ OPPORTUNITIES FOR HIGH-T_C SUPERCONDUCTING SPINTRONICS

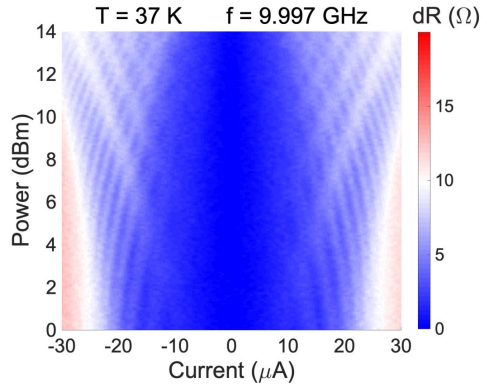
The talk in a nutsell

Proximity effect









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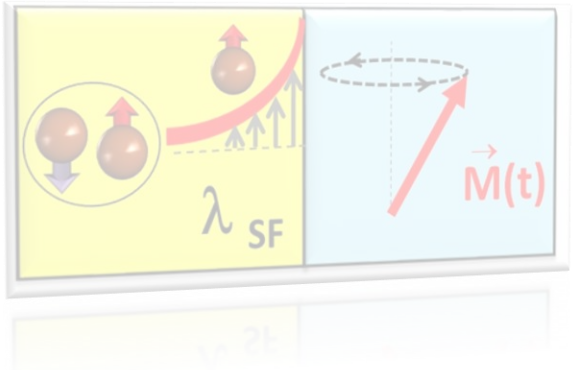

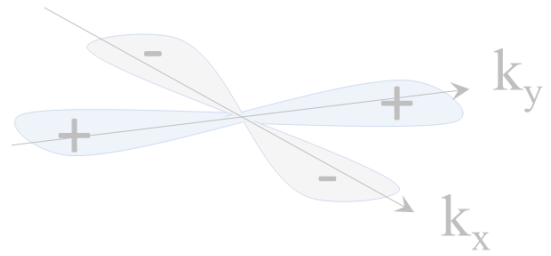

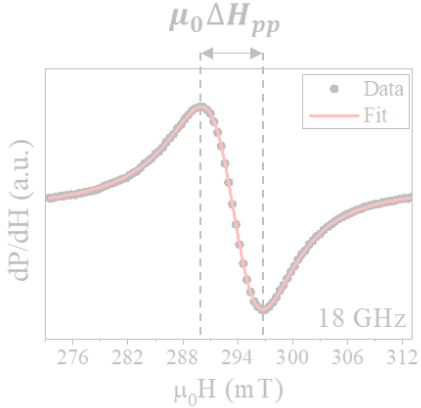

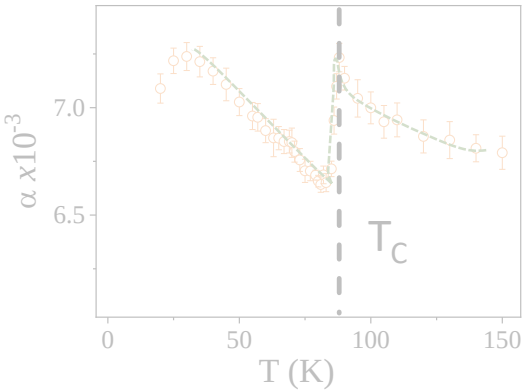

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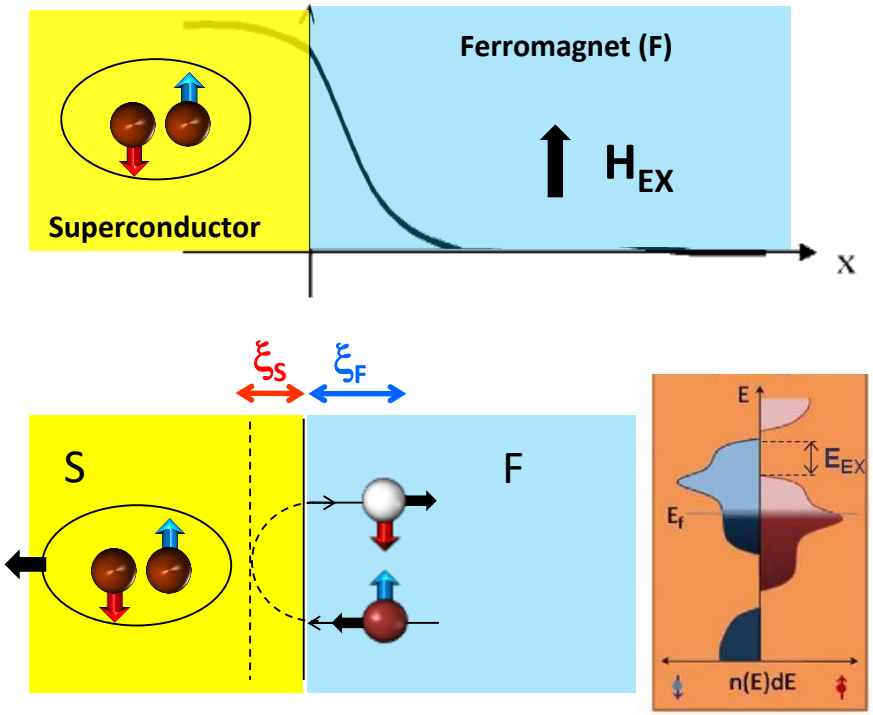
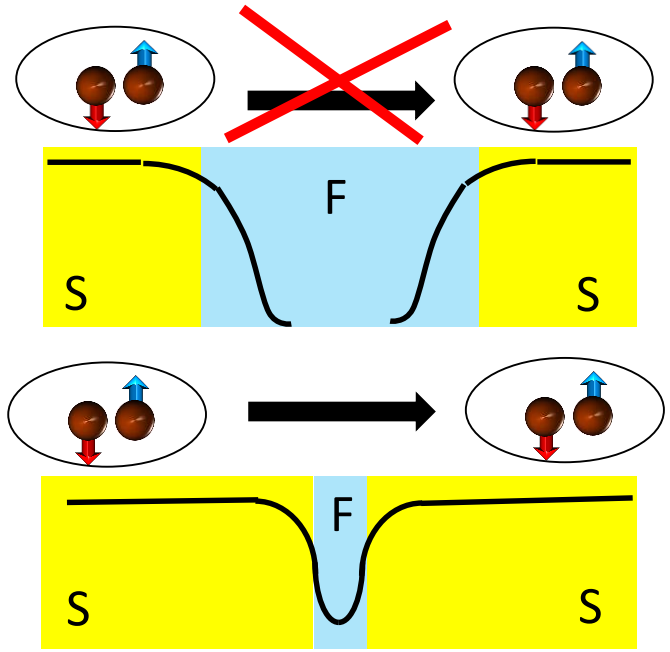
Conventional proximity effect in ferromagnets



$$\xi_F = \frac{\hbar v_F}{2E_{ex}} \sim 1 \text{ nm } ! !$$



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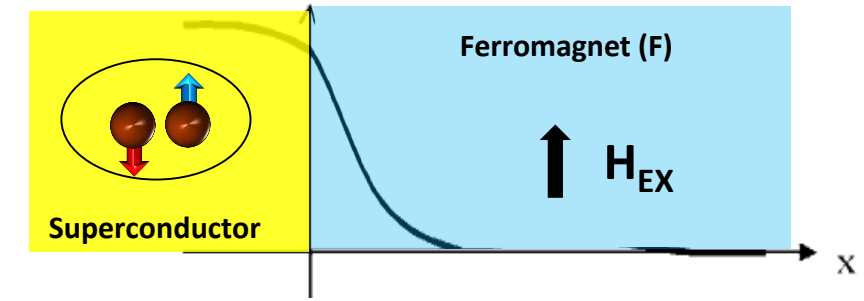

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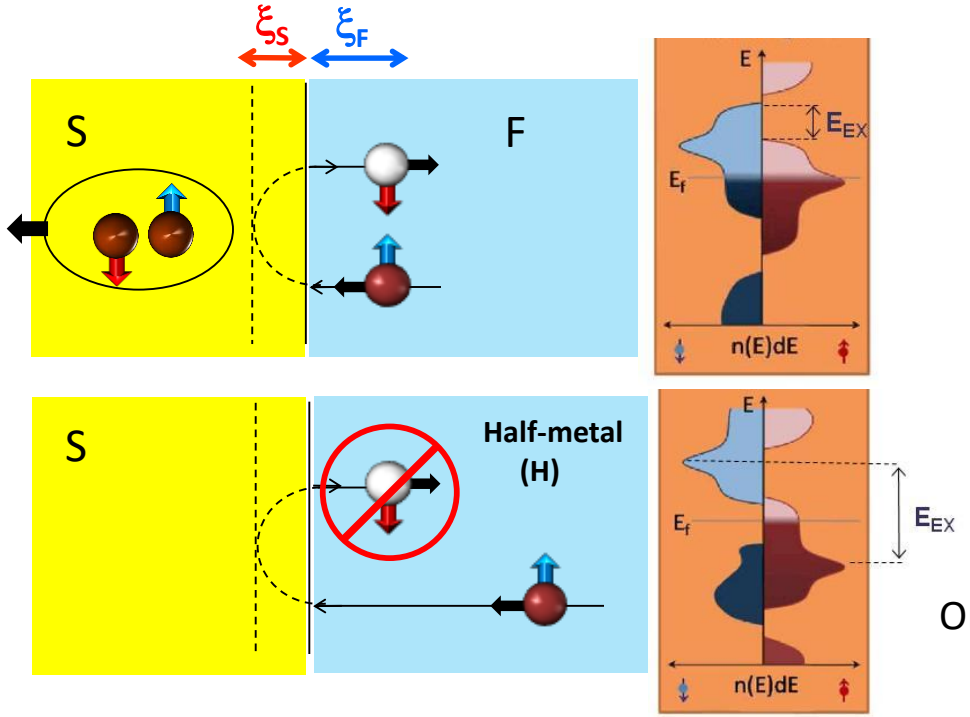
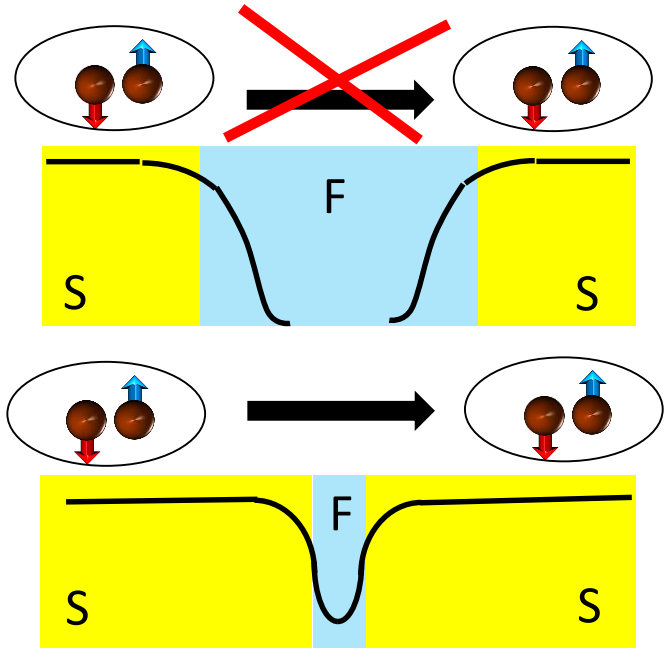
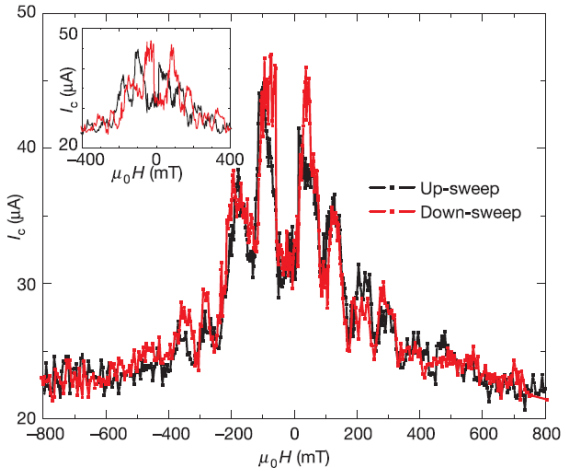


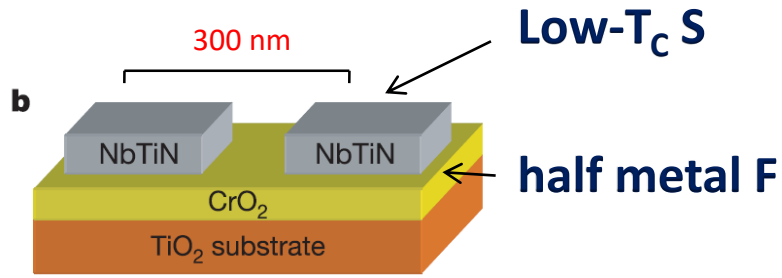


Only <u>short-range</u> supercurrent across the F

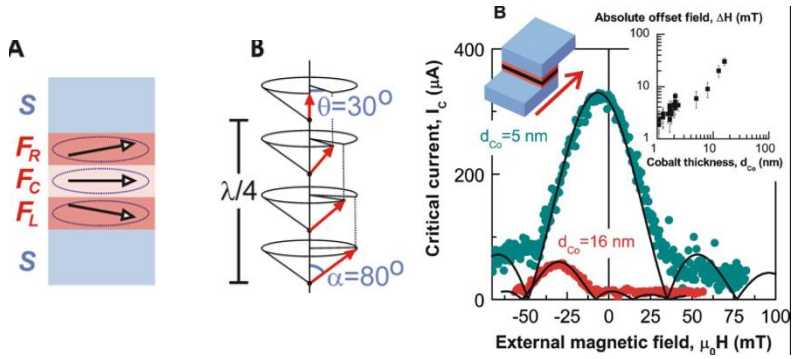
→NO SINGLET SUPERCURRENTS ACROSS HALF-METALS

Early experiments with low-Tc superconductors

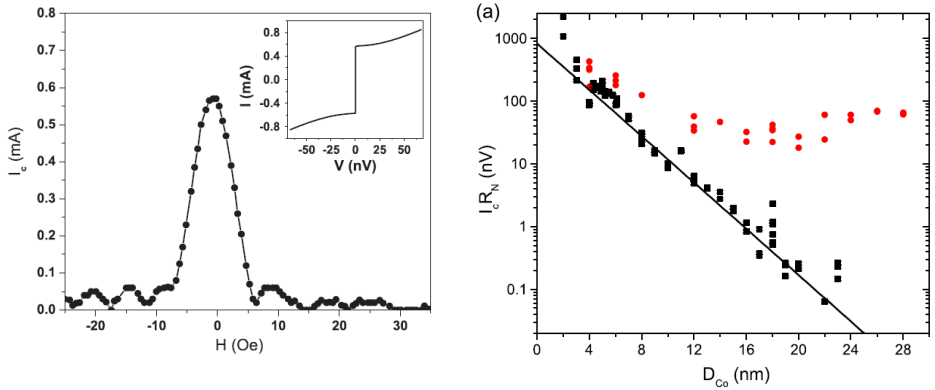




R. S. Keizer et al. Nature 439 (2006)



J. W. A. Robinson *et al*, Science (2010)

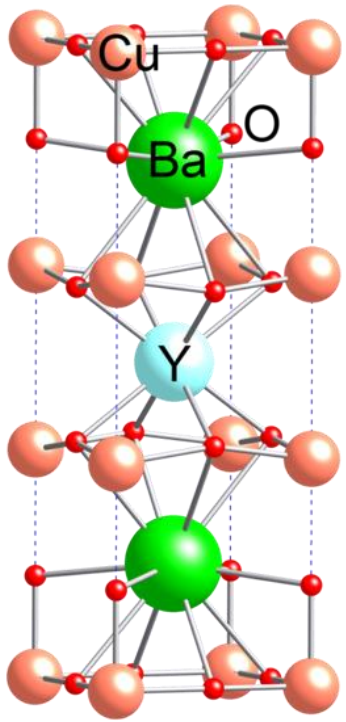


T. Khaire et al, PRL 104, 137002 (2010)

See also: Anwar et al. PRB (2010) & Sprungmann et al. PRB (2010)

→LONG-RANGE JOSEPHSON COUPLING ACROSS STRONG F

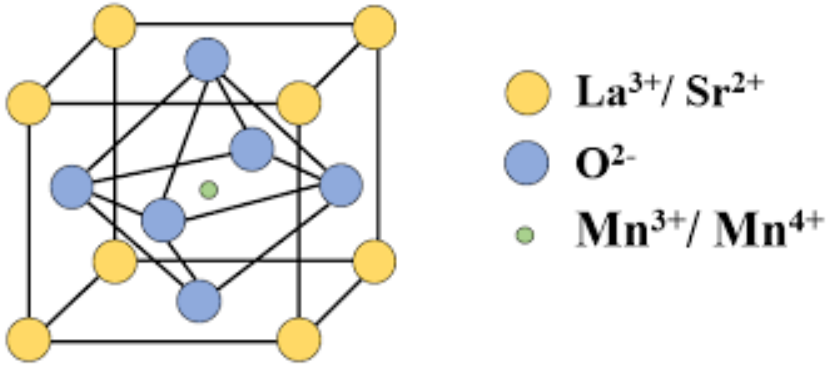
Aim: the case of high-T_C superconductors



<u>Superconductor</u>: $YBa_2Cu_3O_7$ (YBCO)

- d-wave
- high-T_C

<u>Ferromagnets:</u> $La_{0,7}Sr_{0,3}MnO_3$ (LSMO) or $La_{0,7}Ca_{0,3}MnO_3$

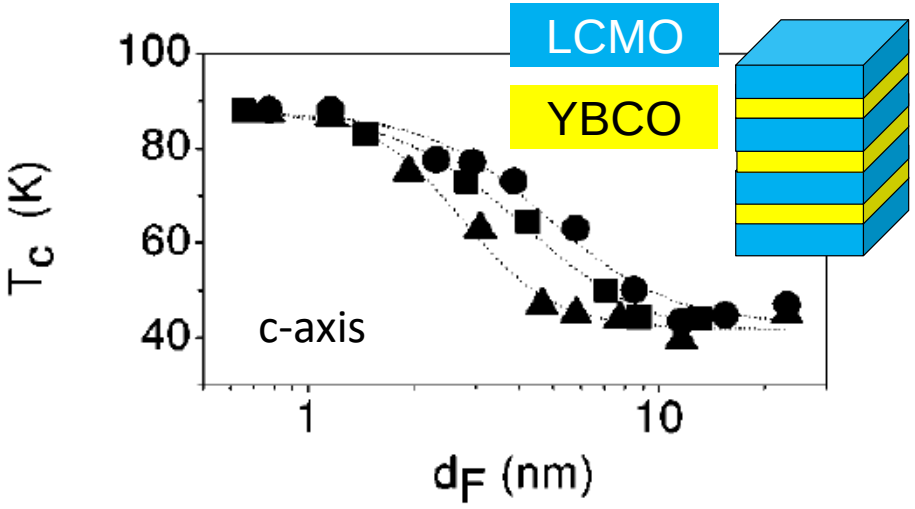


- Half-metal

(100% spin-polarized)

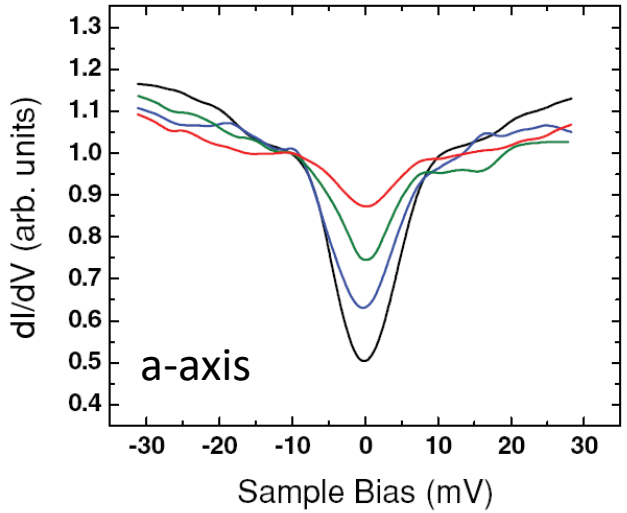
Long-range proximity effect in $YBa_2Cu_3O_7/La_{2/3}Ca_{1/3}MnO_3$

high-temperature superconductor / half-metal ferromagnet

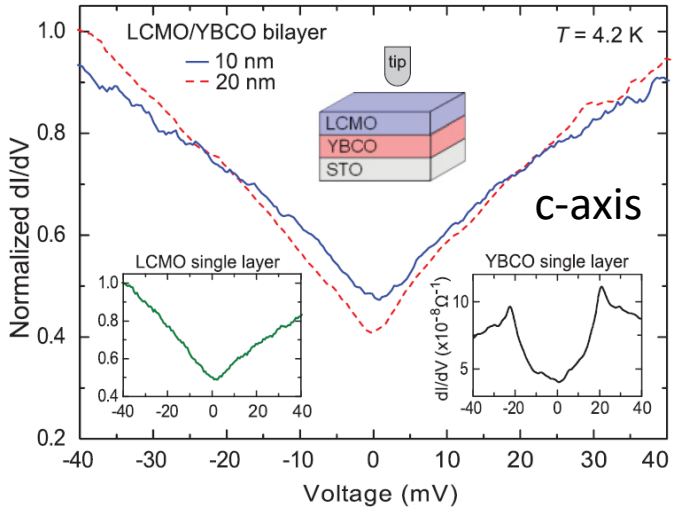


Sefrioui, JEV *et al.* PRB *67, 214511* (2003)
Peña *et al.* PRB 69, 224502 (2004)

T_c DEPRESSION → PROXIMITY EFFECT



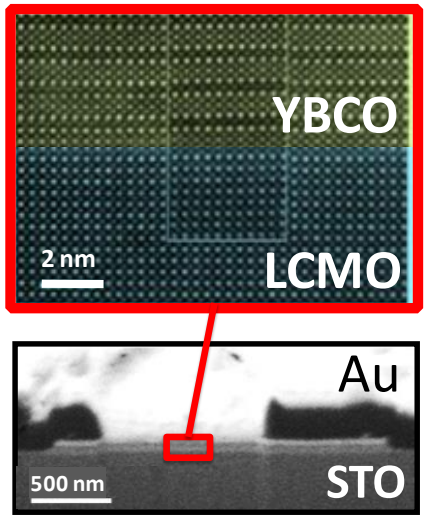
Kalcheim *et al.* Phys. Rev. B 83, 064510 (2011)



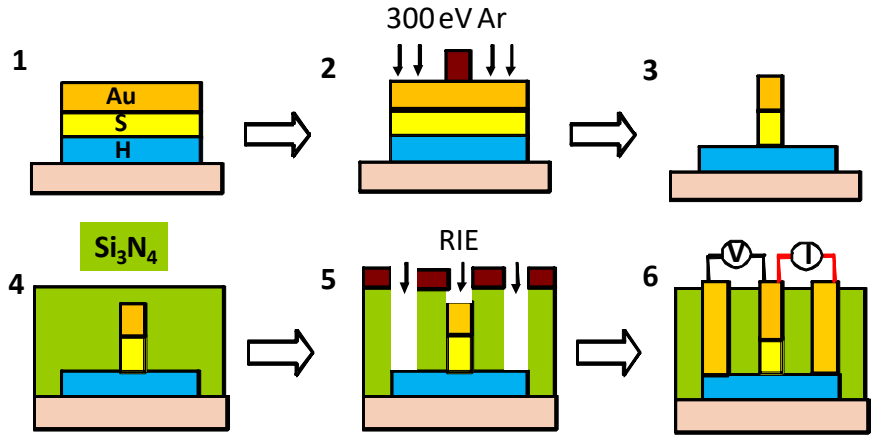
Fridman et al. Phys. Rev. B 84, 104522 (2011)

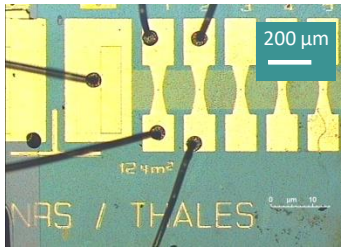
High-T_C/half-metal junctions

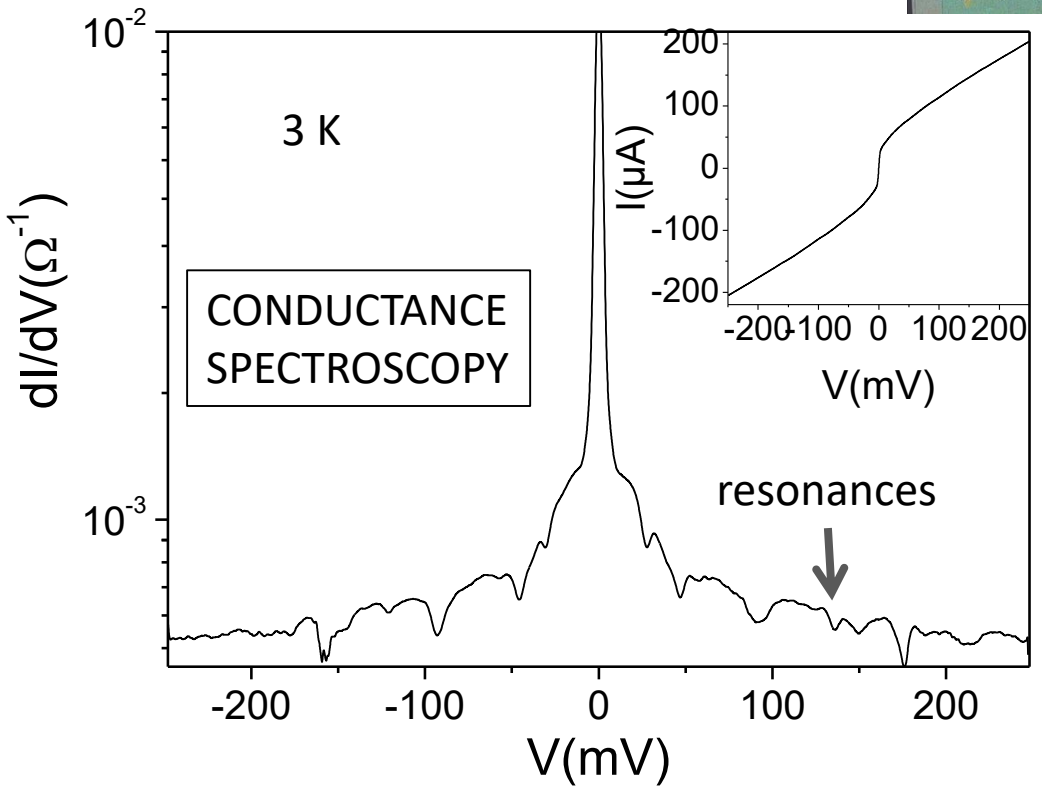
$YBa_2Cu_3O_7$
$La_{2/3}Ca_{1/3}MnO_3$



grown by Santamaria's group (UCM Spain)

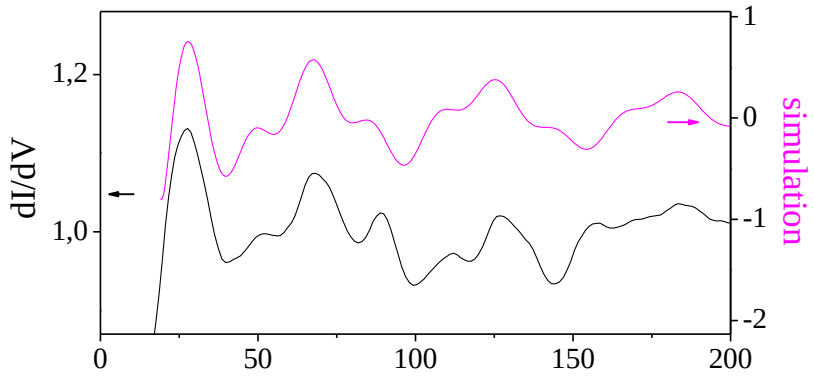




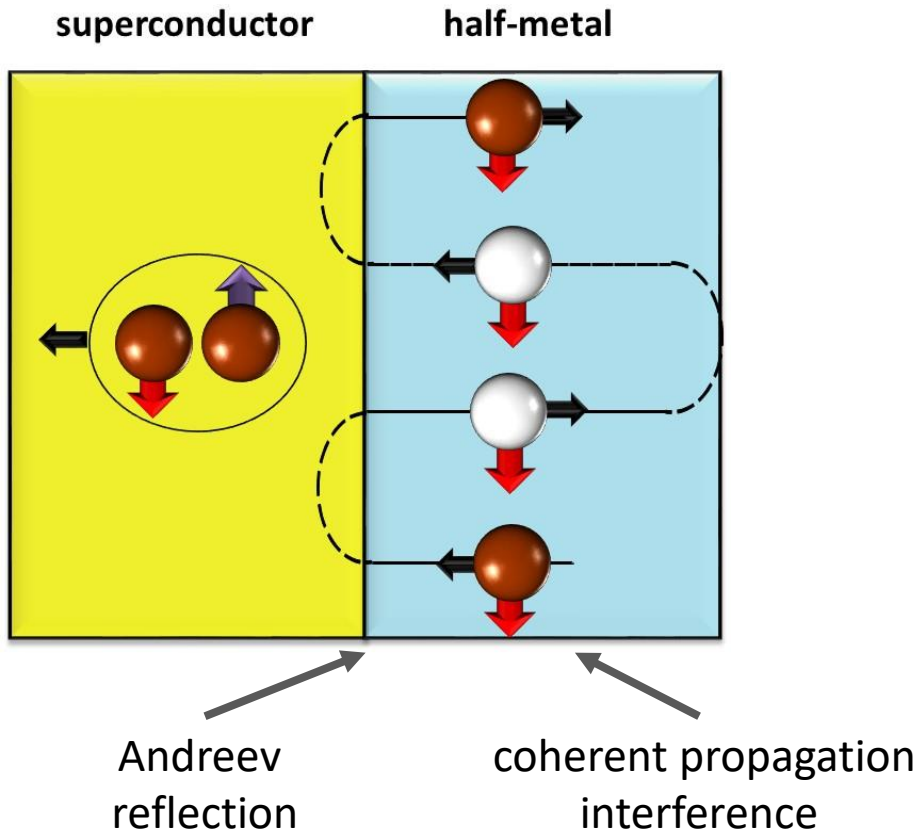


Equal-spin Andreev reflection

Tomasch & McMillan-Rowell resonances



$$V_m = V_0 + \frac{mhv_F^N}{4d_N}$$

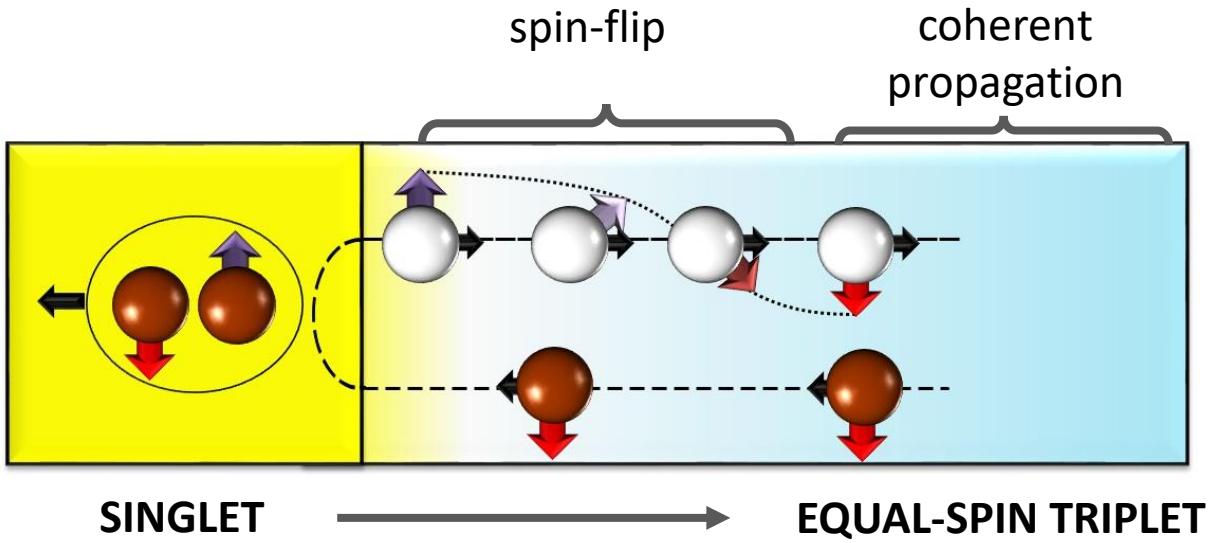


→ ANDREEV REFLECTION

→PHASE COHERENT, SPIN-POLARIZED CHARGE TRANSPORT

Visani, Santamaría, Villegas et al. **Nature Physics** (2012)

Equal-spin triplets: physical origin

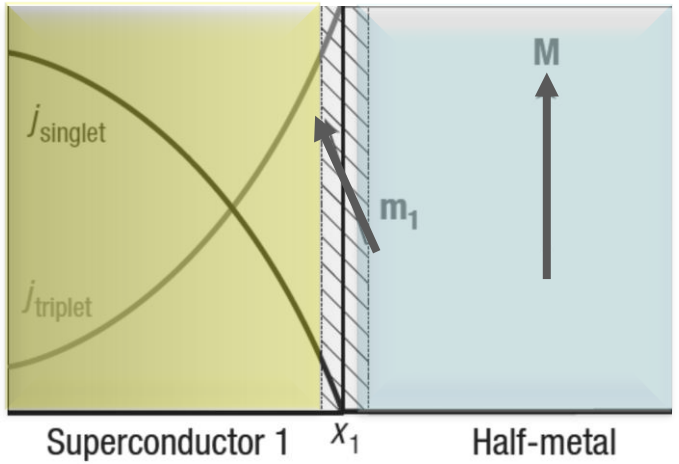


ARTICLES *Nat. Phys.* **4**, 138-143 (2008).

Triplet supercurrents in clean and disordered half-metallic ferromagnets

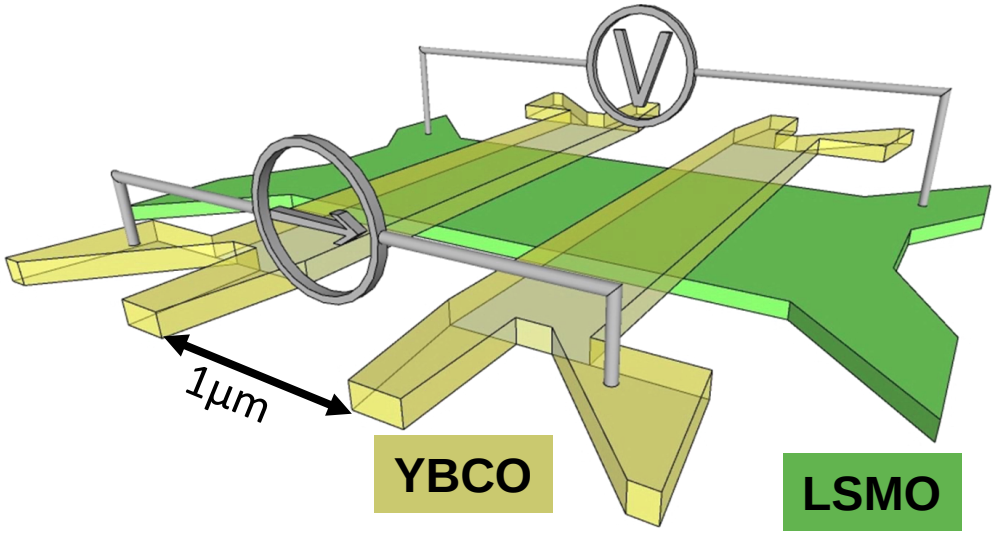
MATTHIAS ESCHRIG* AND TOMAS LÖFWANDER†

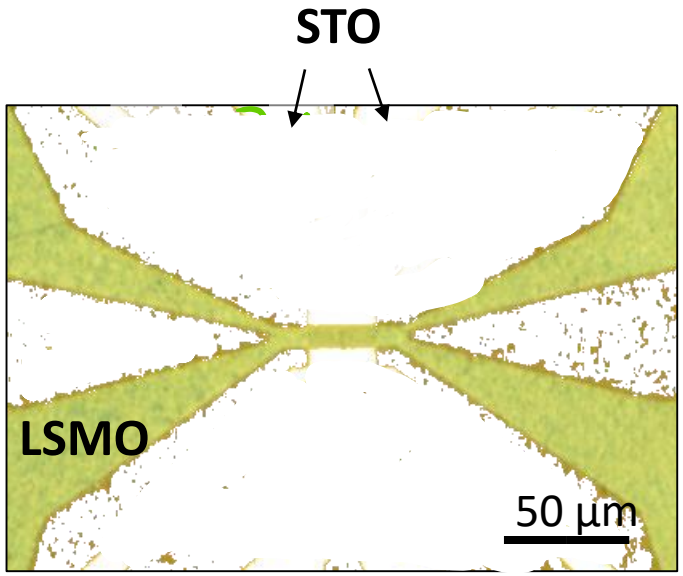
Bergeret et al. *Rev. Mod. Phys.* **77**, 1321-1373 (2005)
Buzdin et al. Phys. Rev. B 76 060504 (2007)
Linder et al. *Phys. Rev. B* **81**, 174526 (2010)



→ **MAGNETIC INHOMOGENEITY YIELDS SPIN-FLIP**

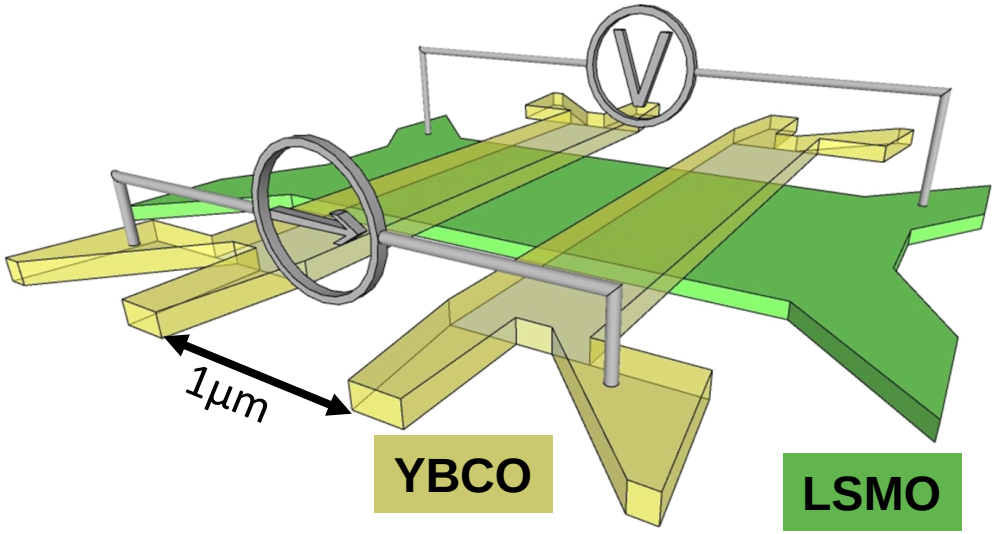
Fabrication of planar Josephson junctions

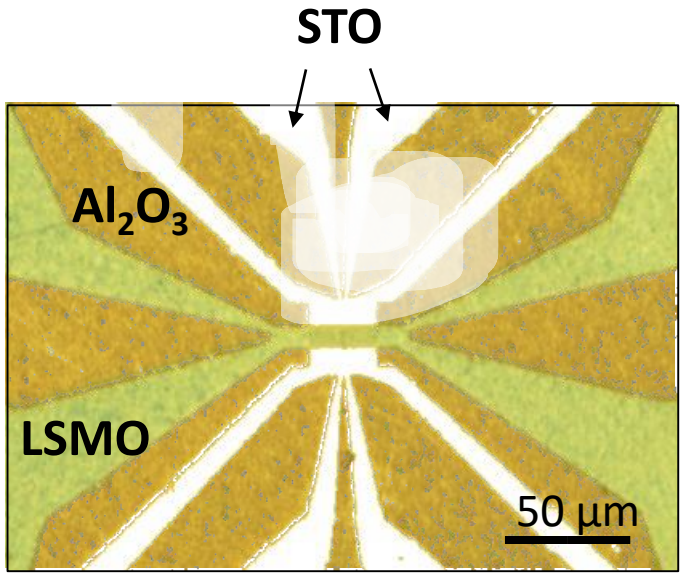




→ **PLD GROWTH OF LSMO AND LITHOGRAPHY**

Fabrication of planar Josephson junctions

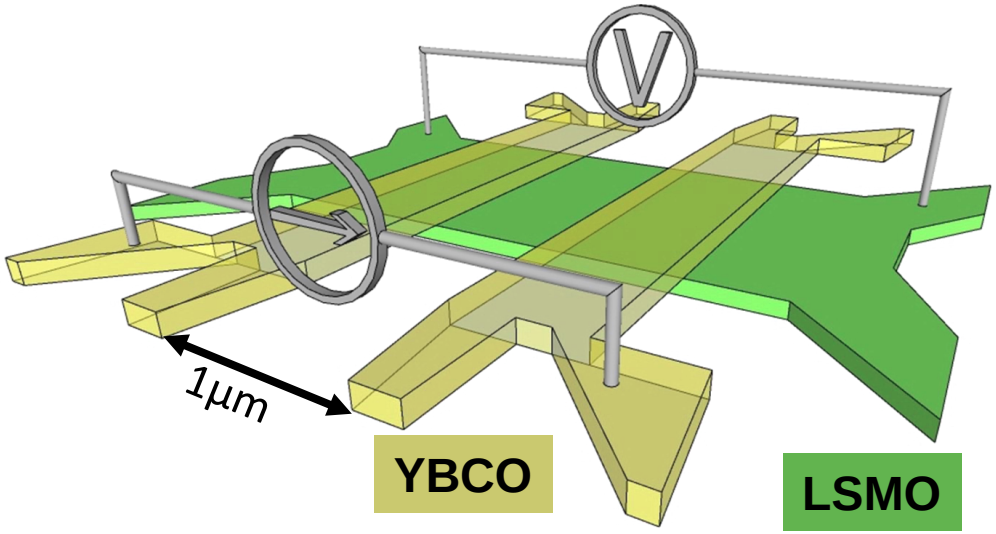




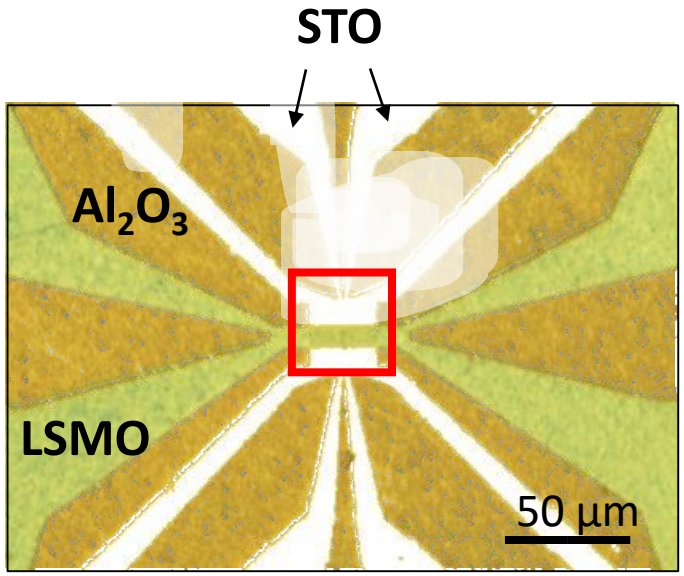
→ **E-BEAM LITHOGRAPHY**

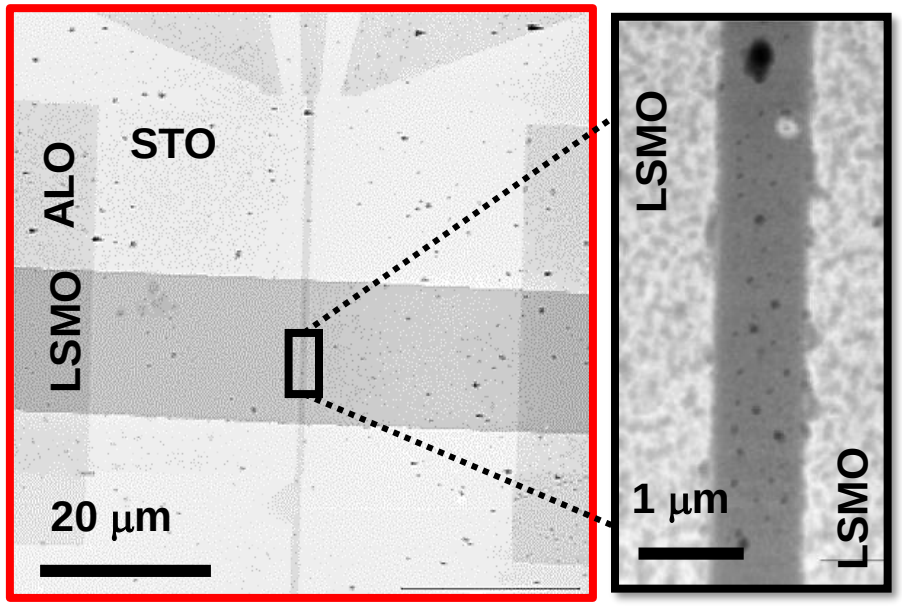
→**DEPOSITION OF AMORPHOUS ALUMINA**

Fabrication of planar Josephson junctions

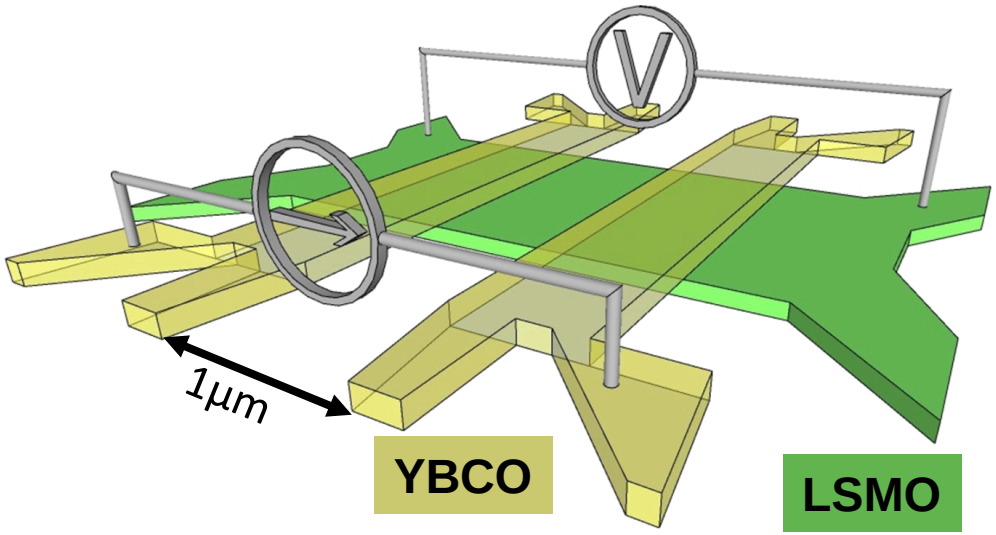


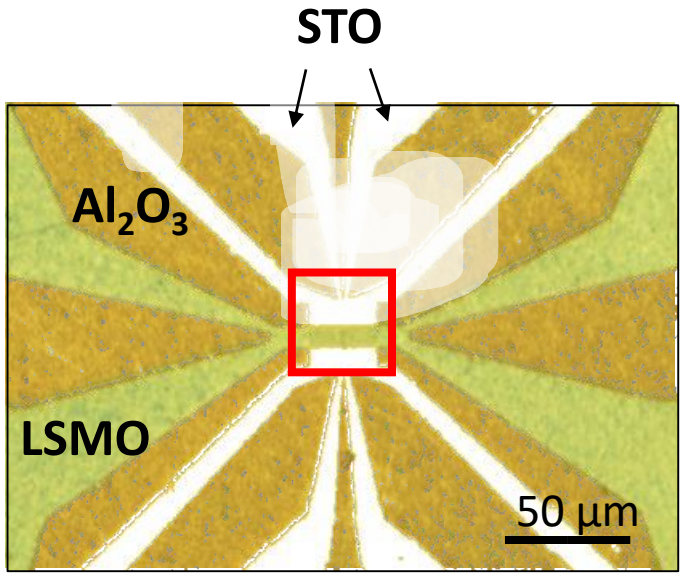
→AMORPHOUS ALUMINA MASK

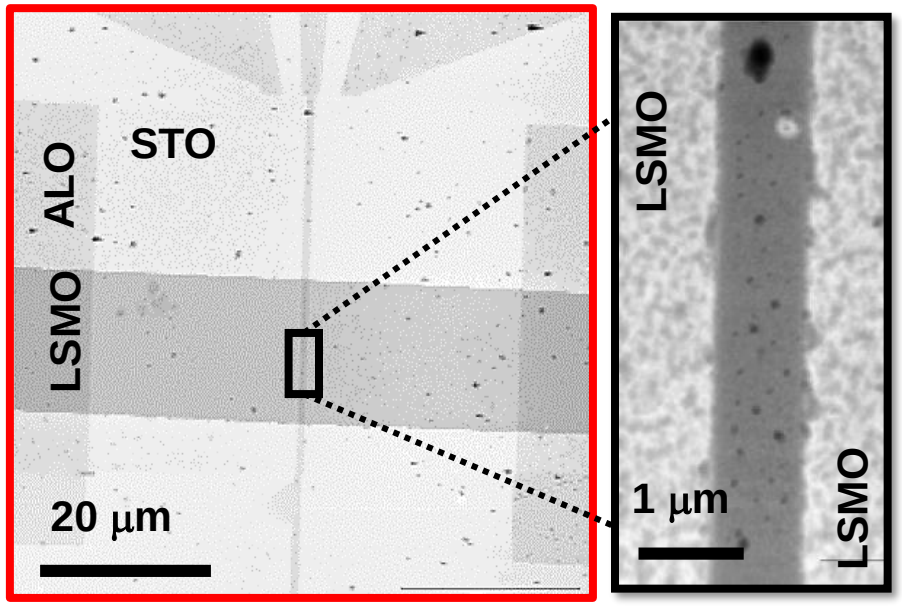




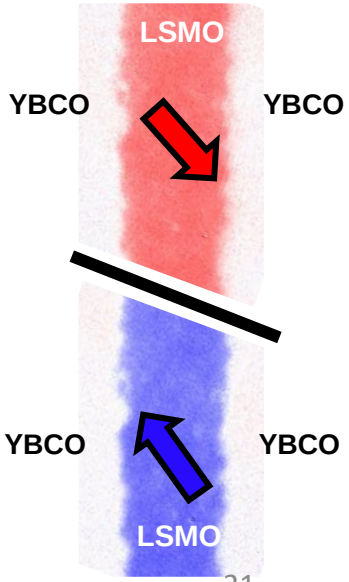
Fabrication of planar Josephson junctions







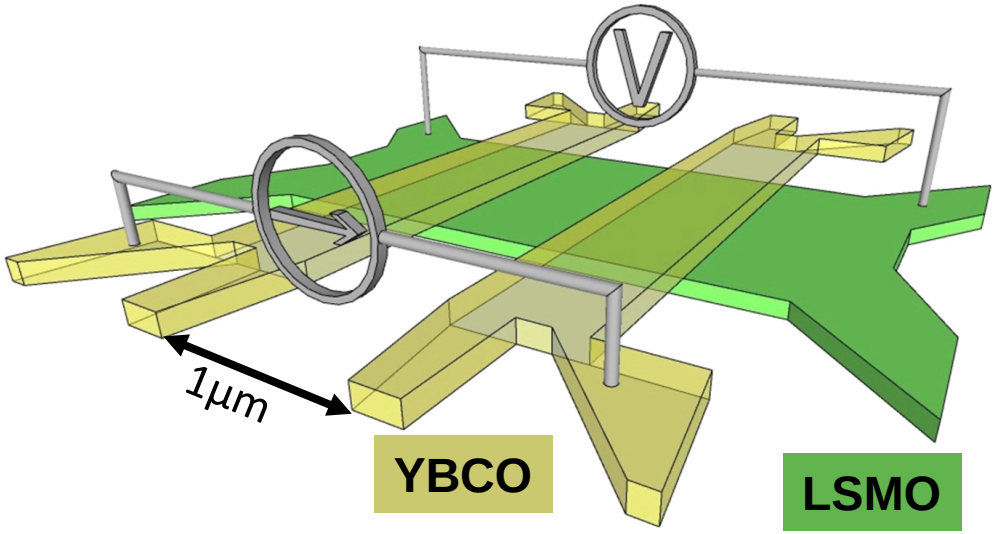
XMCD-PEEM

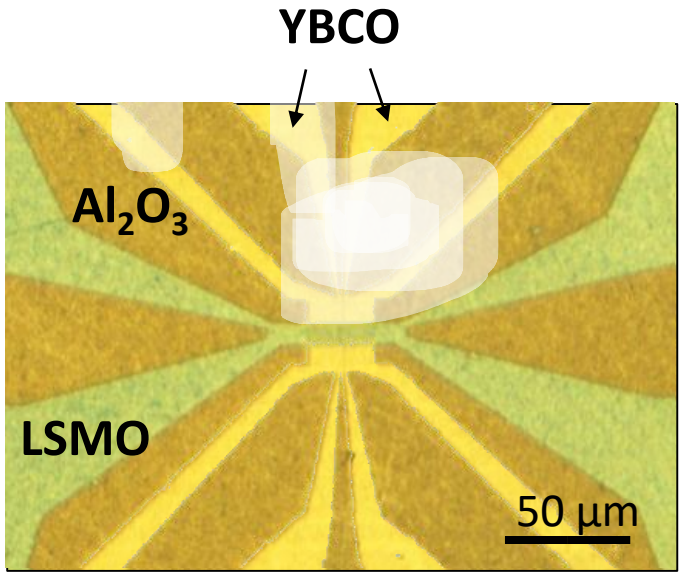


→AMORPHOUS ALUMINA MASK

→LSMO REMAINS MAGNETIC

Fabrication of planar Josephson junctions

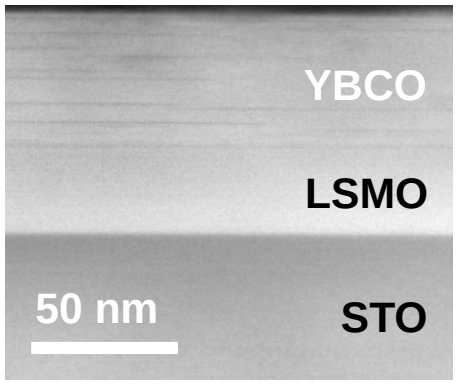


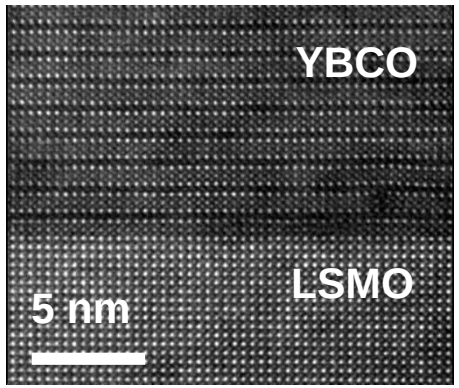


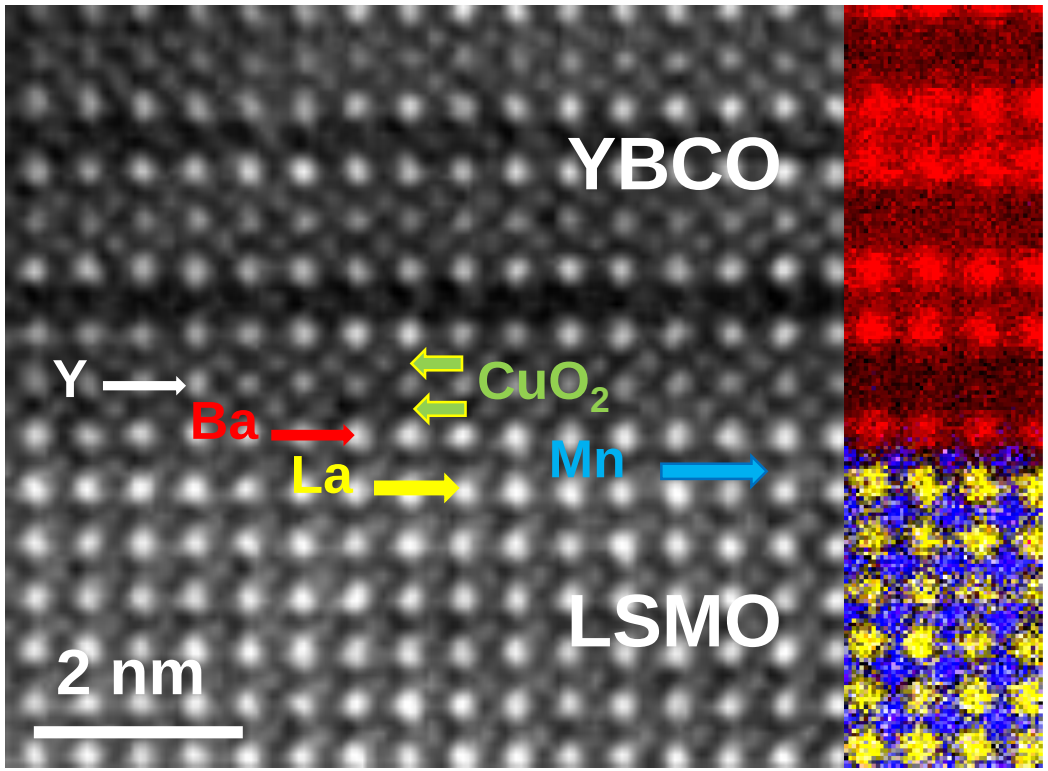
→ **PLD GROWTH OF EPITAXIAL YBCO**

Interface quality

Z-contrast EELS

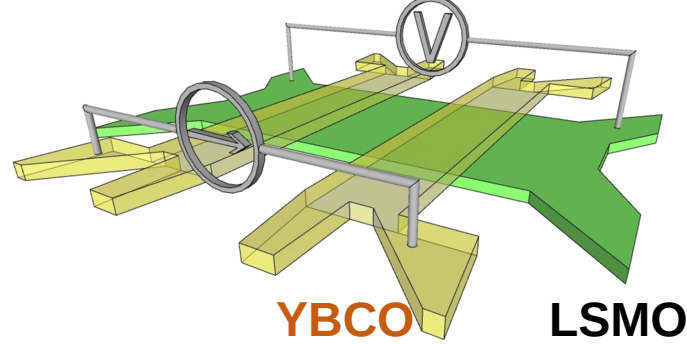


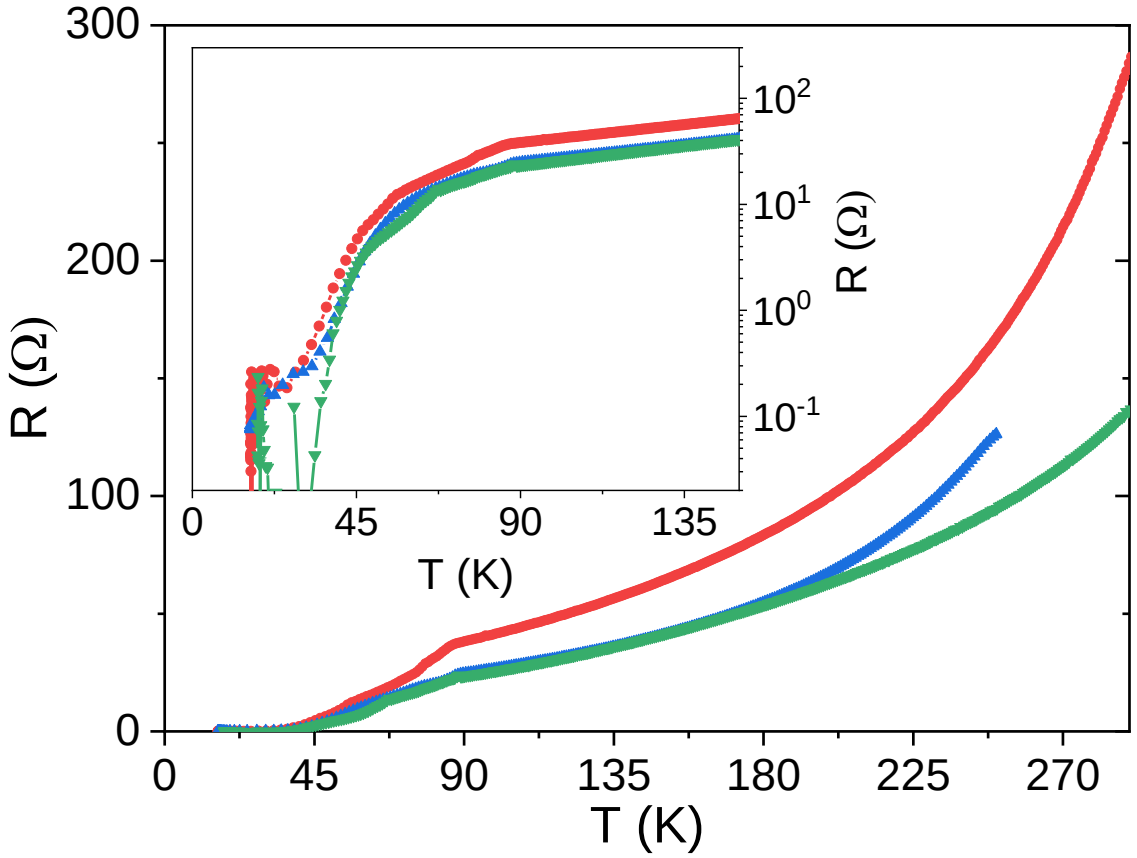


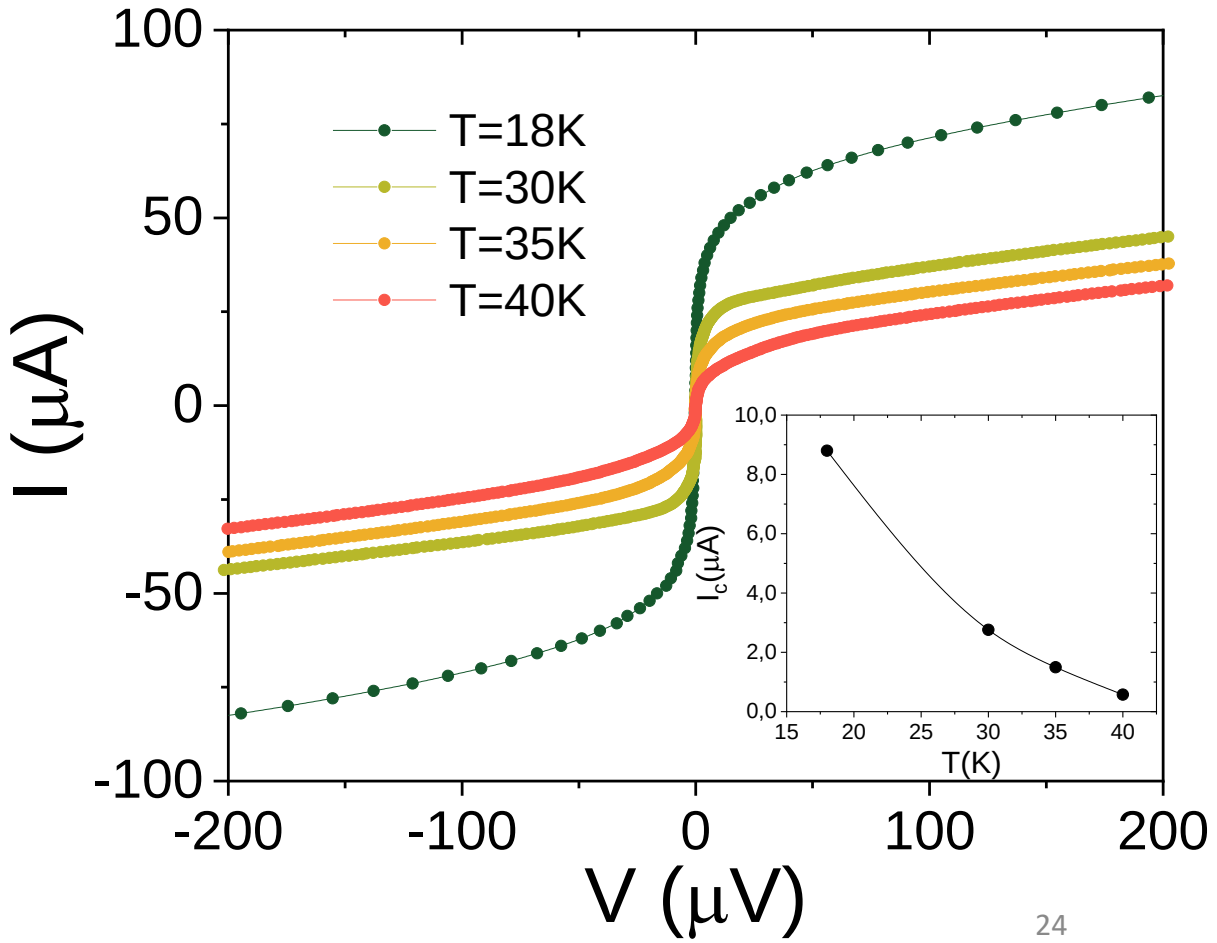


→ **HIGH QUALITY INTERFACES DESPITE EX-SITU GROWTH**

Supercurrents across the device

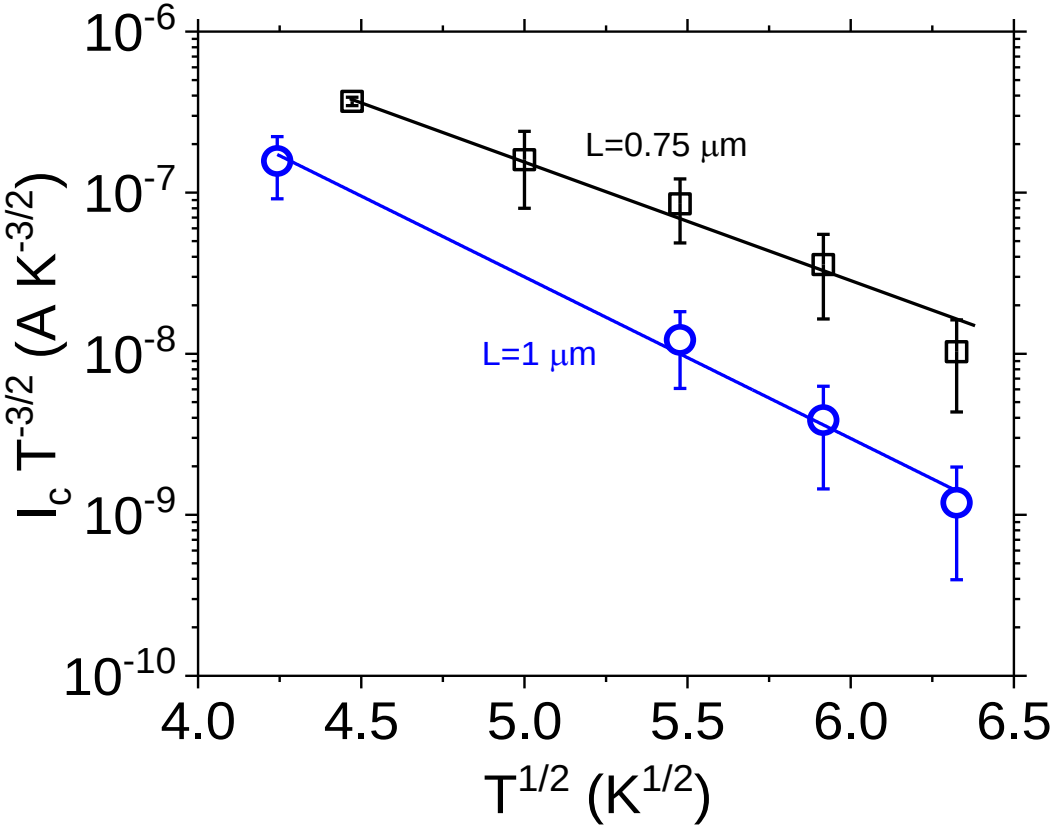






→**ZERO RESISTANCE STATE AT ~ 40K**

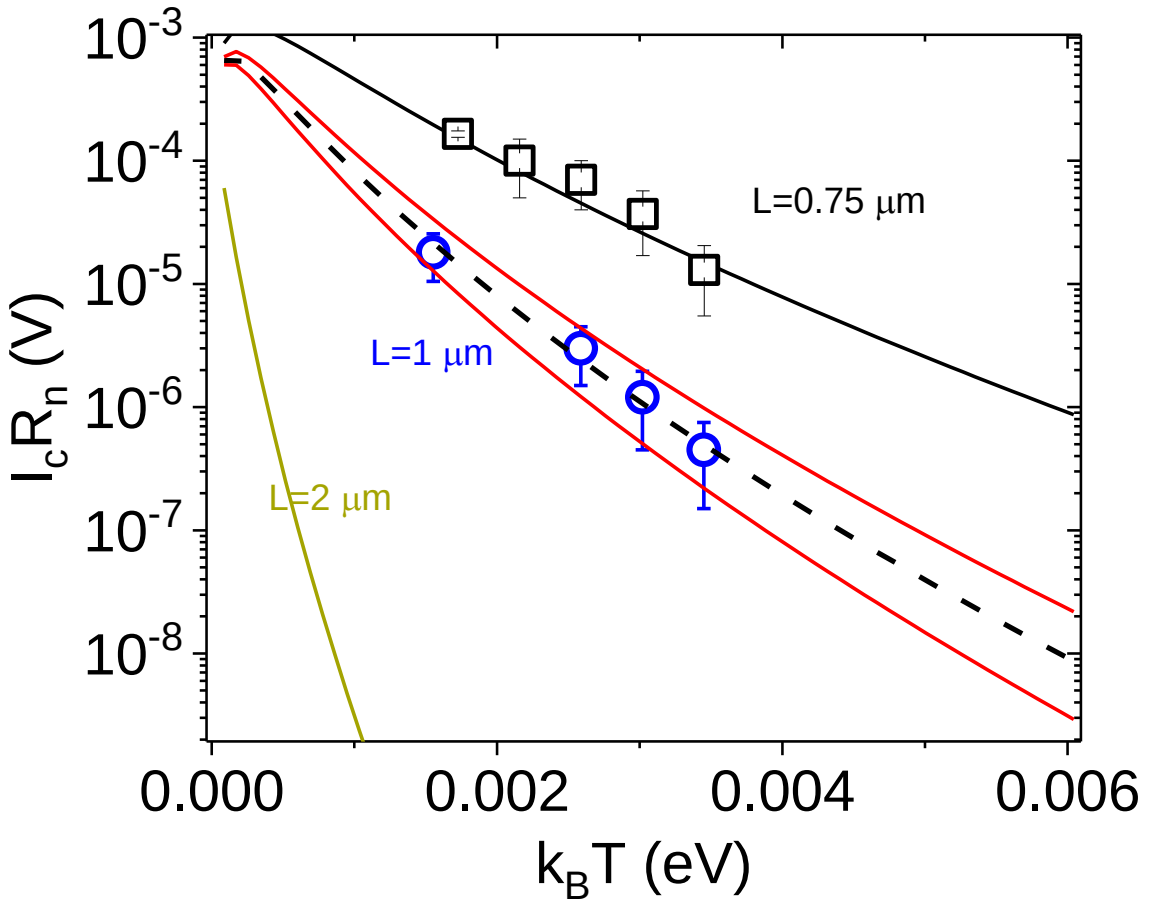
Size of critical current



$I_c \propto T^{3/2} \exp(\sqrt{2\pi k_B T / E_{Th}}) \rightarrow \ln(I_c) - \frac{3}{2} ln(T)$ vs $\sqrt{T}$

$$\boldsymbol{E_{Th} = 100 \pm 10\ \mu eV\ (for\ 1 \mu m)}$$

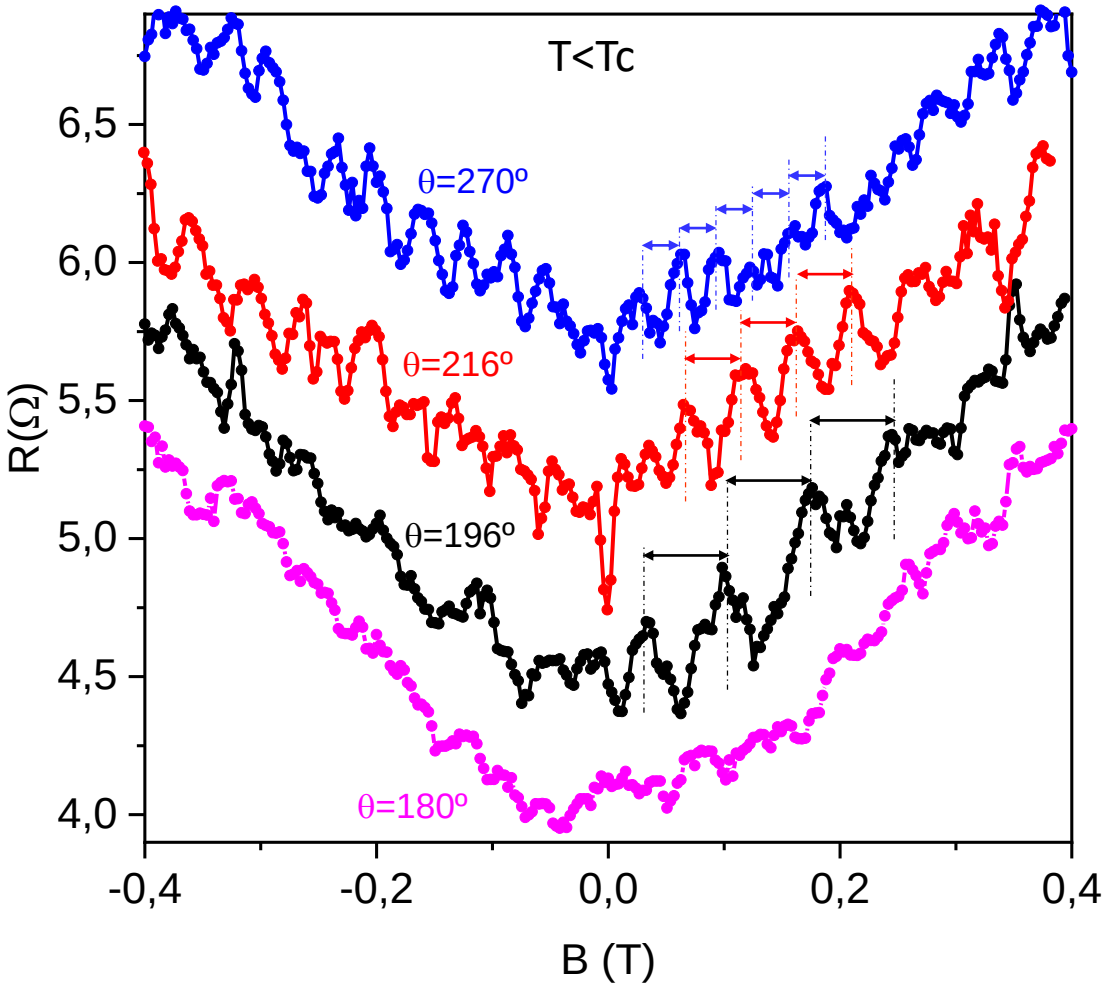
From: Anwar et al, Appl. Phys. Lett. 100, 052602 (2012)

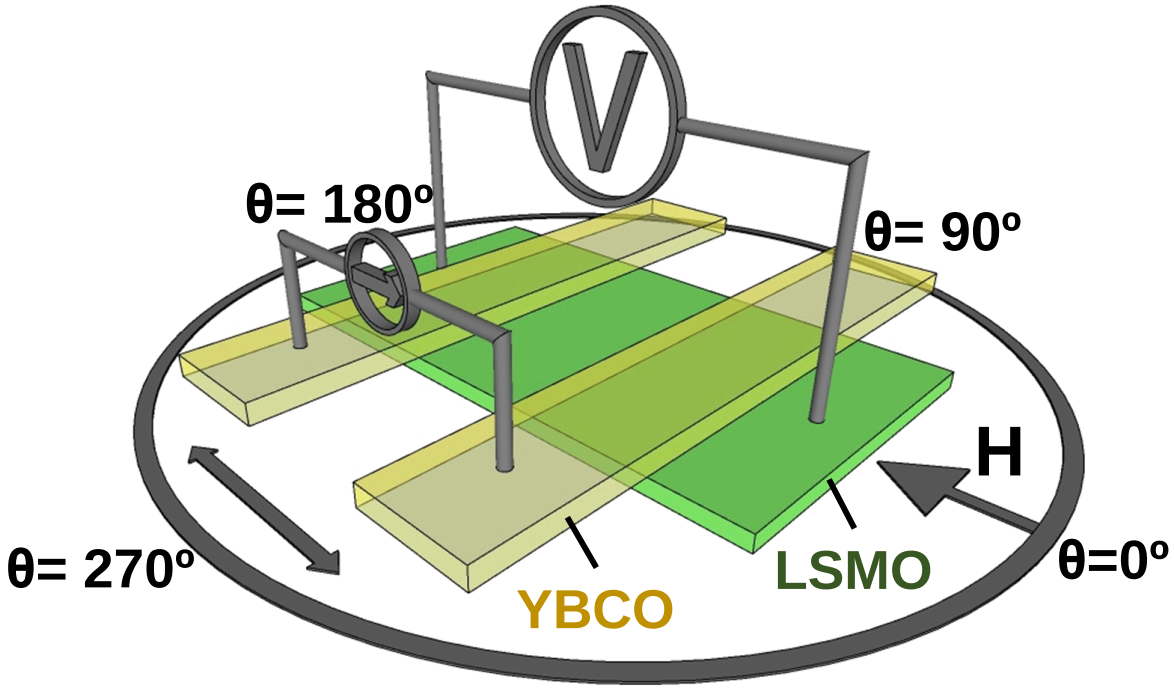


$$eI_c R_n = \frac{32}{3 + 2\sqrt{2}} E_{Th} \left[\frac{2\pi k_B T}{E_{Th}}\right]^{3/2} e^{-[2\pi k_B T / E_{Th}]^{1/2}}$$

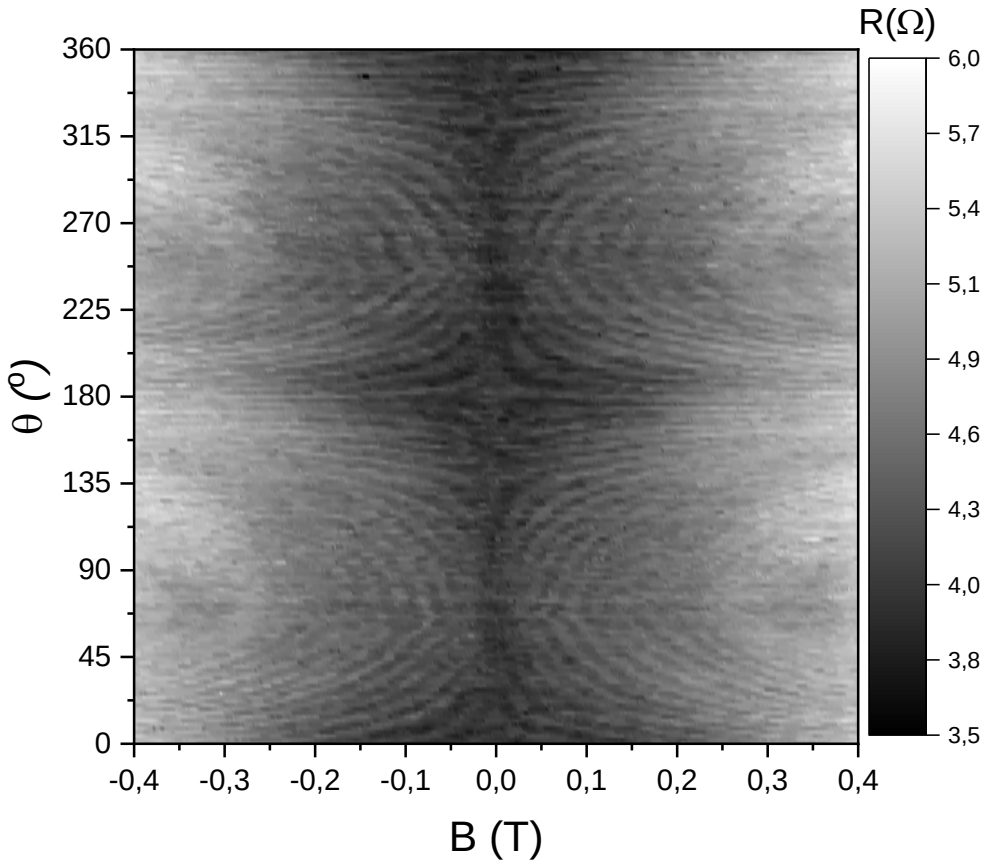
From: Dubos et al, Phys. Rev. B 63, 064502 (2001)

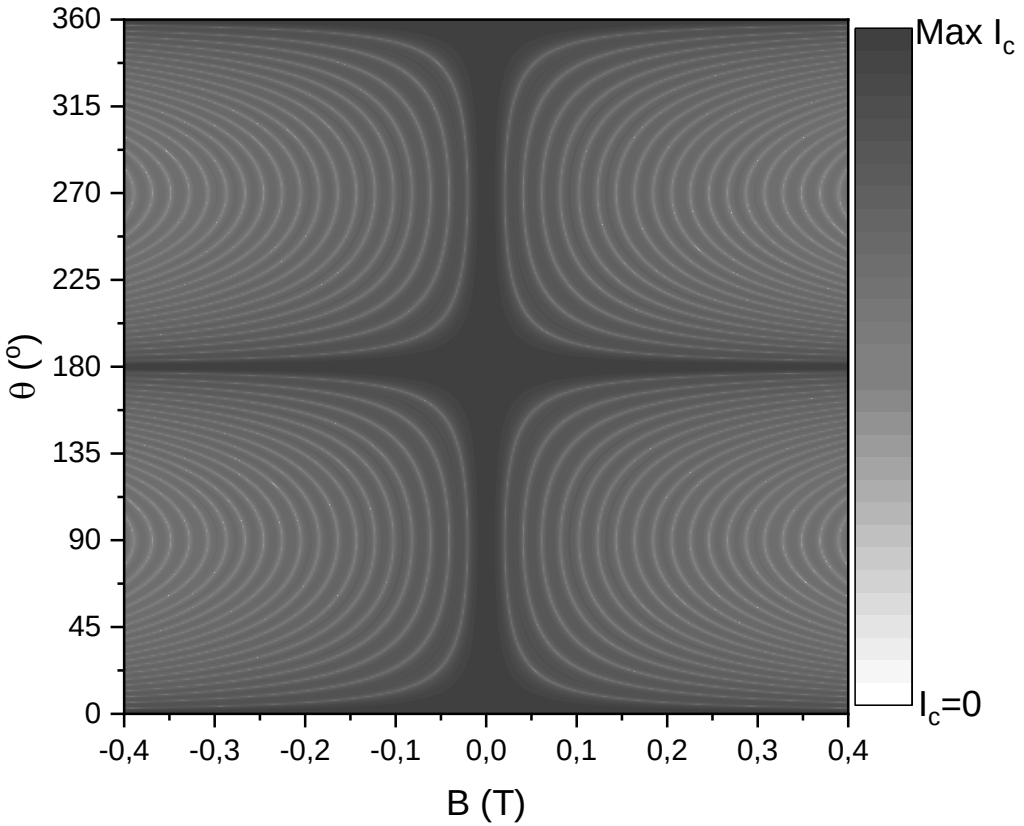
Magnetic flux quantization: angular dependence

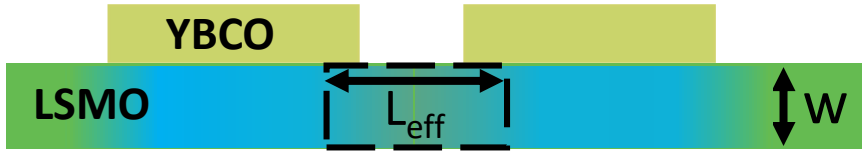




Magnetic flux quantization: angular dependence





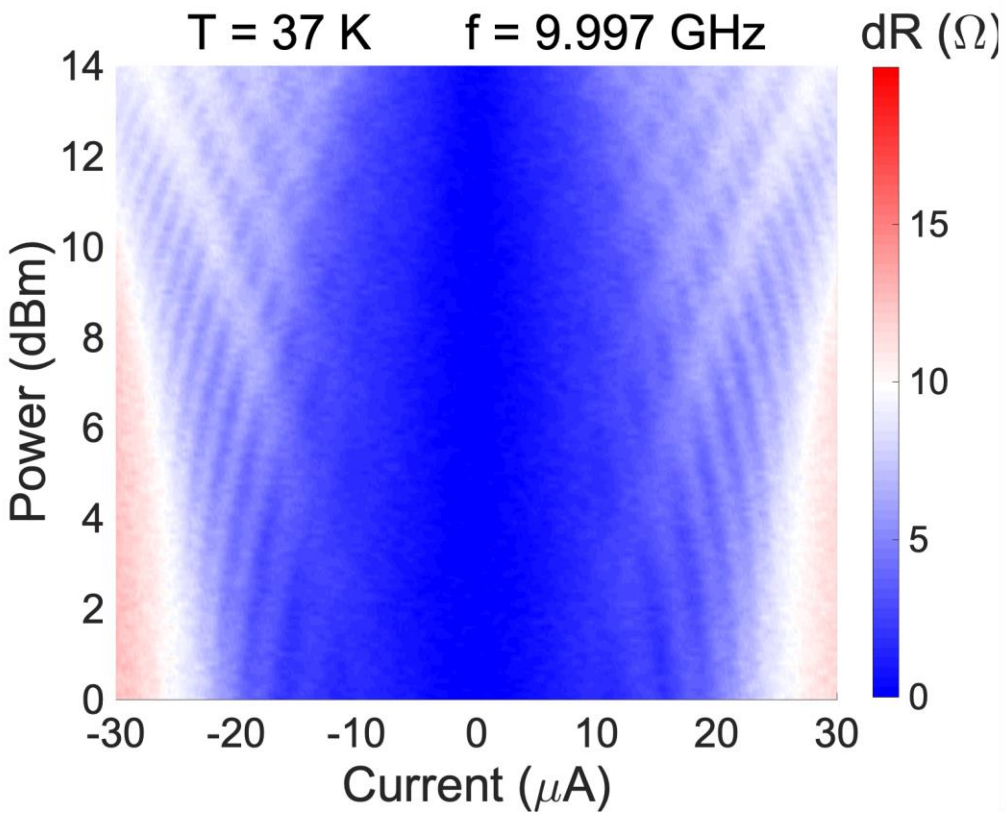


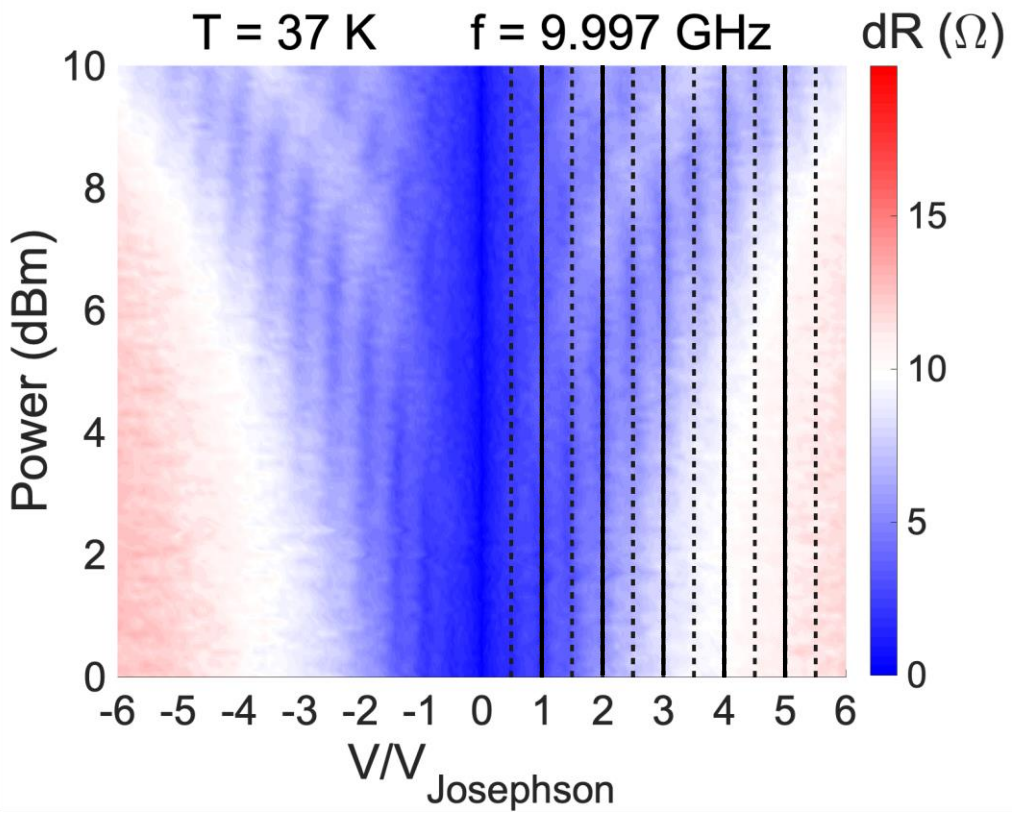
$$I_c = I_0 \left| \frac{\sin\left(\frac{\pi\phi}{\phi_0}\right)}{\left(\frac{\pi\phi}{\phi_0}\right)} \right| = I_0 \left| \frac{\sin\left(\frac{\pi H_\perp wL}{\phi_0}\right)}{\left(\frac{\pi H_\perp wL}{\phi_0}\right)} \right| = I_0 \left| \frac{\sin\left(\frac{\pi H \sin\theta\, wL}{\phi_0}\right)}{\left(\frac{\pi H \sin\theta\, wL}{\phi_0}\right)} \right|$$

L_{eff}= 3,4μm

$L_{eff}= L_{junction}+2\lambda_{YBCO}$

Shapiro steps: quantum interference





$$V_{Josephson} = n\frac{\hbar\omega}{4e}$$

$$I_c = I_0\left|\frac{\sin\left(\frac{2\pi\phi}{\phi_0}\right)}{\left(\frac{2\pi\phi}{\phi_0}\right)}\right|$$

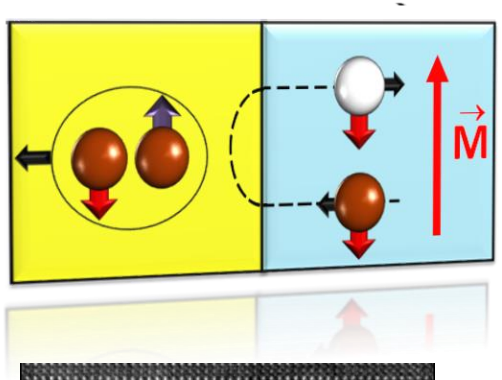
Half integer Shapiro steps→ Second harmonic component

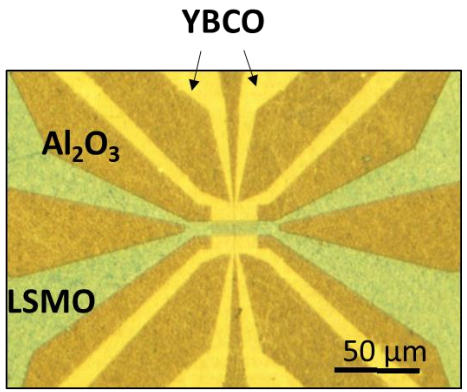
Richard, C., Houzet, M. & Meyer, J. S. *Phys. Rev. Lett.* **110**, 1–5 (2013).

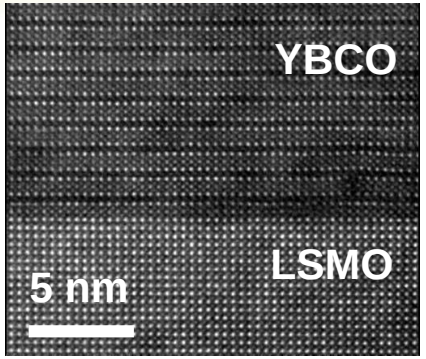
Can explain $L_{eff} = 2 \times (L_{junction} + 2\lambda_{YBCO})$

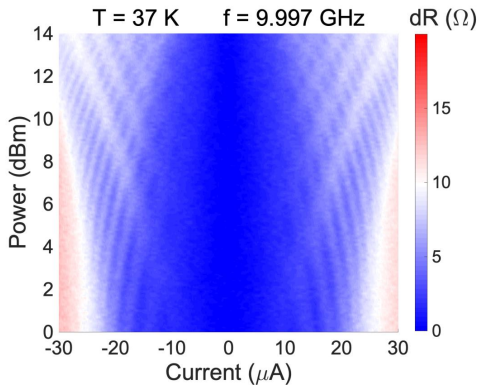
The talk in a nutsell

Proximity effect







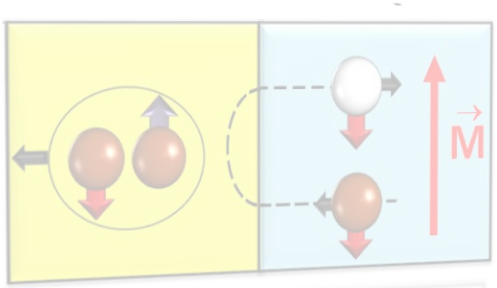


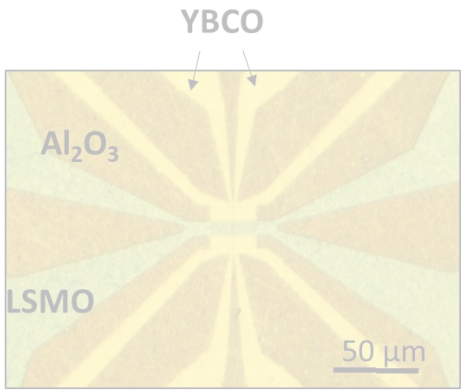
Fully spin-polarized, high-T_C Josephson supercurrents
Quantum phase coherence effects

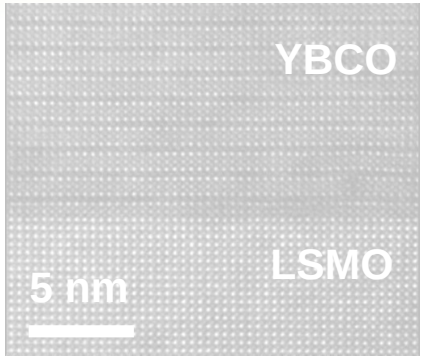
Sanchez-Manzano *et al.* Nature Materials (2022)

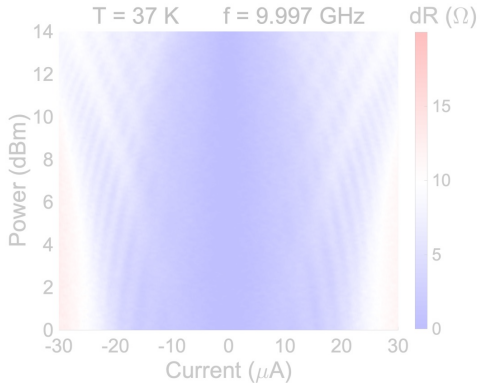
The talk in a nutsell

Proximity effect







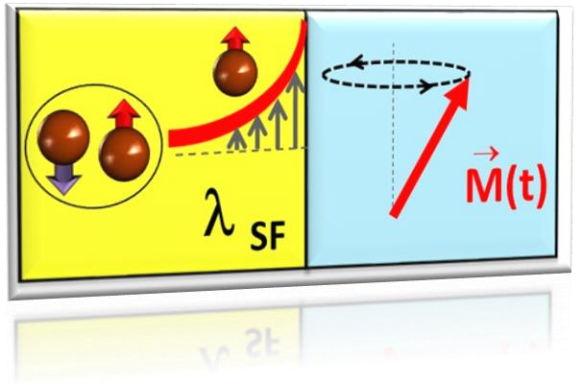


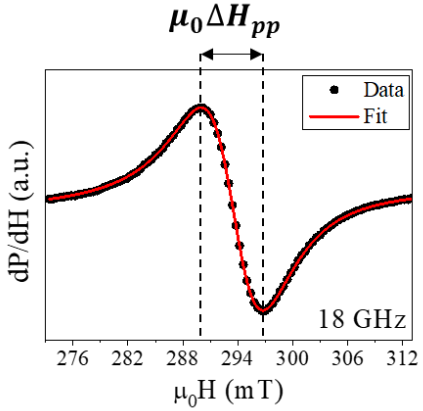
Fully spin-polarized, high-T_C Josephson supercurrent

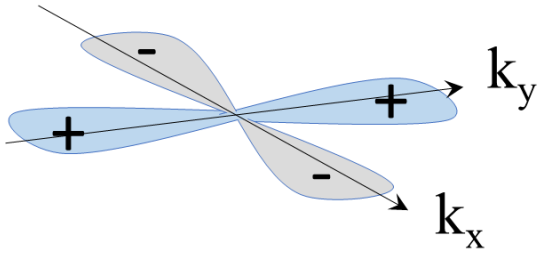
Quantum phase coherence effects

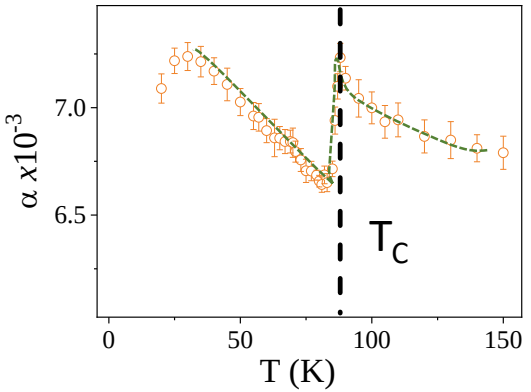
Sanchez-Manzano *et al.* Nature Materials (2022)

Dynamic coupling









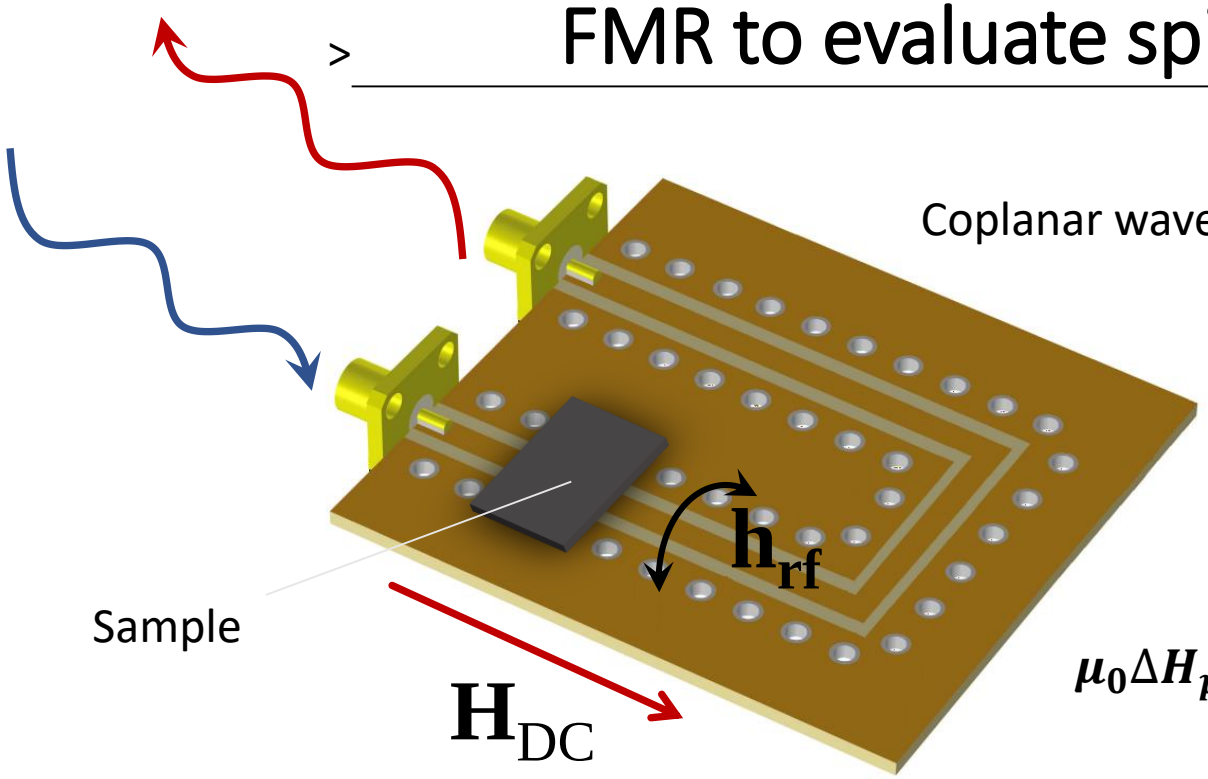
Tunable spin sink

d-wave effects

Carreira *et al.* PRB (2021)

→ OPPORTUNITIES FOR HIGH-T_C SUPERCONDUCTING SPINTRONICS

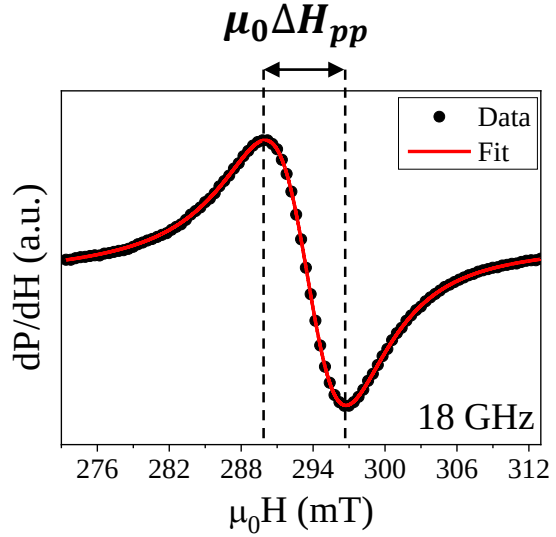
FMR to evaluate spin absorption by SC

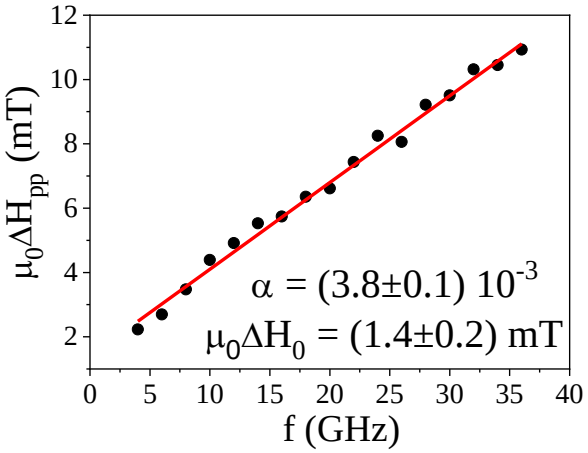


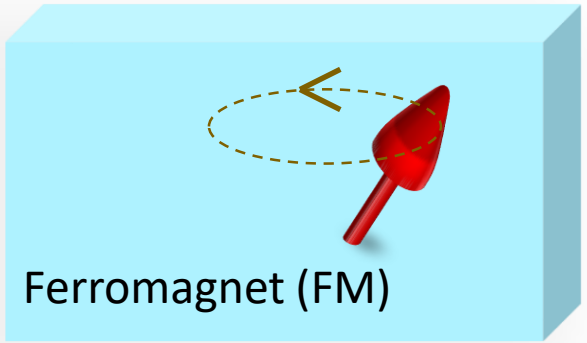
Inhomogeneous broadening

Damping

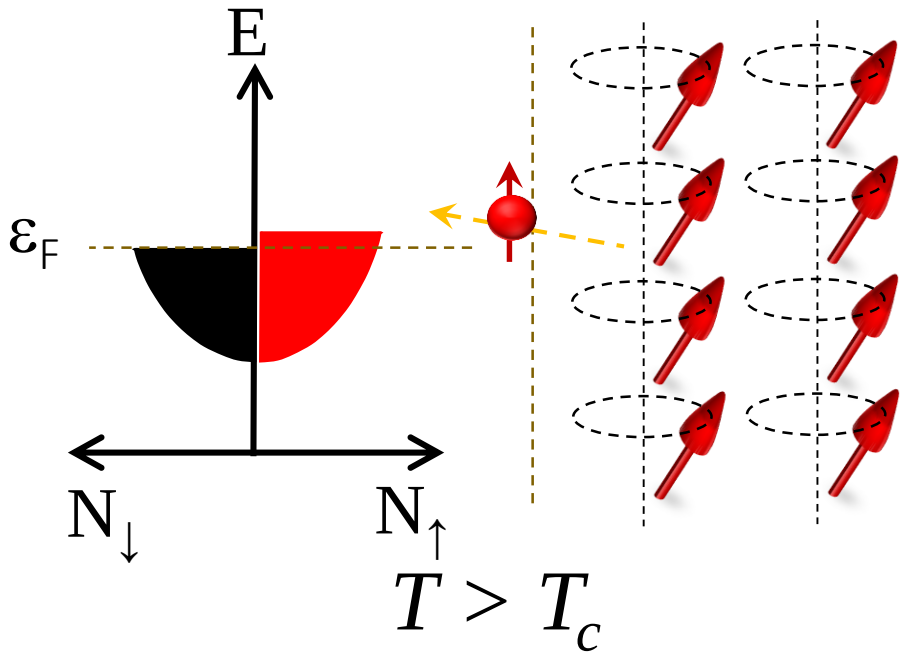
$$\mu_0 \Delta H_{pp} = \frac{2\alpha}{\sqrt{3}\gamma} f + \mu_0 \Delta H_0$$



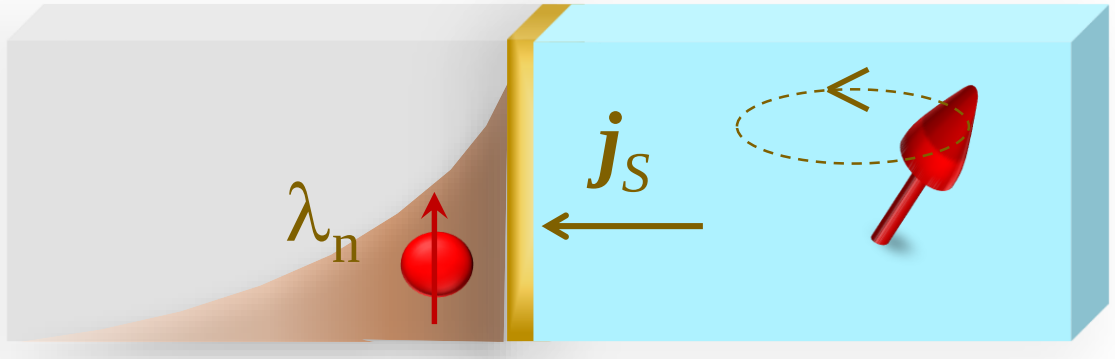




Spin pumping into normal-metal

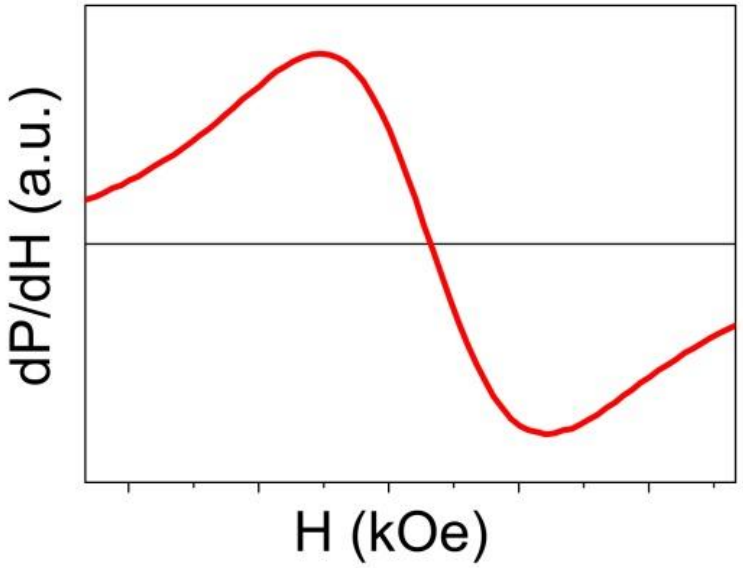


Normal metal (NM) Ferromagnet (FM)

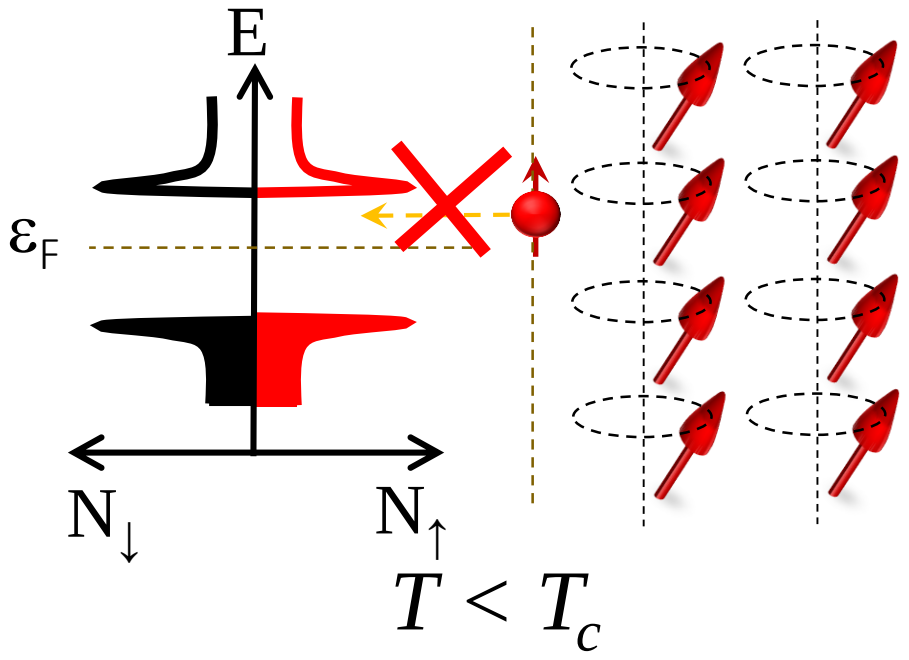


Spin sinking

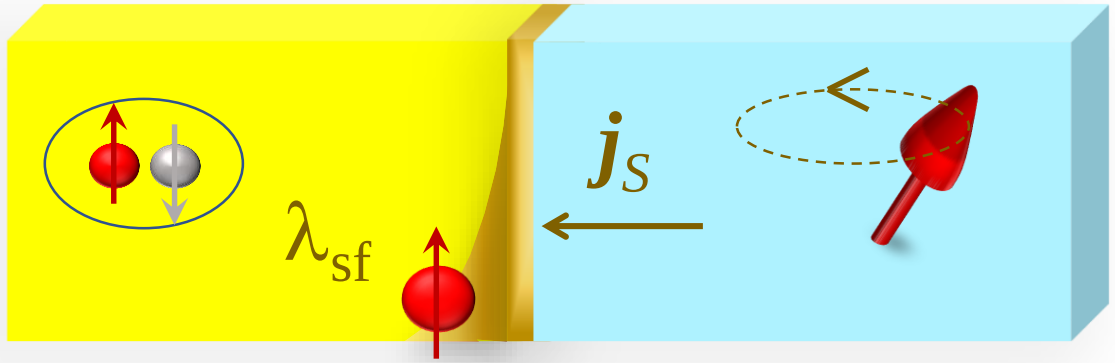
linewidth broadening



Spin pumping into a superconductor

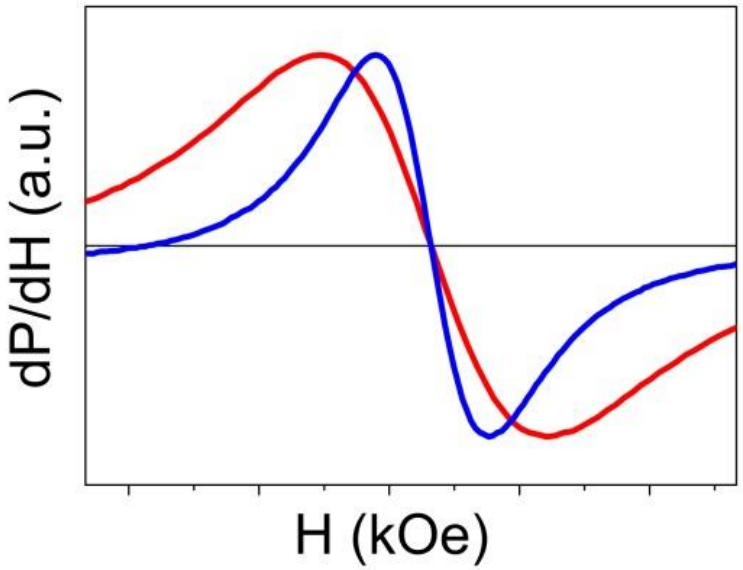


Superconductor (SC) Ferromagnet (FM)

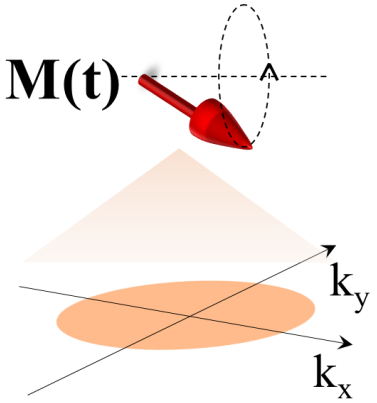


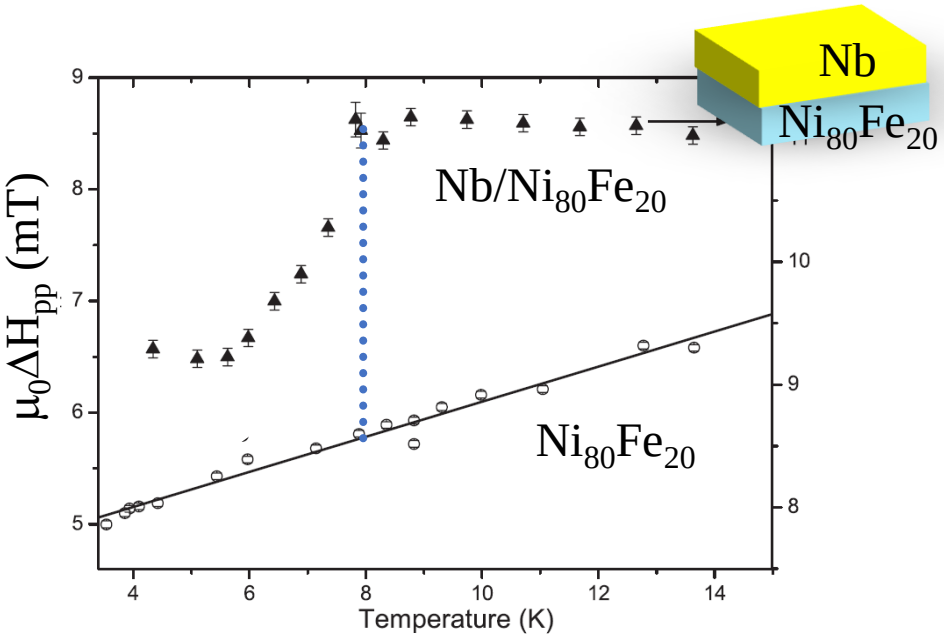
Vanishing DOS reduces spin sinking

linewidth narrowing

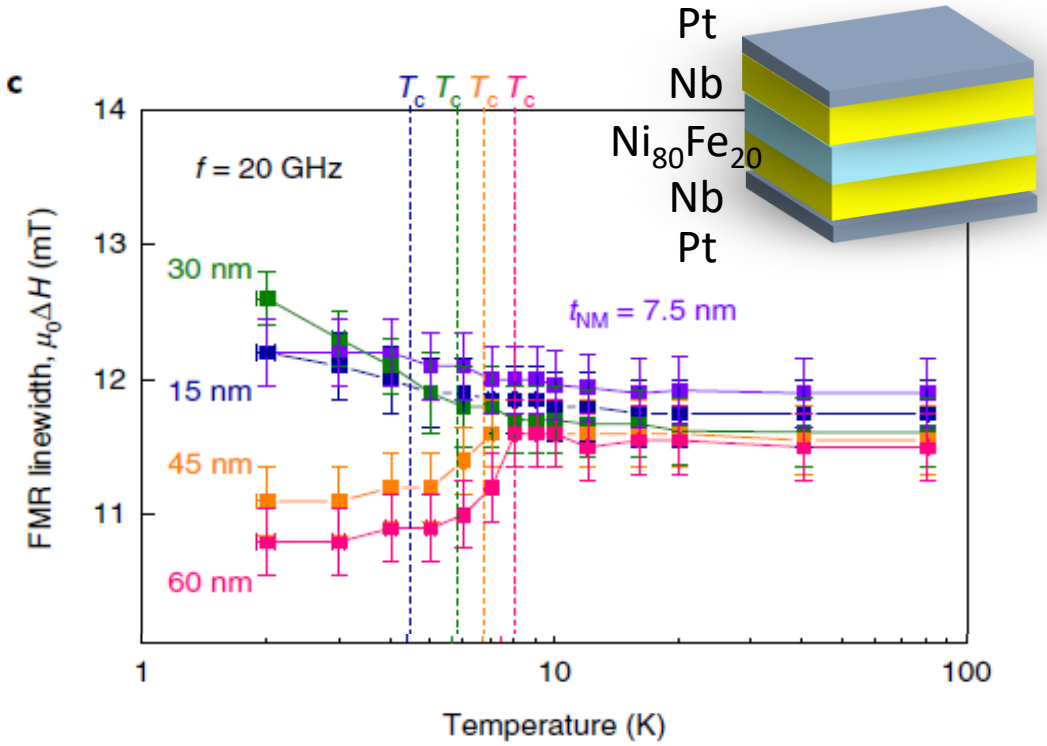


Experiments with s-wave superconductors



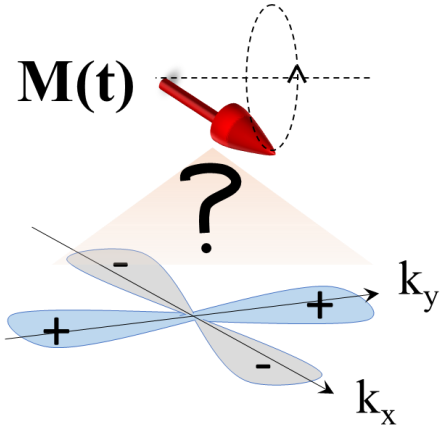


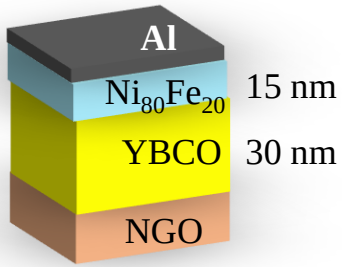
C. Bell et al, *Phys. Rev. Lett.* **100**, 047002 (2008)

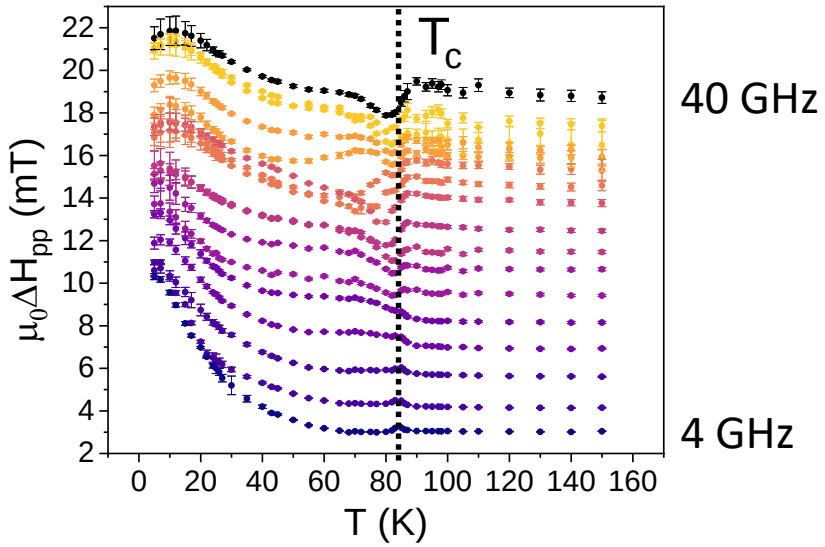


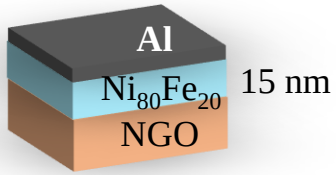
K. Jeon *et* al. *Nat. Mater.* **17,** 499–503 (2018)

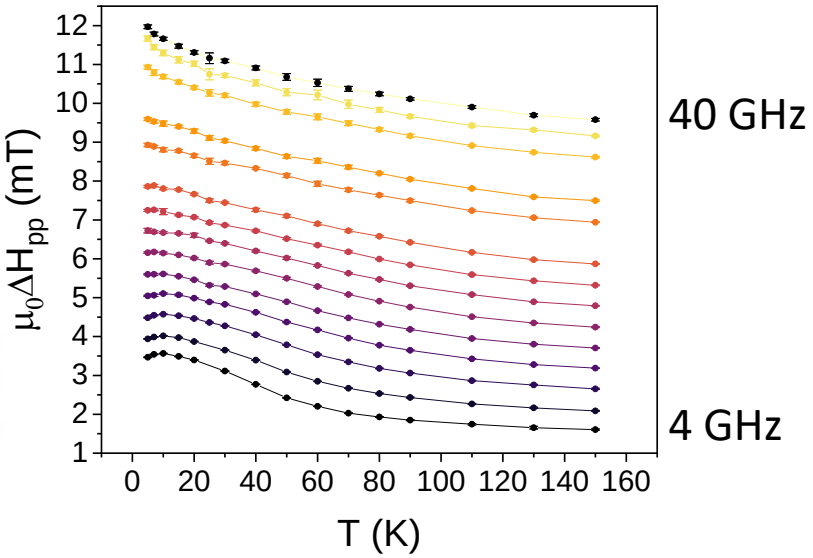
Experiments with d-wave superconductors







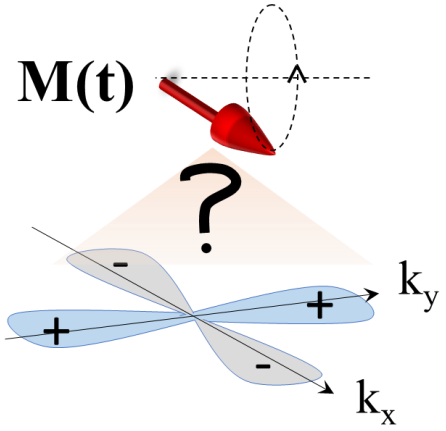


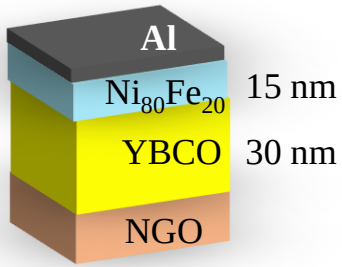


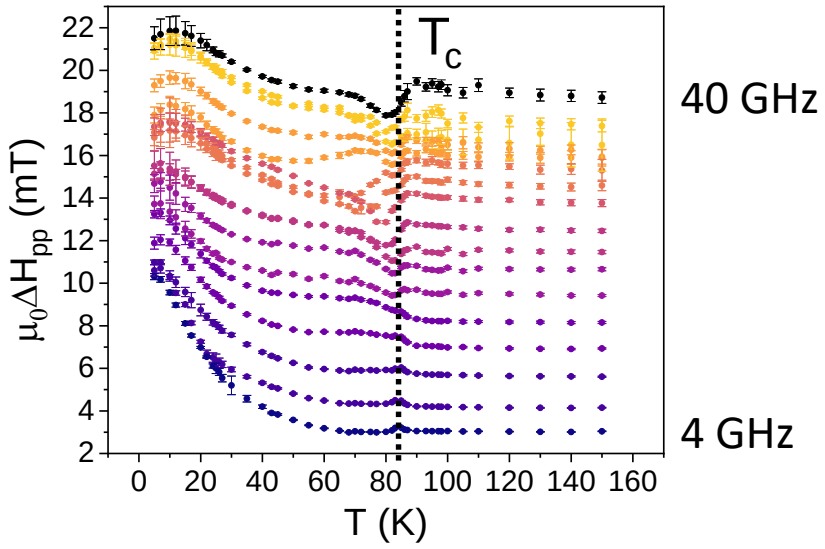
→ **Drastic change below T_C**

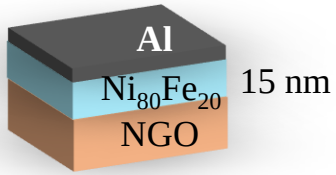
→ **Frequency dependent**

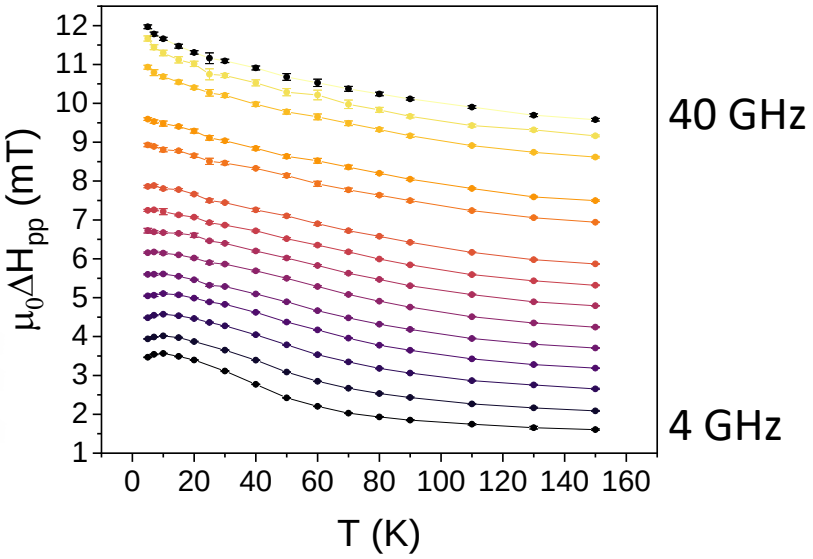
Experiments with d-wave superconductors







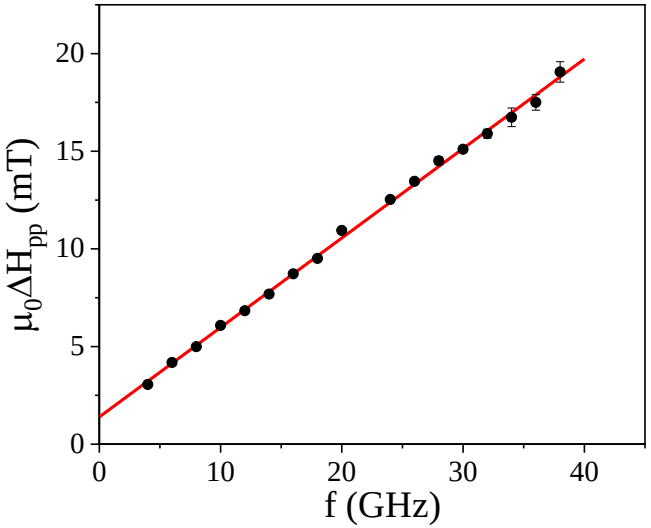




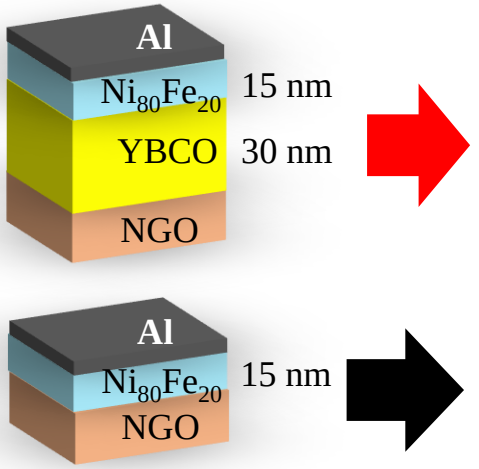
→ **Drastic change below T_C**

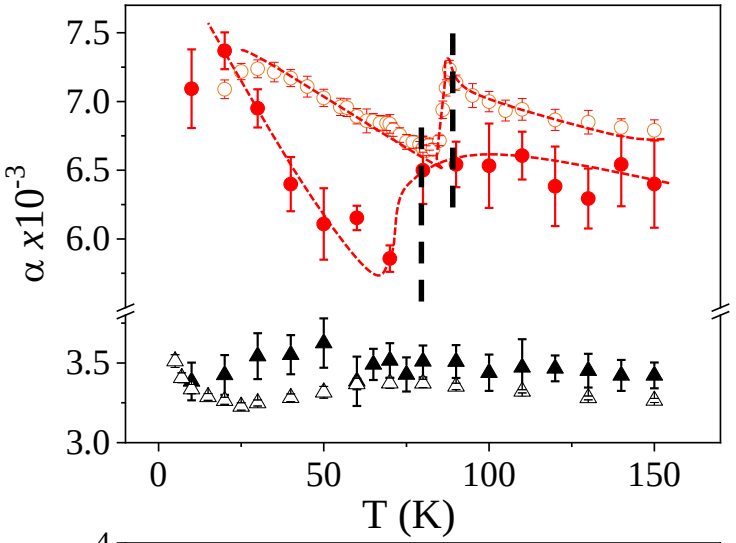
→ **Frequency dependent**

$$\Delta H_{pp} = \frac{2\alpha}{\sqrt{3}\gamma\mu_0} f + \Delta H_0$$



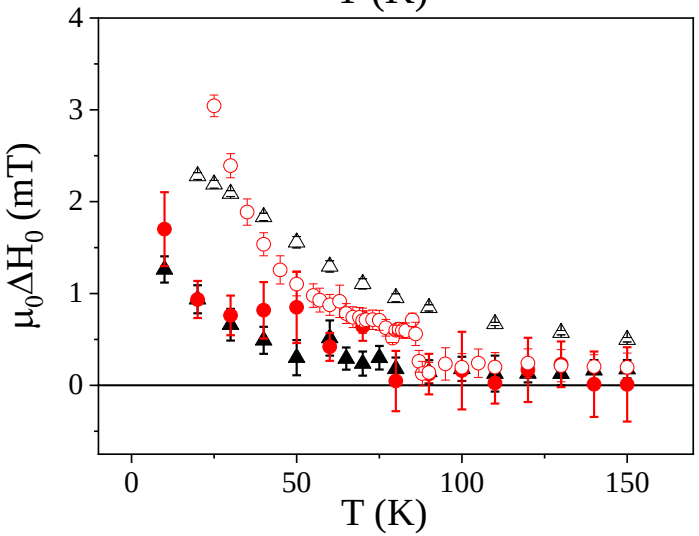
Experiments with d-wave superconductors





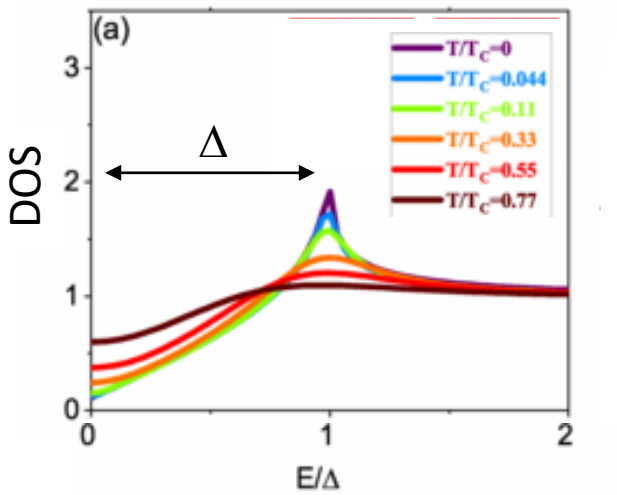
→ α drops at T_c

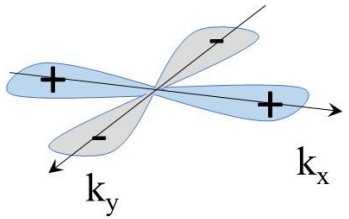
→ unexpected upturn further below



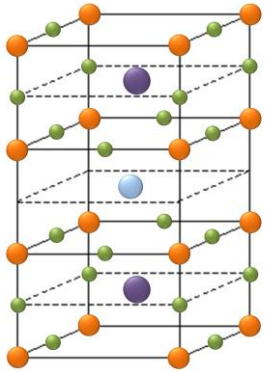
→ ΔH_0 not affected by SC

Anisotropic DOS as a function of temperature



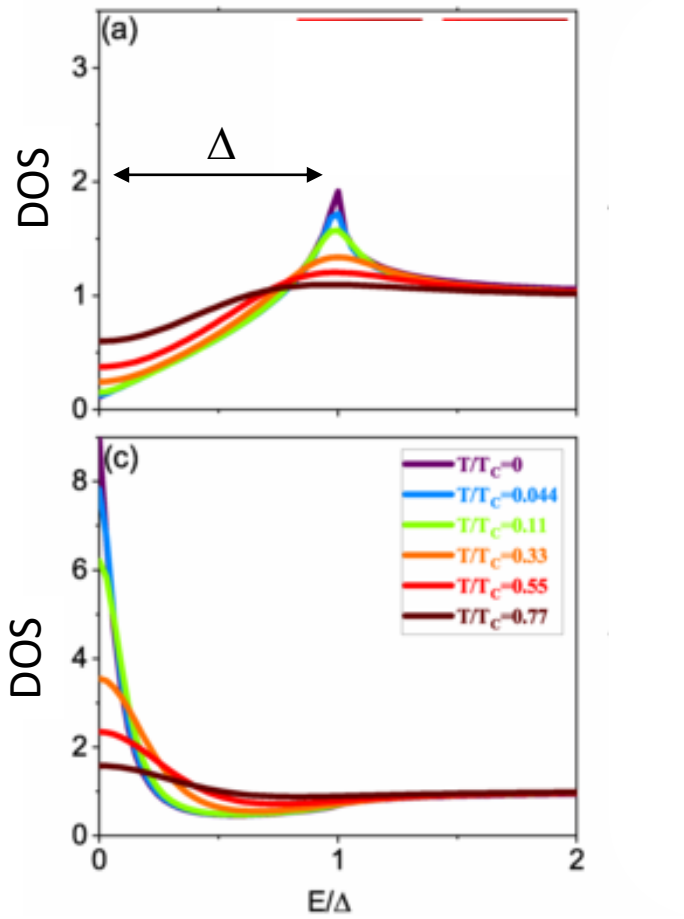


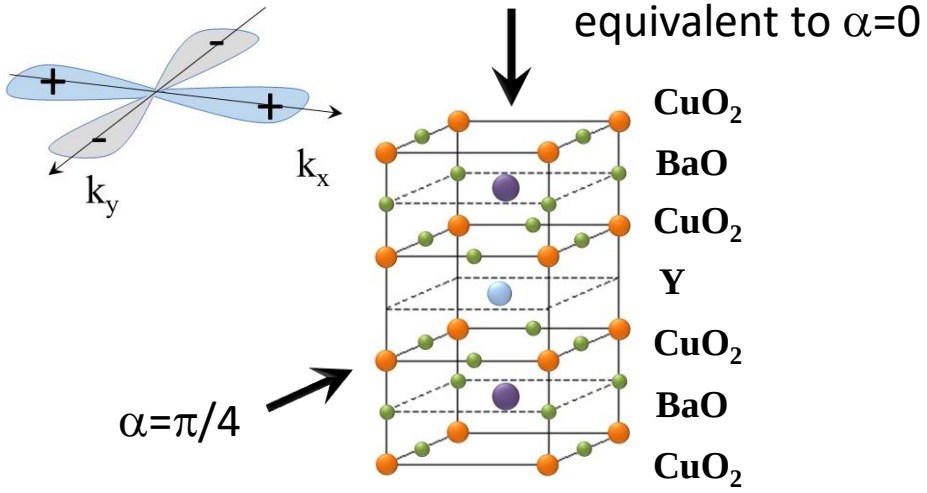
equivalent to α=0



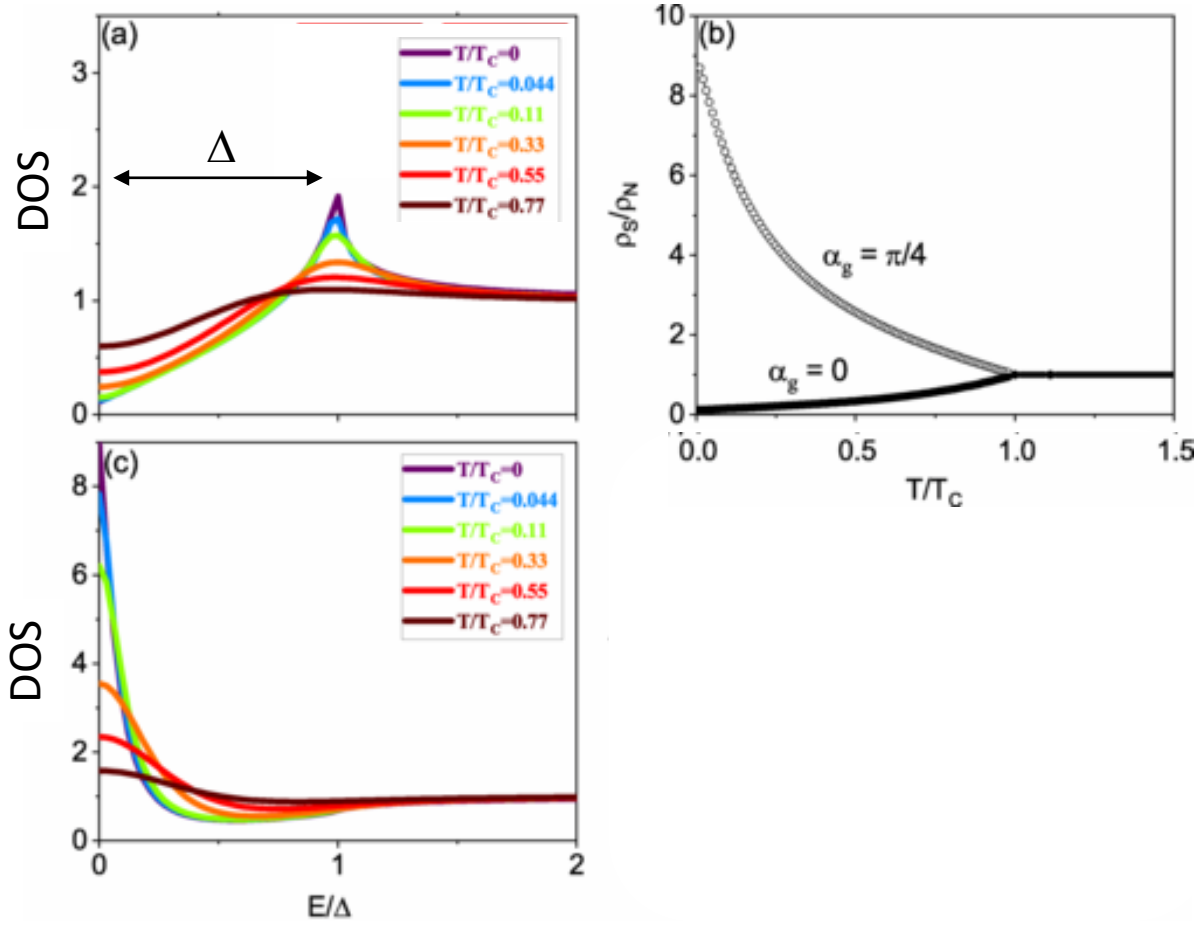
CuO_2
BaO
CuO_2
Y
CuO_2
BaO
CuO_2

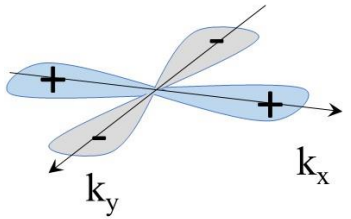
Anisotropic DOS as a function of temperature





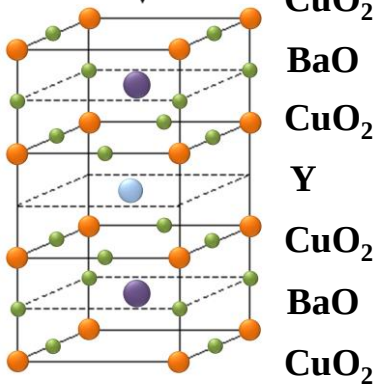
Anisotropic DOS as a function of temperature



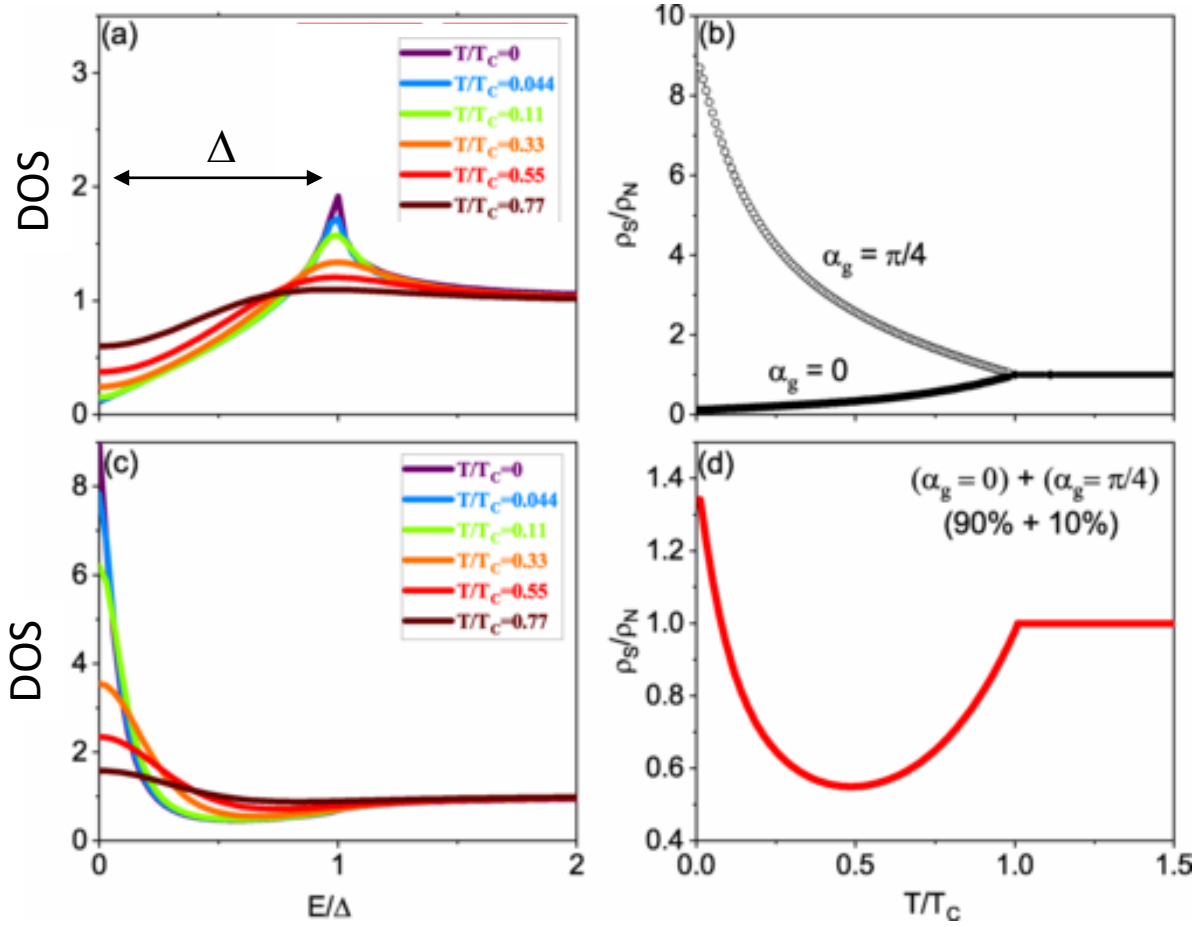


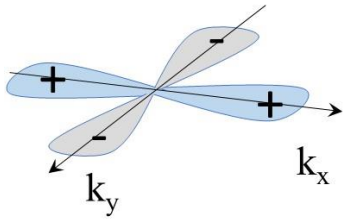
equivalent to $\alpha=0$

$\alpha=\pi/4$



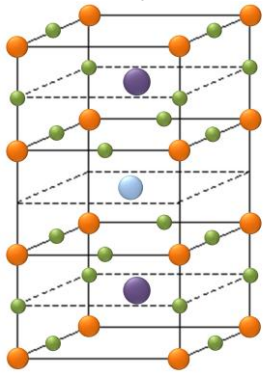
Anisotropic DOS as a function of temperature



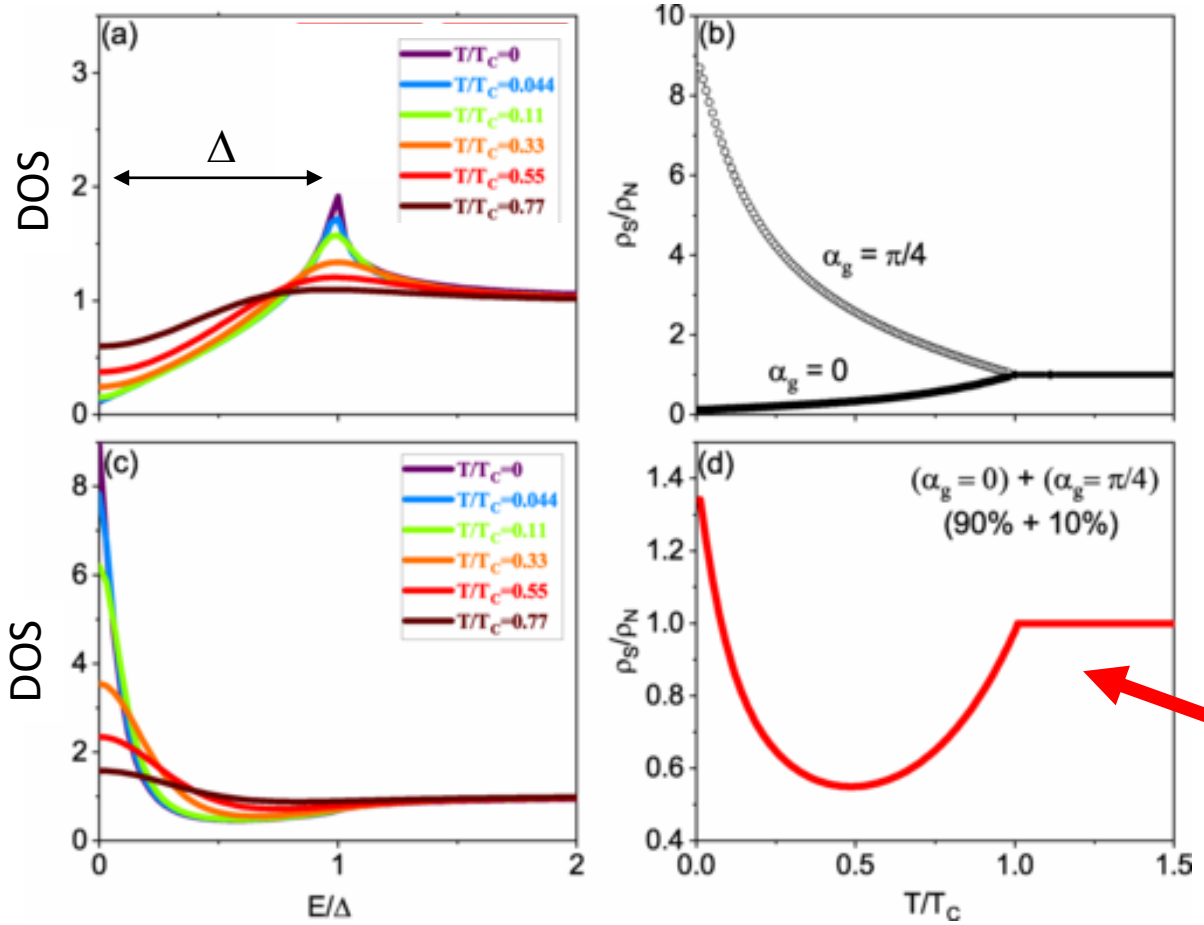


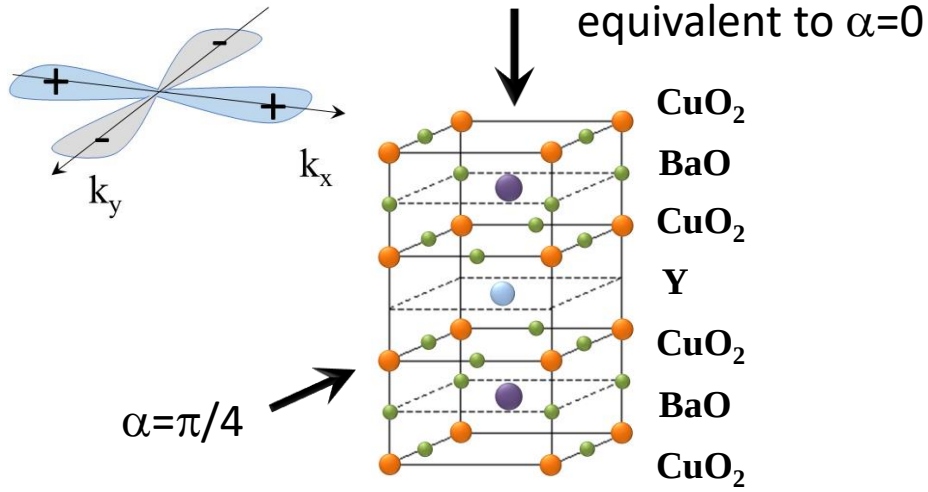
equivalent to α=0

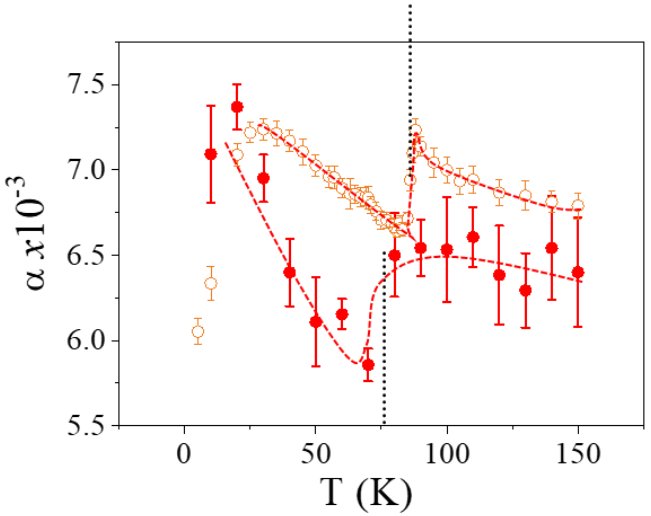
α=π/4



Anisotropic DOS as a function of temperature

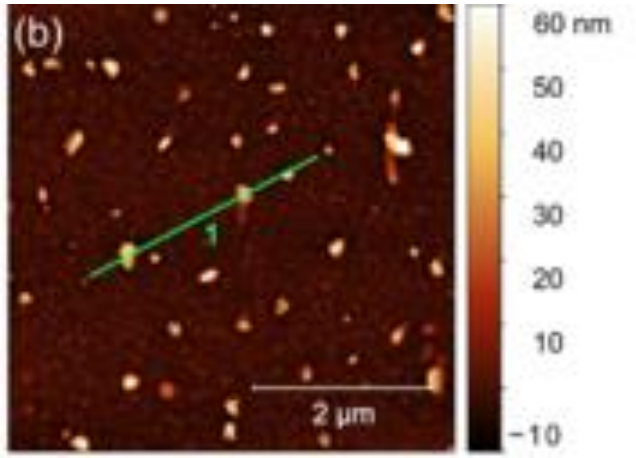


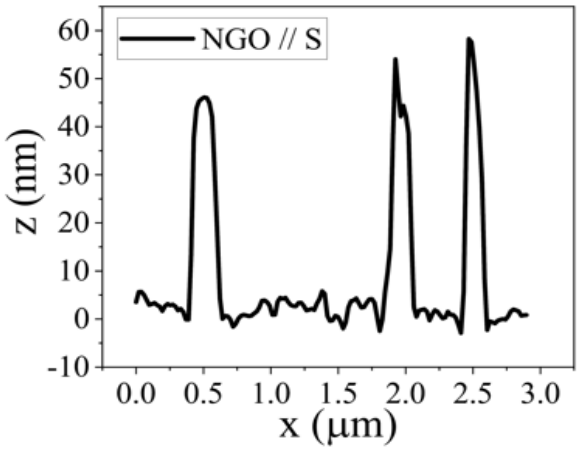


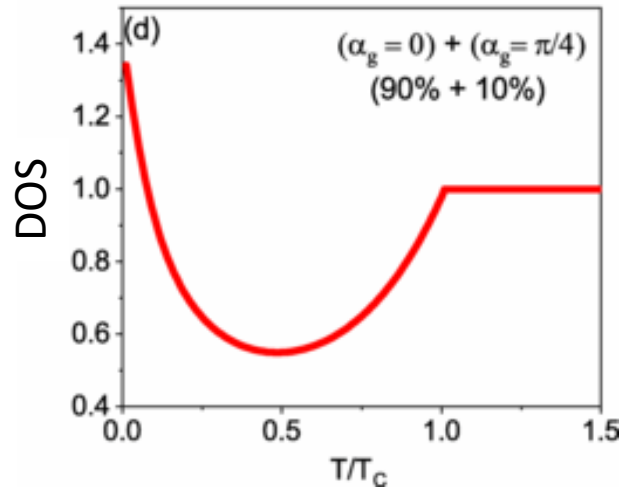


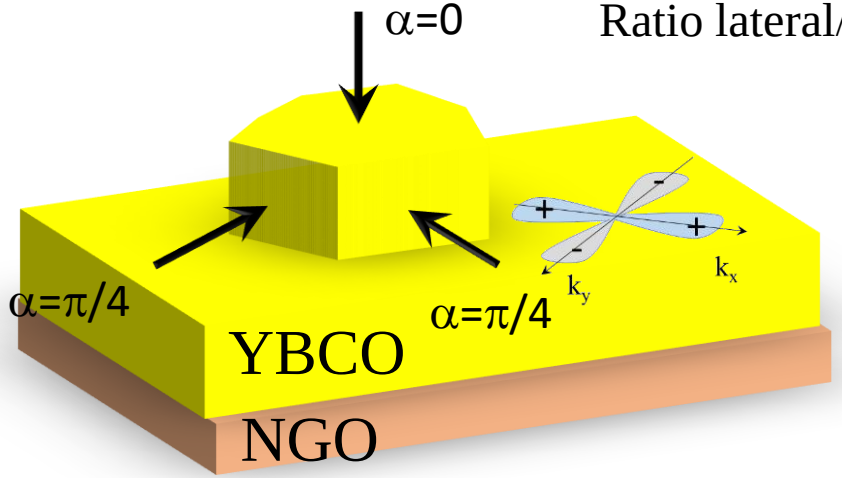
→ **TEMPERATURE DEPENDENT QUASIPARTICLE DENSITY EXPLAINS α(T)**

Surface topography and effective DOS

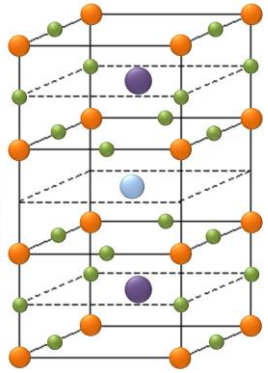


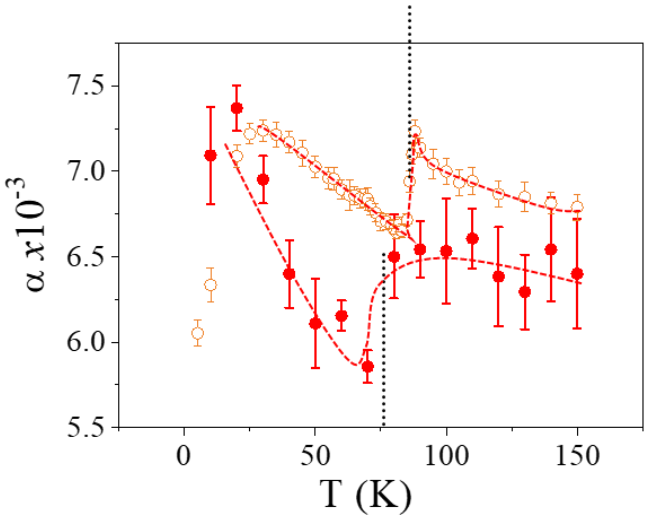






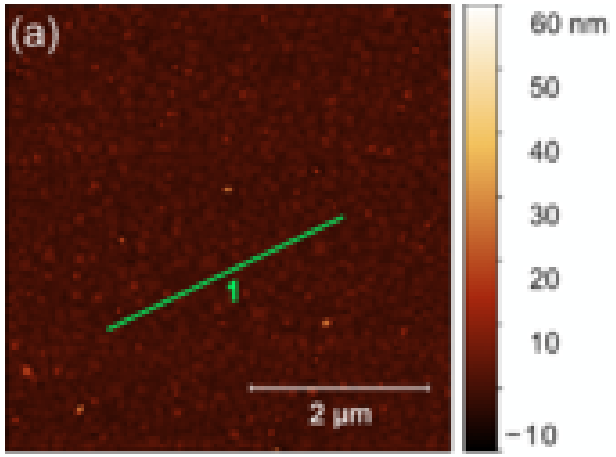
Ratio lateral/vertical surface ≈ 10 %

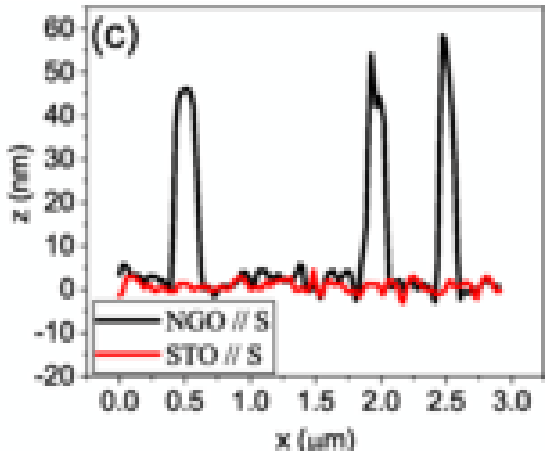


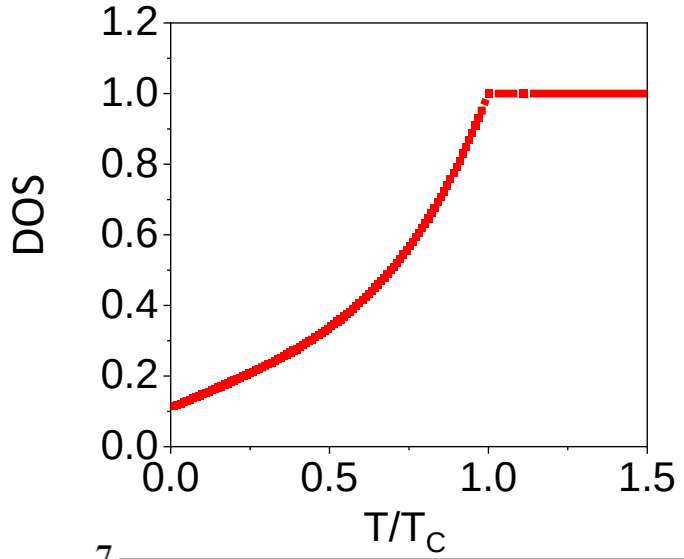


→TOPOGRAPHY ALLOWS ACCESS TO LARGE QUASIPARTICLE DOS

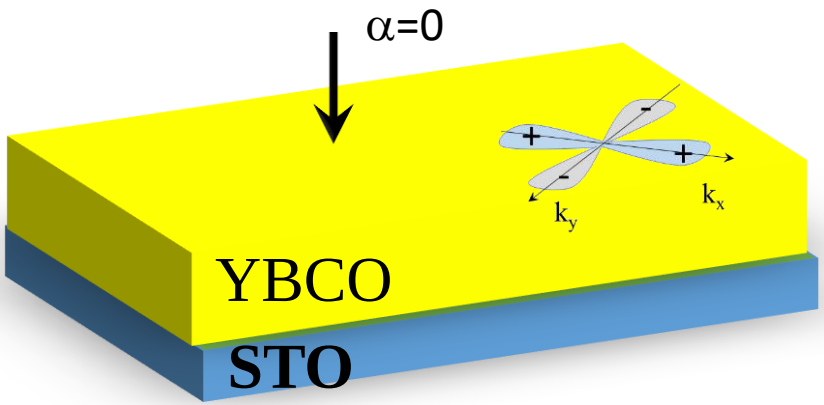
Surface topography and effective DOS

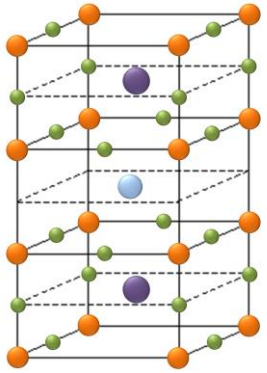


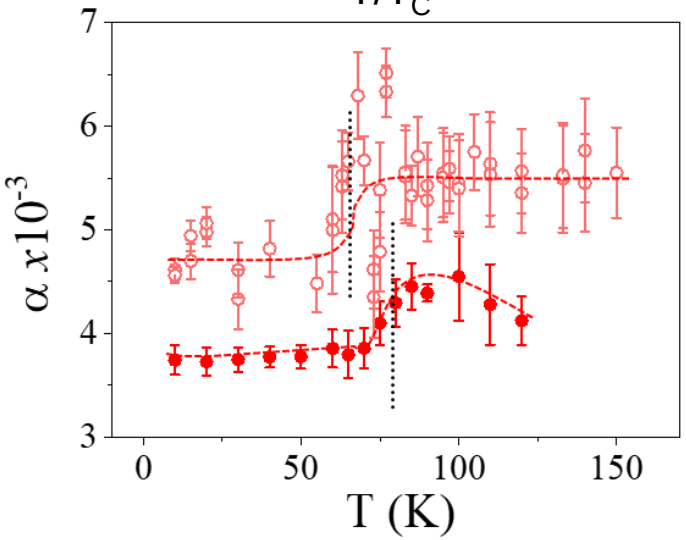




vertical surface ≈ 100 %





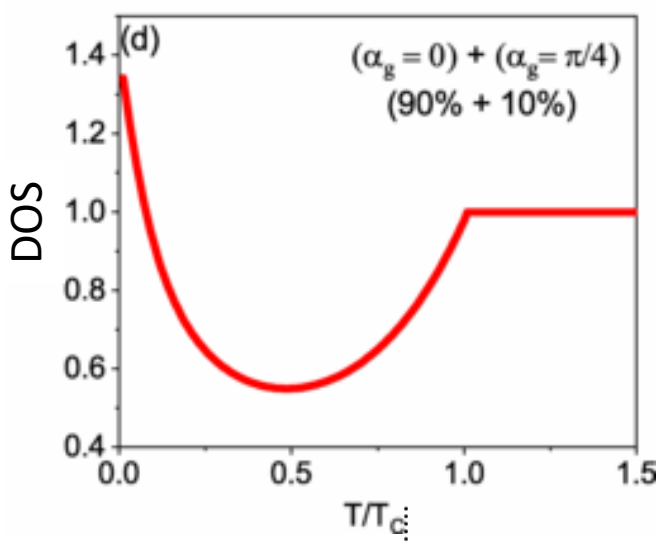


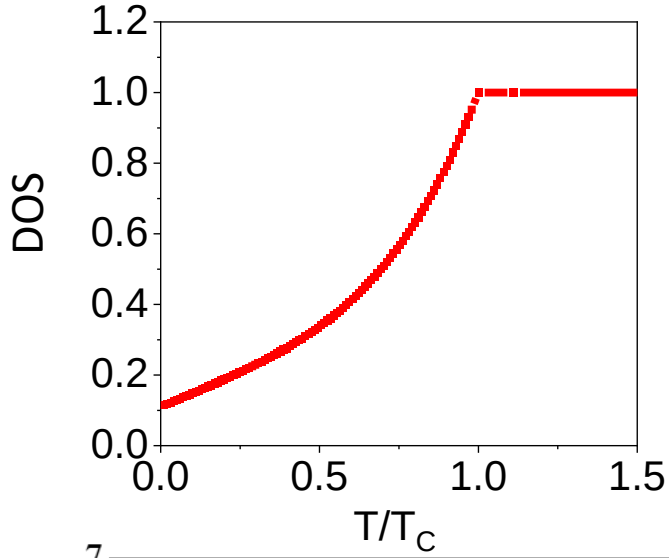
→FLAT SURFACE IMPEDES LIMITS ACCES TO QP BOUND STATES

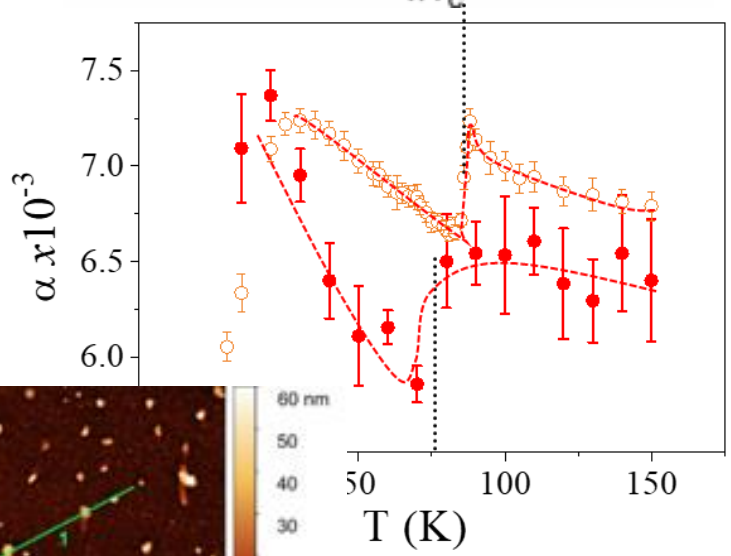
→ BEHAVIOR AS WITH S-WAVE SUPERCONDUCTOR

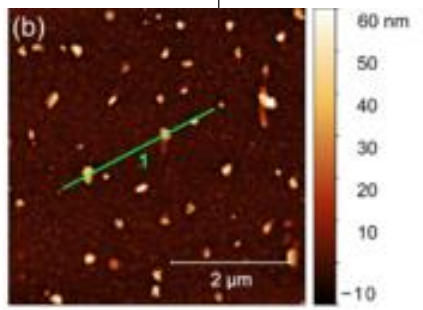
Surface topography and effective DOS

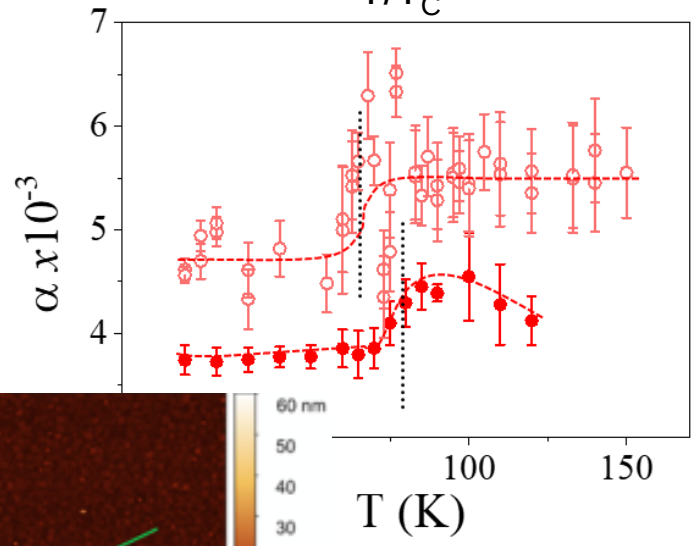
→UNUSUAL UPTURN EXPLAINED BY QP BOUND STATES

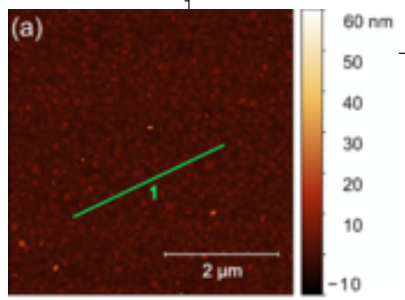






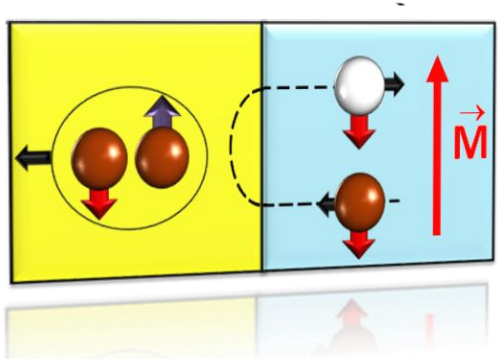


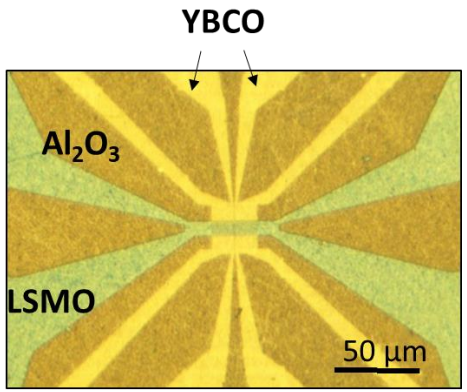


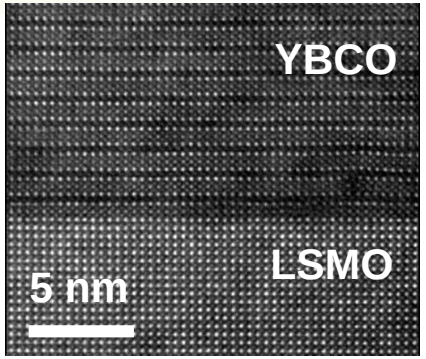


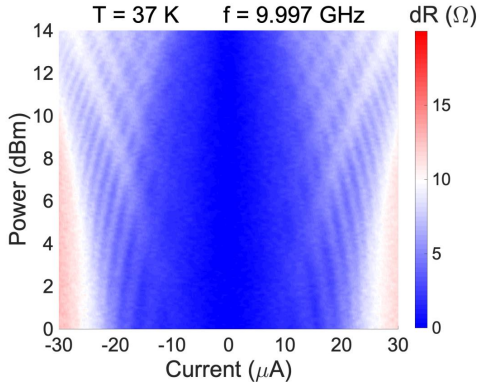
Conclusions

Proximity effect





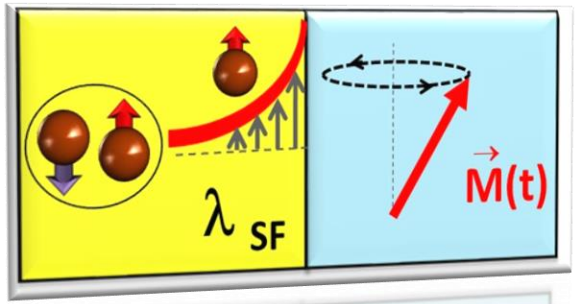


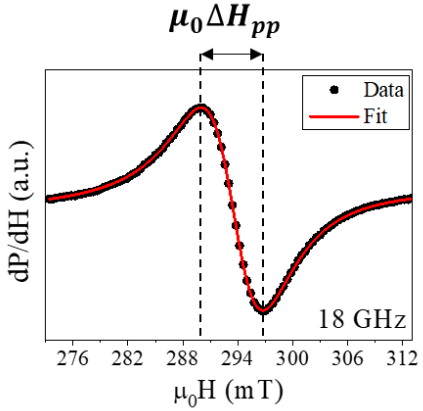


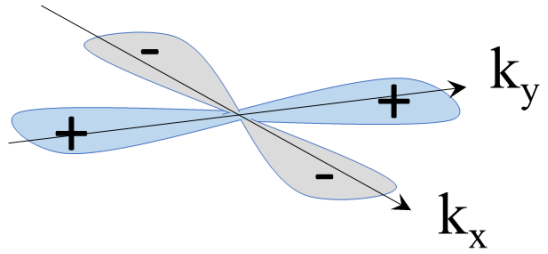
Fully spin-polarized, high-T_C Josephson supercurrents
Quantum phase coherence effects

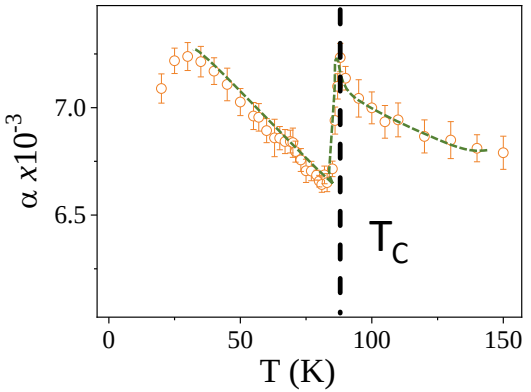
Sanchez-Manzano *et al.* Nature Materials (2022)

Dynamic coupling





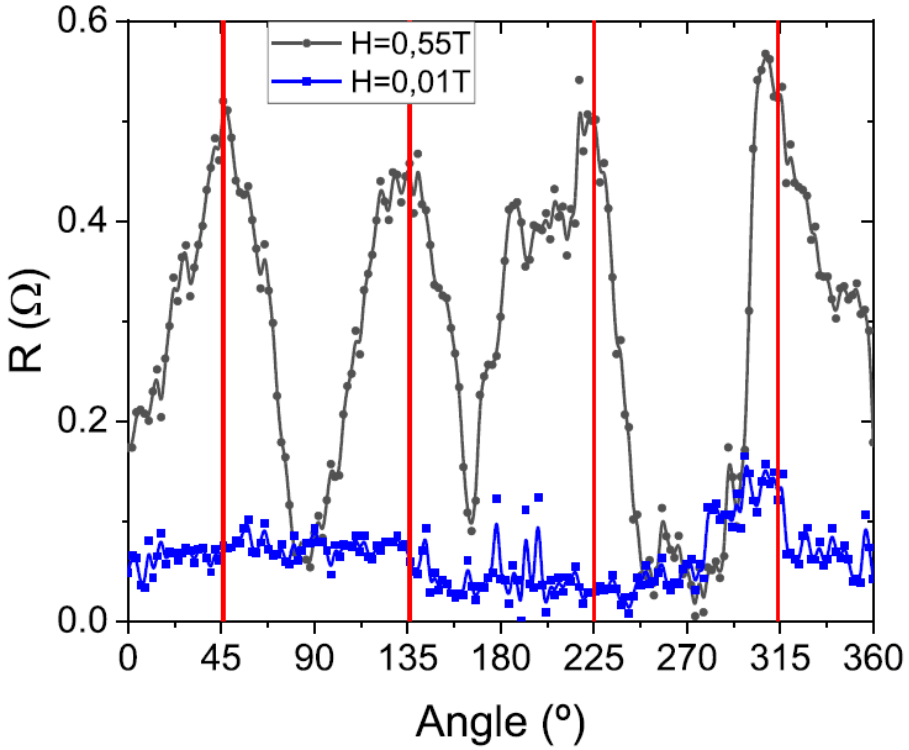




Tunable spin sink
d-wave effects

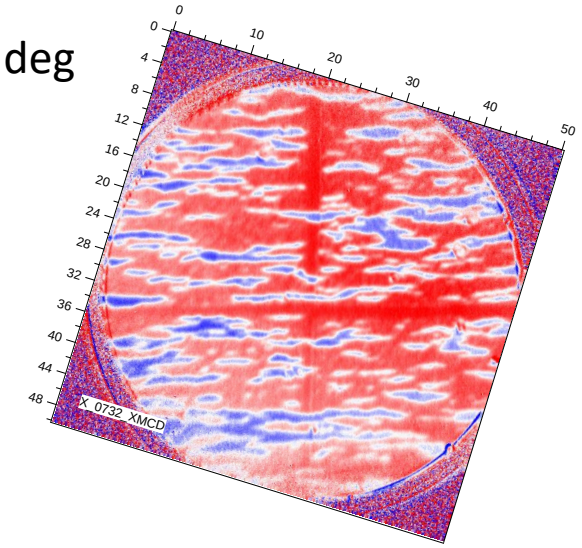
Carreira *et al.* PRB (2021)

→ OPPORTUNITIES FOR HIGH-T_C SUPERCONDUCTING SPINTRONICS



θ=45, 135, 225, 315 deg

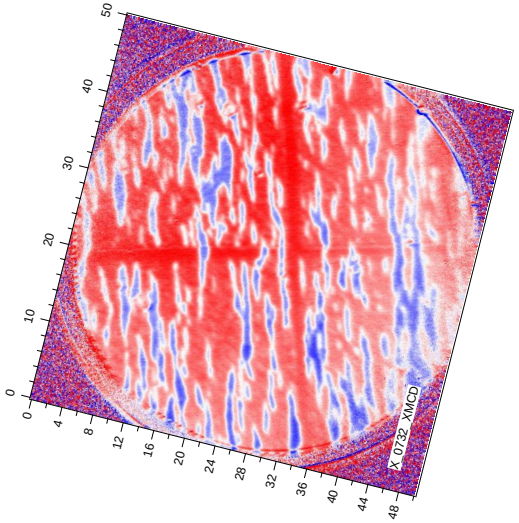
H



|| easy axis

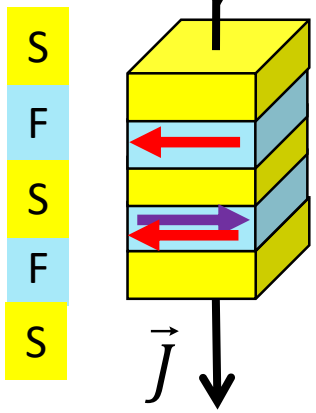
θ=90, 180, 270, 360 deg

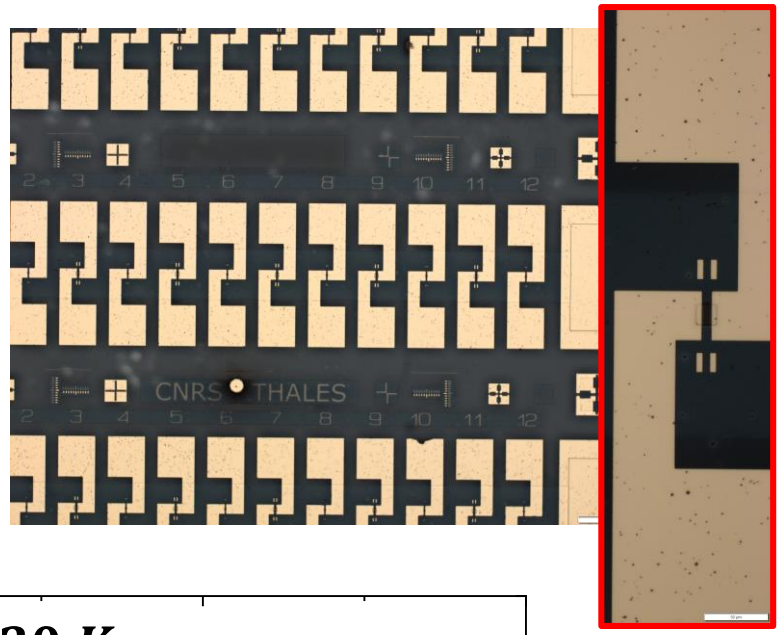
H

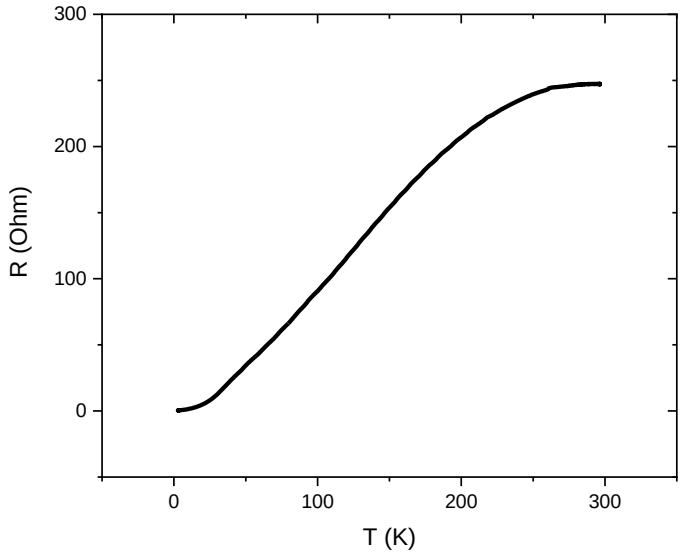


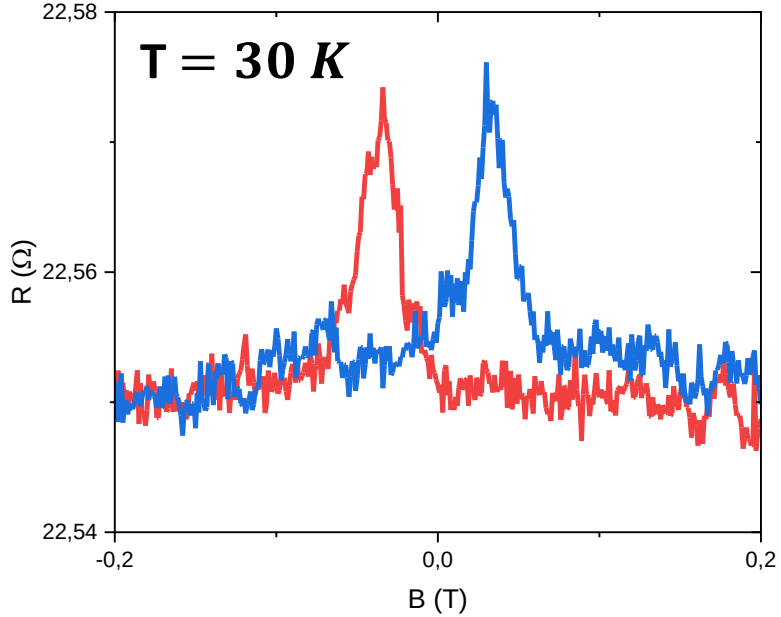
⊥ easy axis

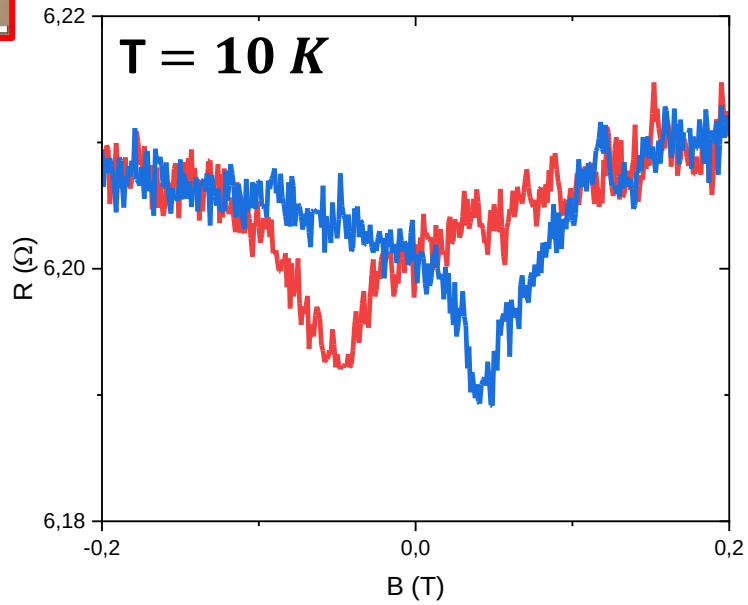
High-T_C Josephson spin valves: preliminary results







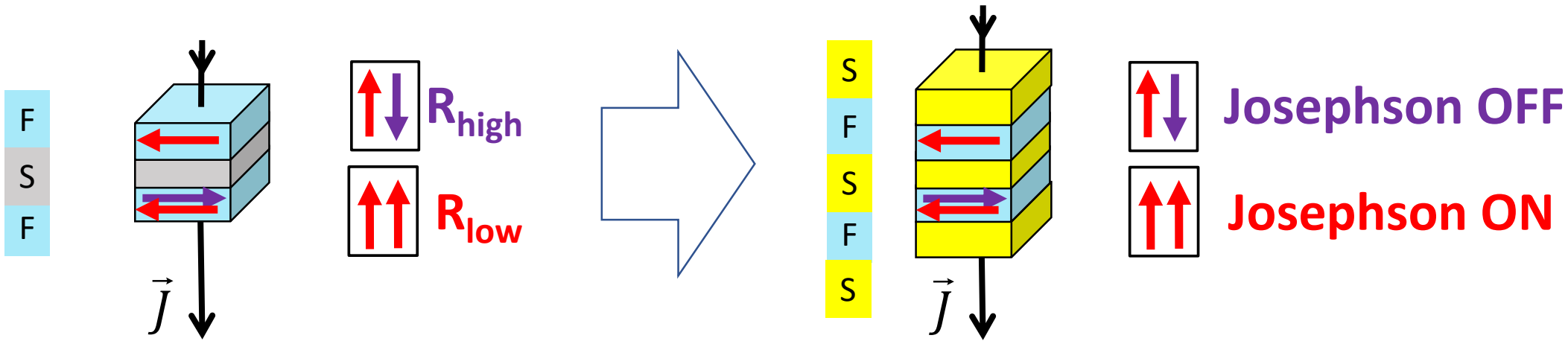




High-T_C Josephson spin valves

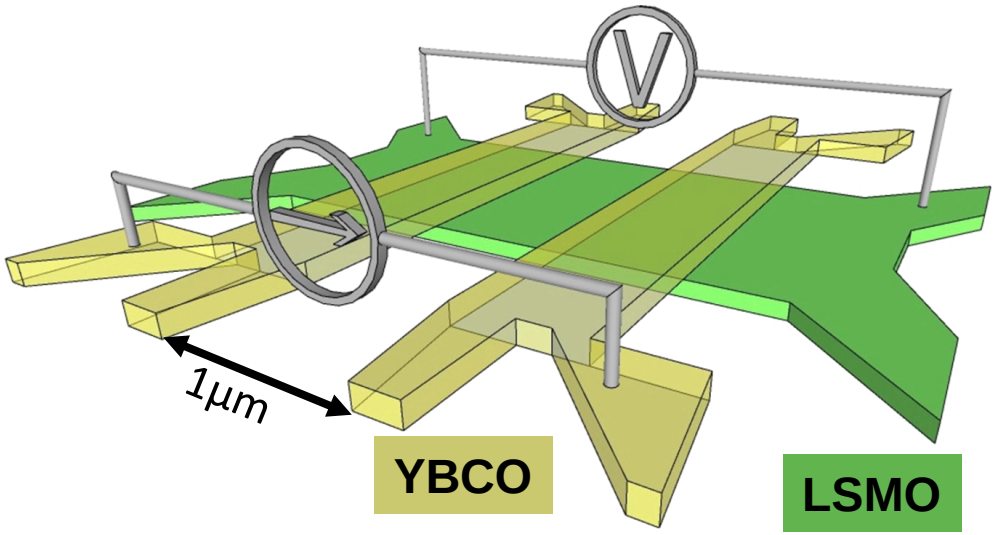
conventional spin valve

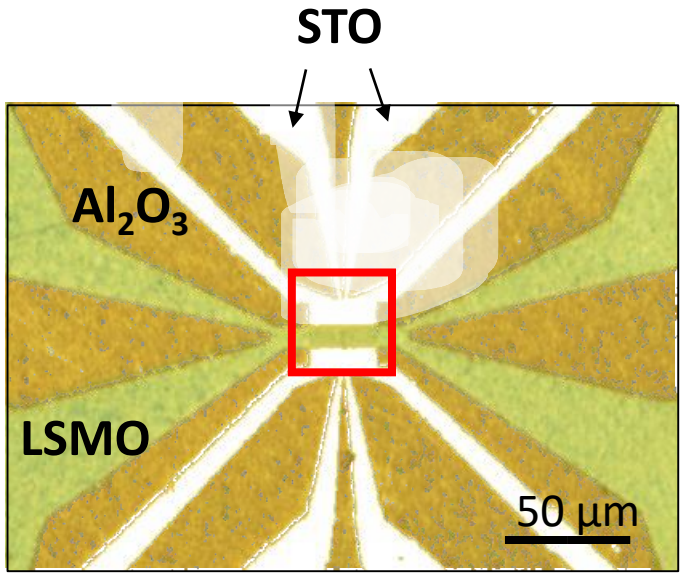
Josephson spin valve

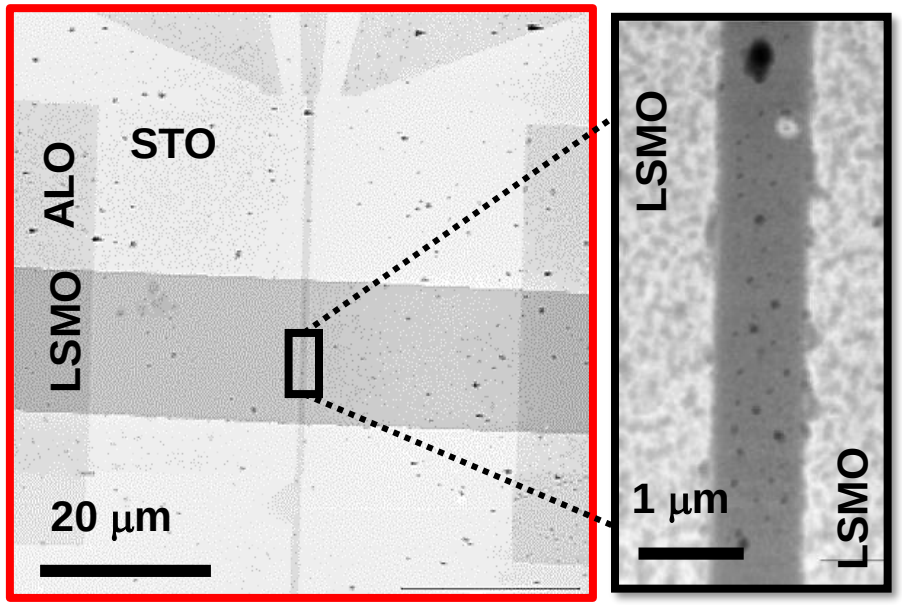


→JOSEPHSON SPIN-VALVES… SPIN TORQUES, AND BEYOND?

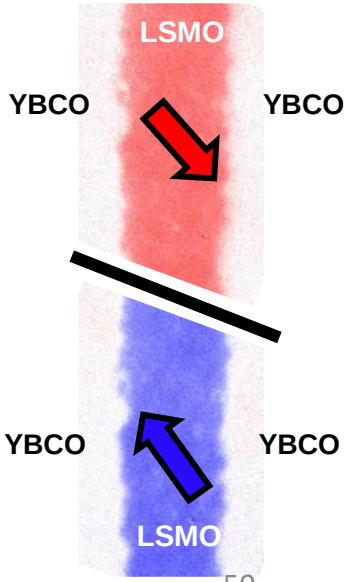
Fabrication of planar Josephson junctions







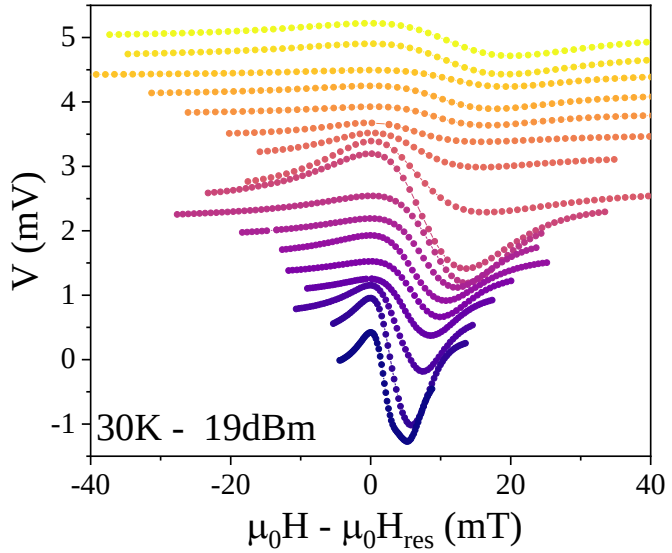
XMCD-PEEM



→AMORPHOUS ALUMINA MASK

→LSMO REMAINS MAGNETIC

FMR experiments – Damping and inhomogeneous broadening

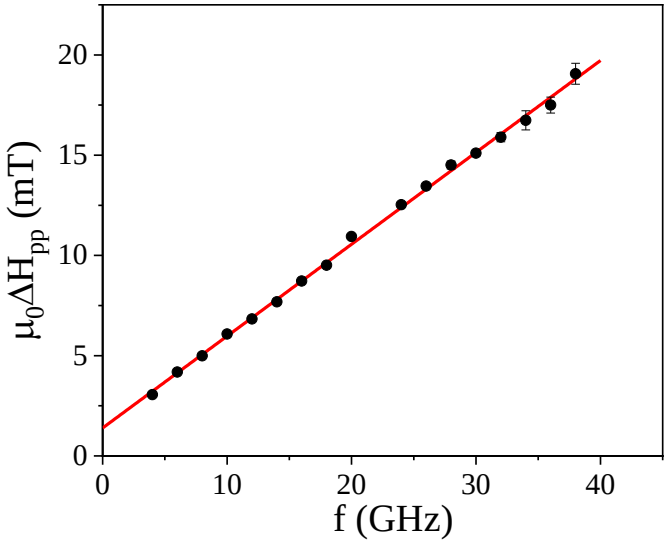


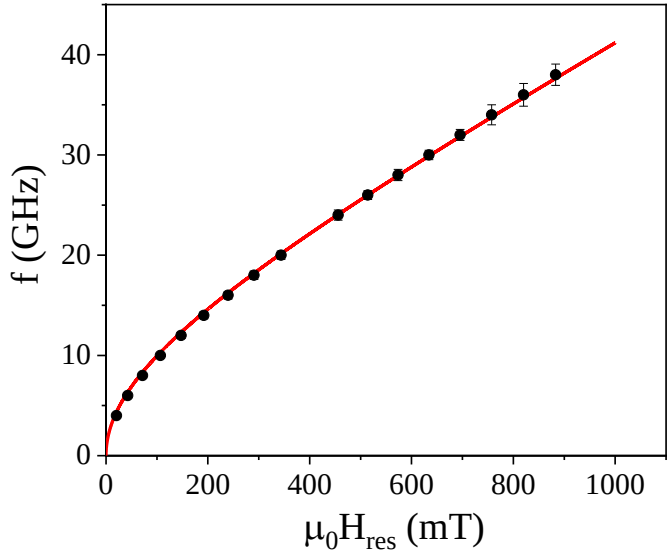
$$\Delta H_{pp} = \frac{2\alpha}{\sqrt{3}\gamma\mu_0} f + \Delta H_0$$

$$f = \gamma\mu_0 \sqrt{H_{res}\left(H_{res} + M_{eff}\right)}$$

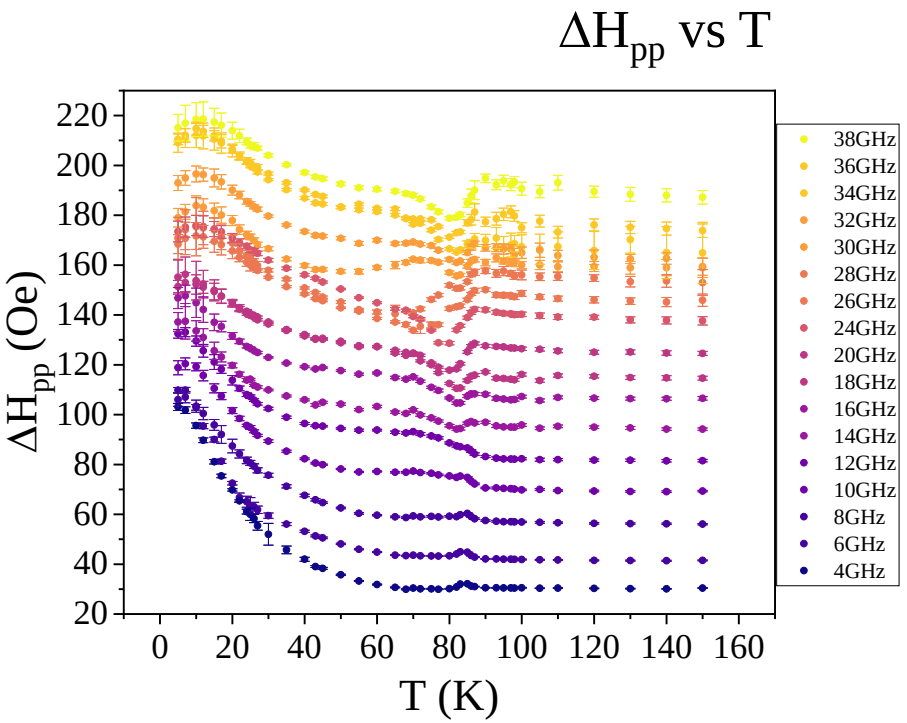
α : *Gilbert damping*

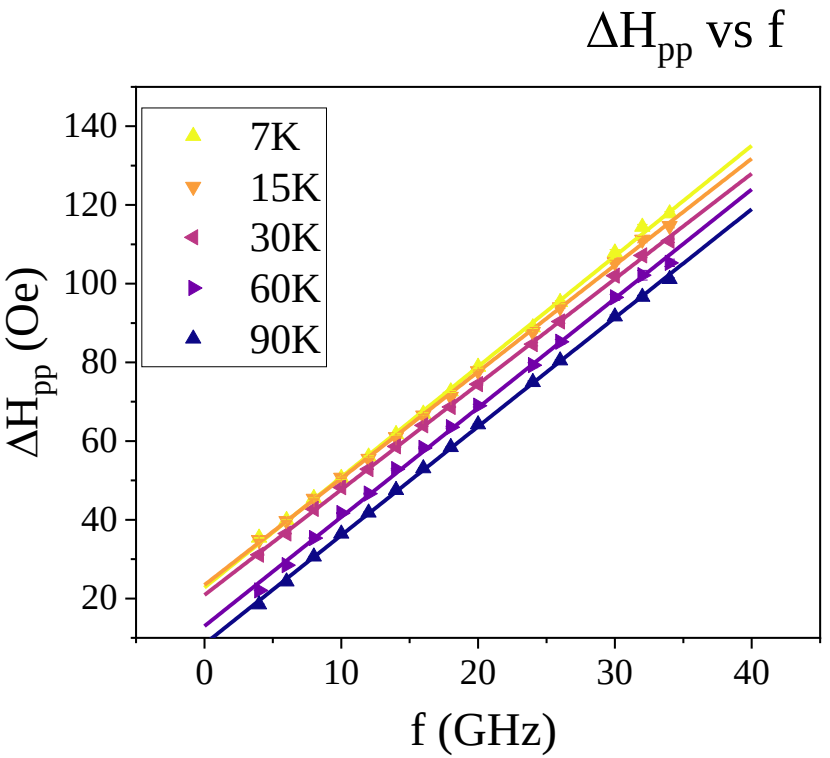
ΔH_0 : *inhomogeneous broadening*

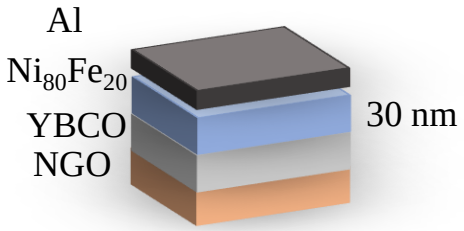




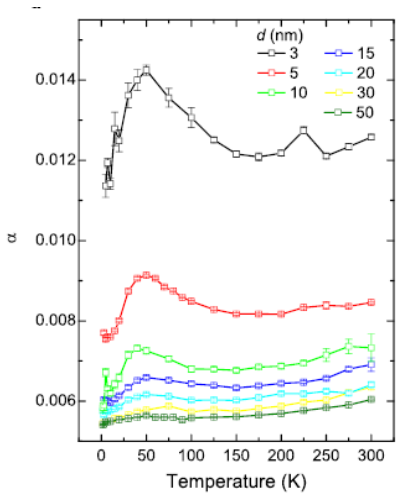
Linewidth vs T and vs f for the sample grown on NGO



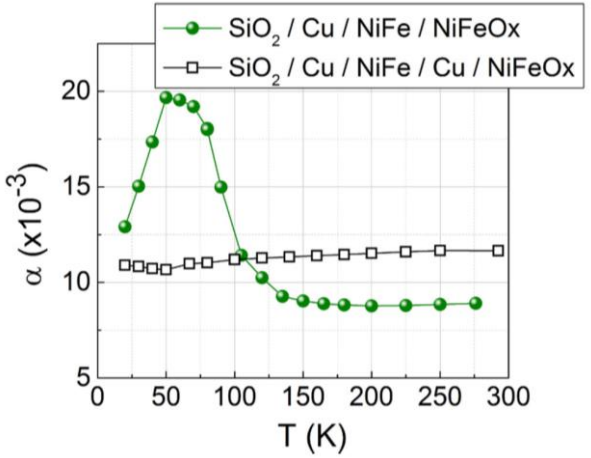




Intrinsic broadening of the linewidth at low temperatures in NiFe thin films



Y. Zhao et al, *Sci. Rep*. 6, 22890 (2016)



L. Frangou et al. *Phys. Rev.* B **95**, 054416 (2017)

Magnetic inhomogeinities at the interface due to the oxidation of the Py

↓

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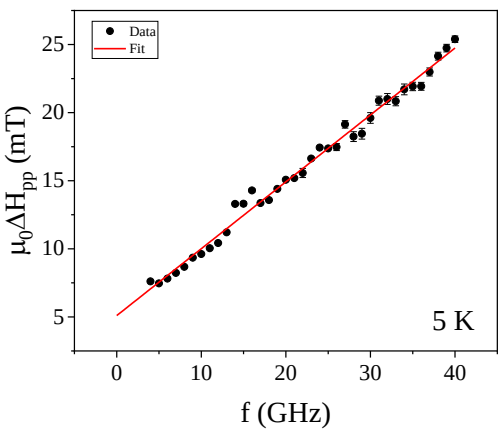
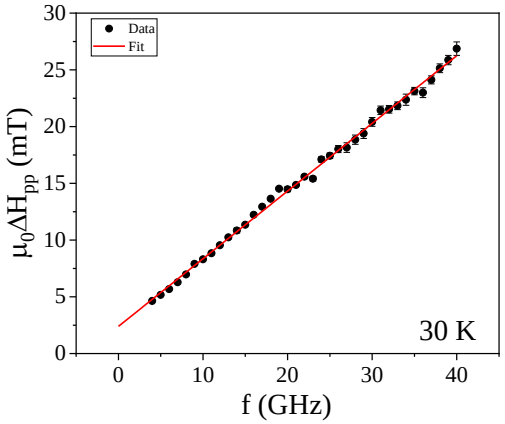
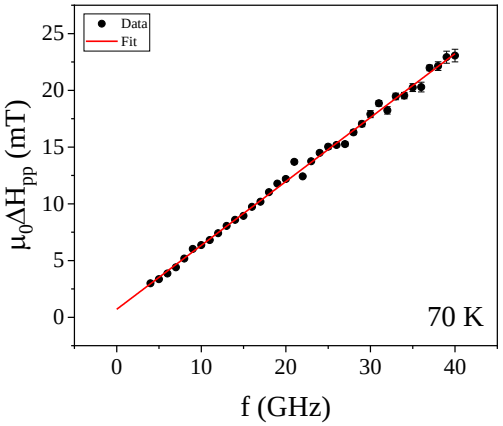
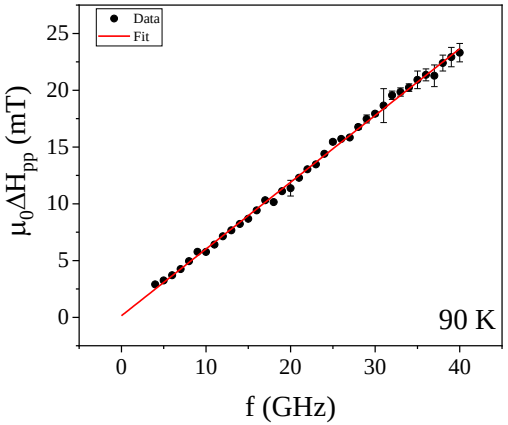
Ferromagnetic resonance experiments – Damping calculation









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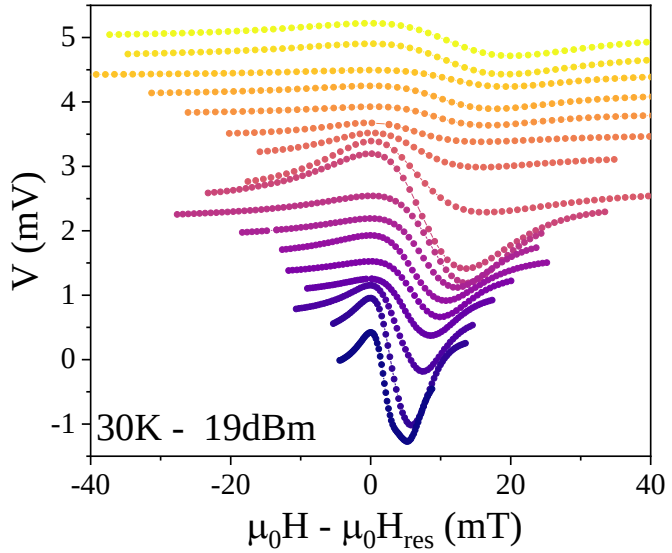

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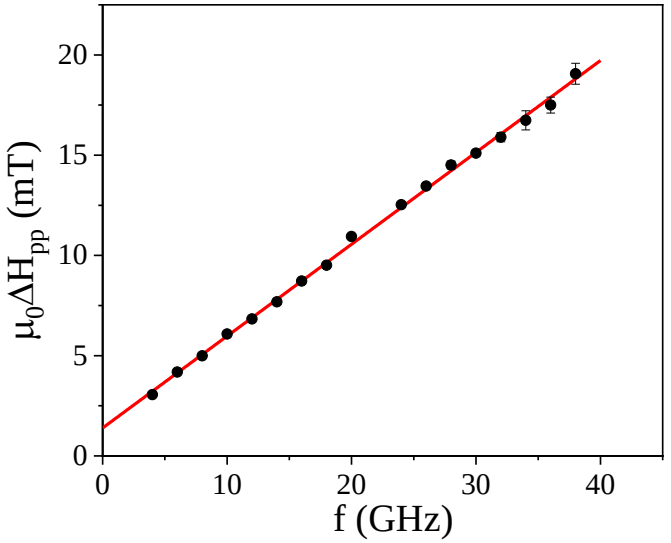

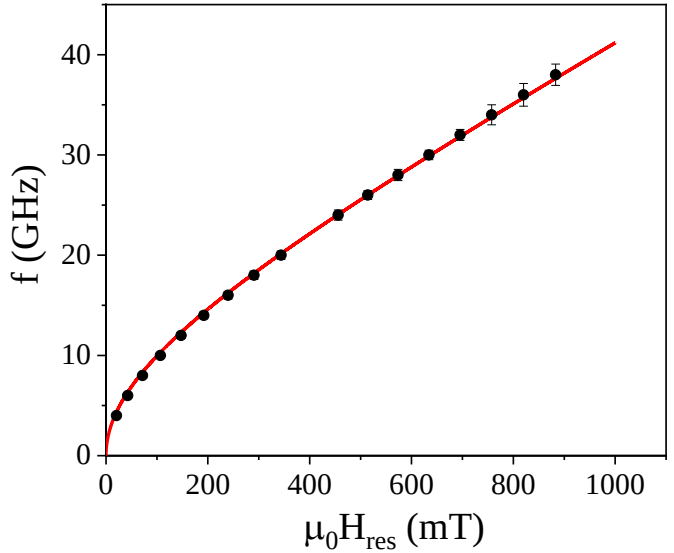

Spin pumping in d-wave superconductors – S. J. Carreira

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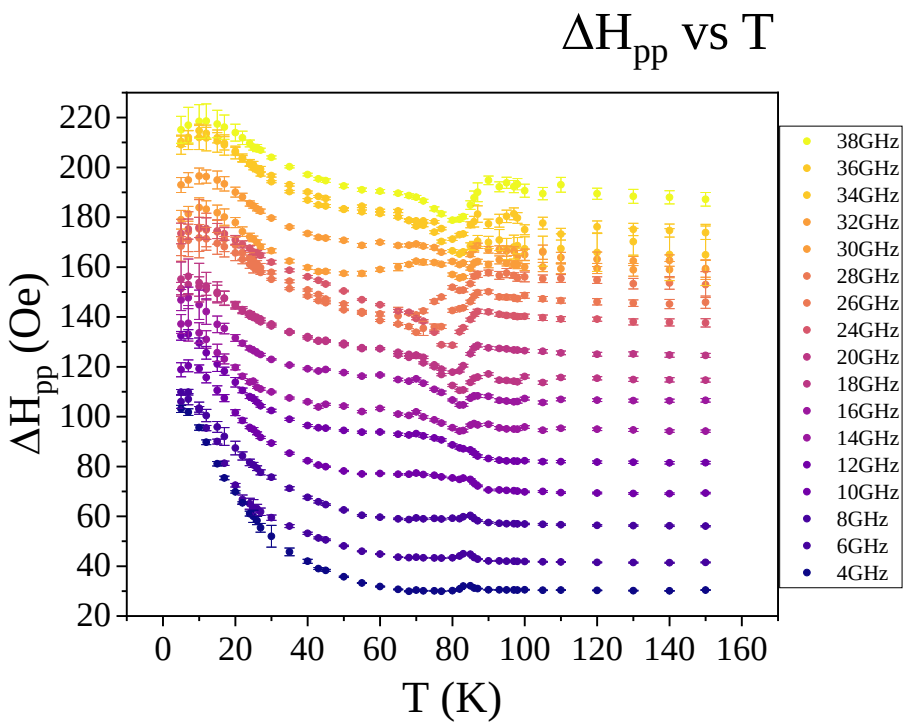

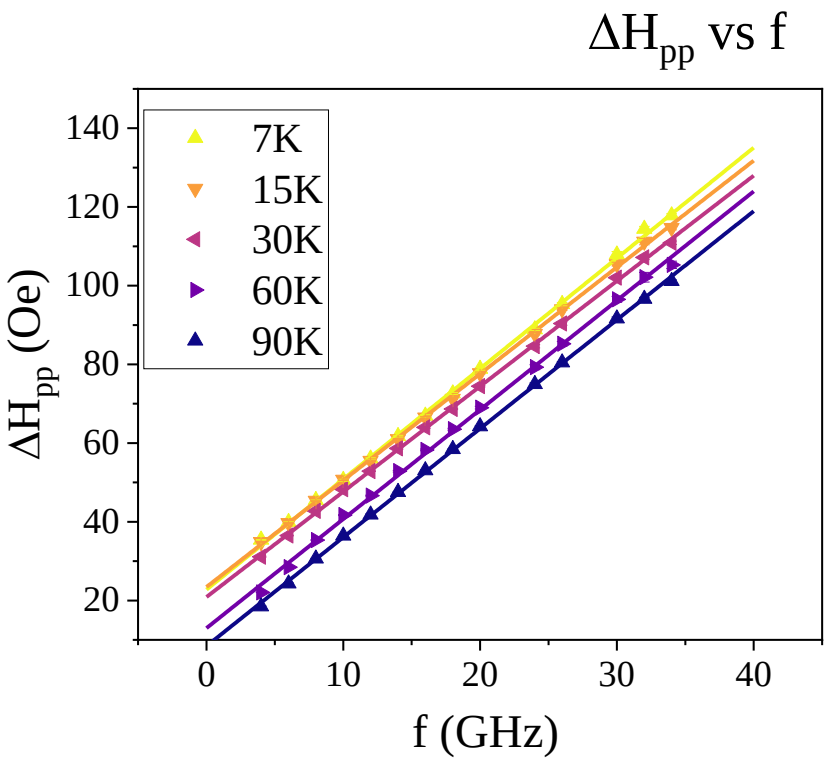

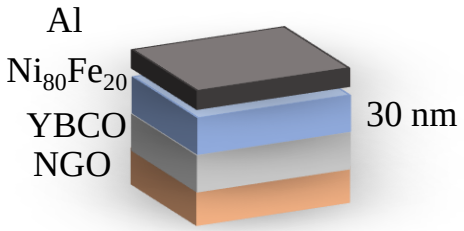

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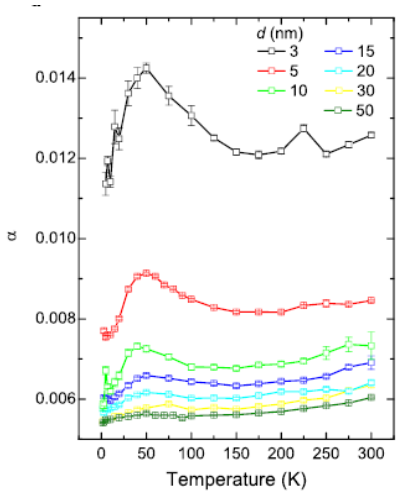

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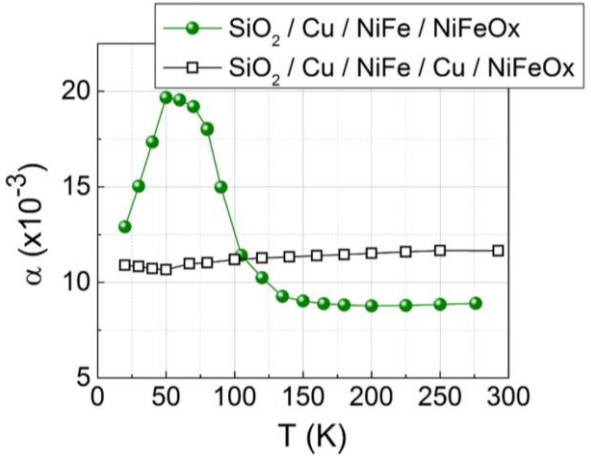

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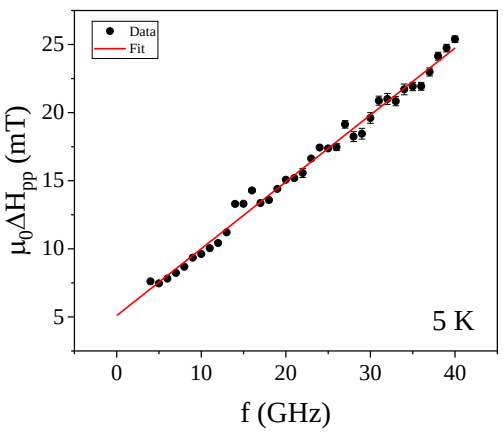

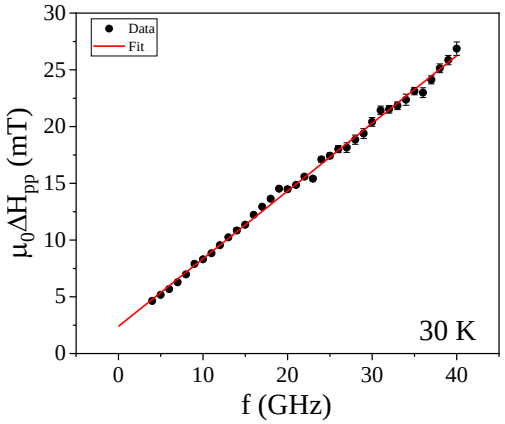

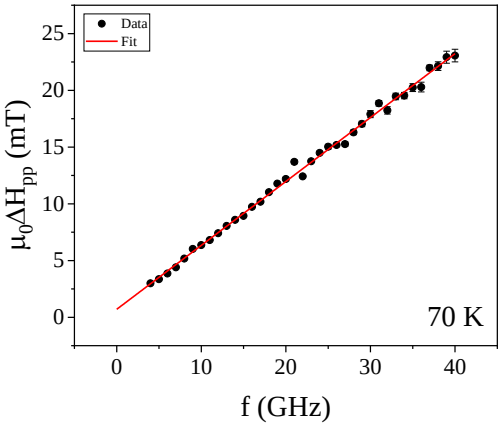

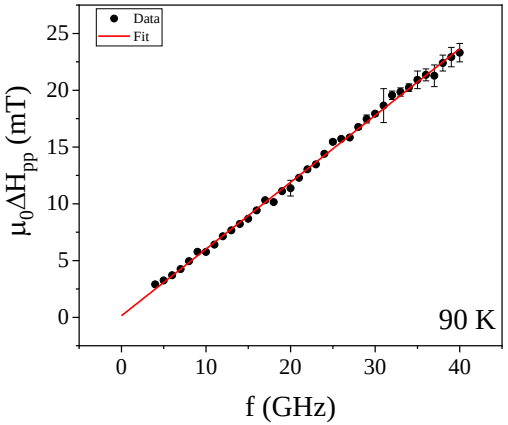

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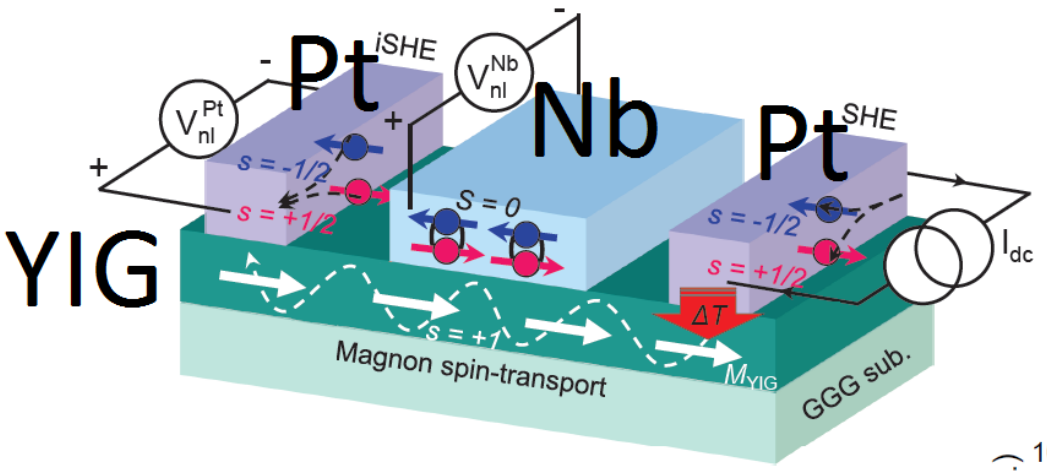
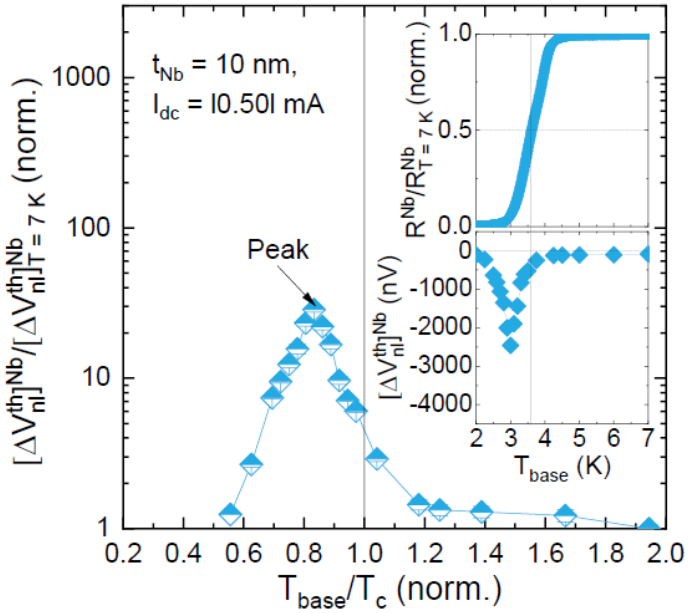
Different designs to study spin injection in S/F hybrids



Non-local spin injection devices.
Inject angular momentum using magnons instead of spin polarized electrons

Spin injection efficiency in Nb increases below Tc!



K.-R. Jeon *et* al. **arXiv**:2004.09467 (2020)

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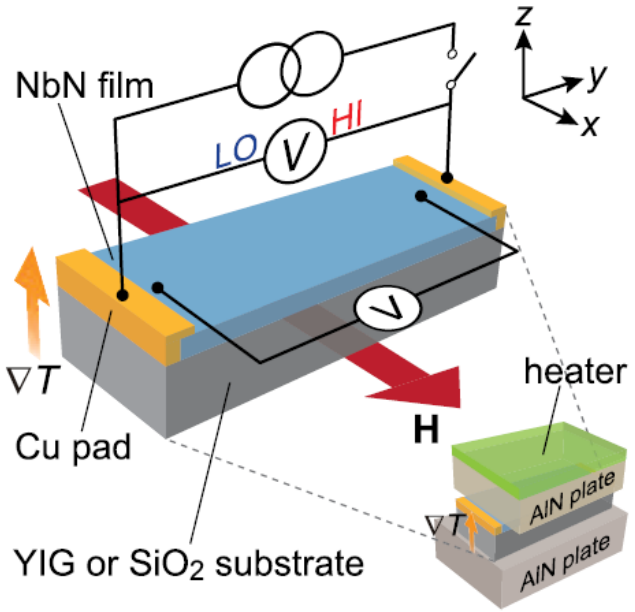
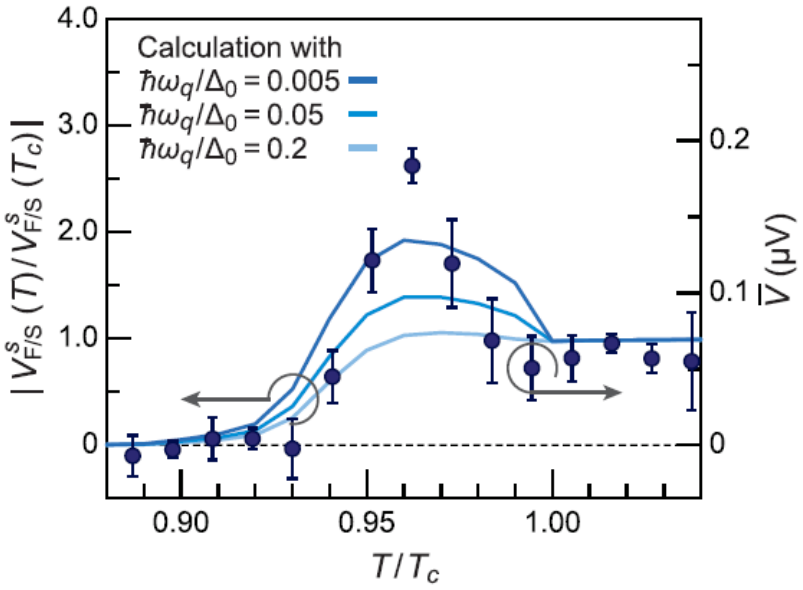


Spin injection using a thermal gradient
(Spin Seebeck effect)



M. Umeda *et* al. *Appl. Phys. Lett.* **112**, 232601 (2018)