Towards Magnetization-Dynamics-Driven Superconducting Spin Currents

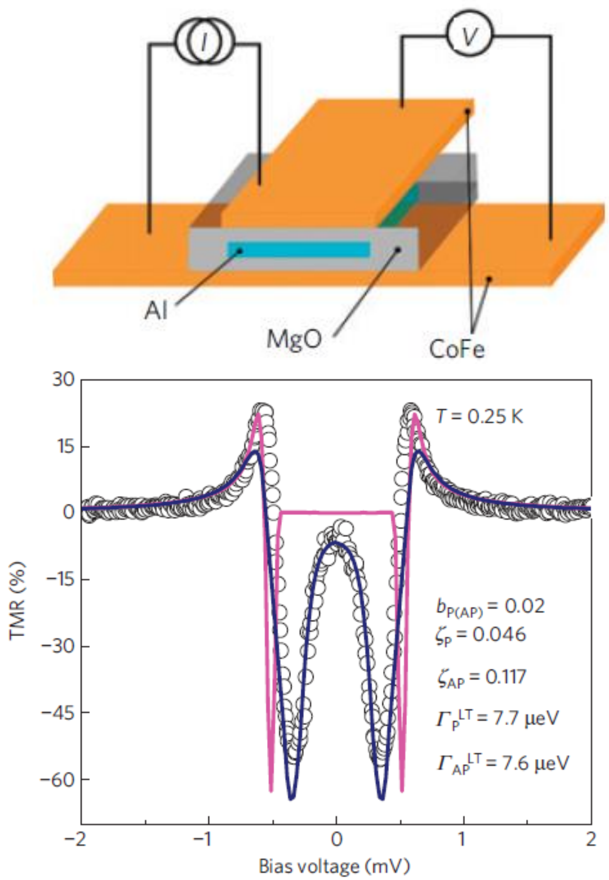
Kun-Rok Jeon,[1] Chiara Ciccarelli,[1] Andrew J. Ferguson,[1] Hide Kurebayashi,[2] Lesley F. Cohen,[3] Xavier Montiel,[4] Matthias Eschrig,[4] Jason W. A. Robinson[1] & Mark G. Blamire[1]

[1]University of Cambridge, UK. [2]University of College London, UK. [3]Imperial College London, UK. [4]Royal Holloway, UK.

- Spin-polarized quasiparticles in supercondutors

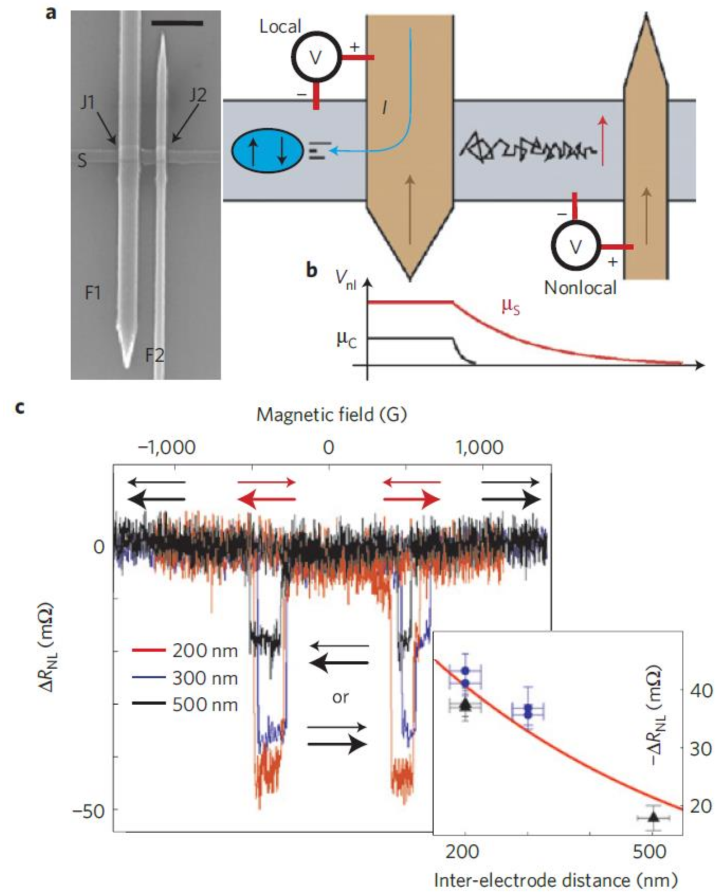
[*probed by direct means under non-equilibrium condition*]

➢ *Enhanced spin lifetime*



Yang *et al., Nat. Mater.* **9,** 586 (2010)

➢ *Spin & charge decoupling*

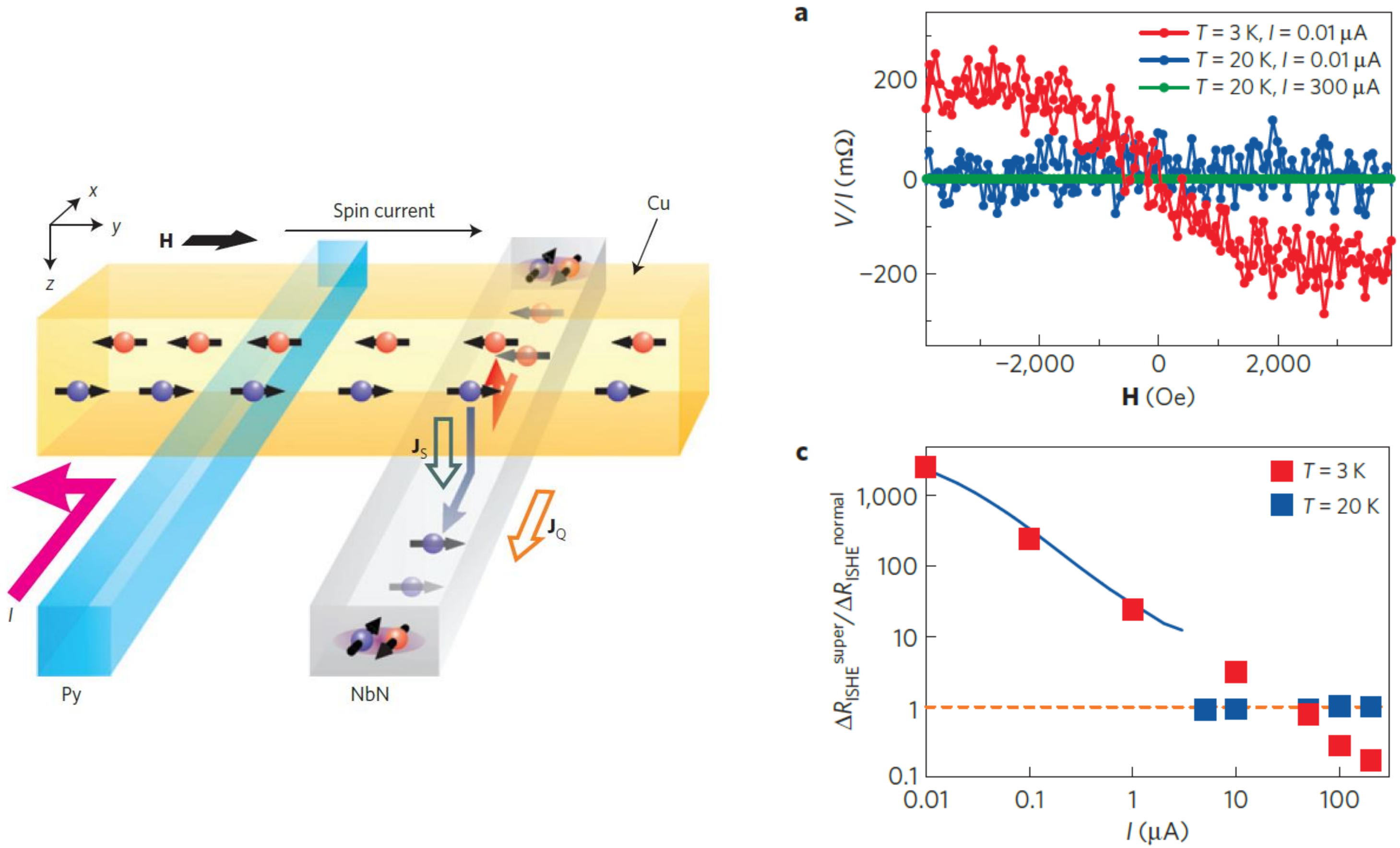


Quay *et al., Nat. Phys.* **9,** 84 (2013)

- Spin-polarized quasiparticles in superconducotors

[*probed* *by direct means under non-equilibrium condition*]

➢ *Giant spin Hall effect*

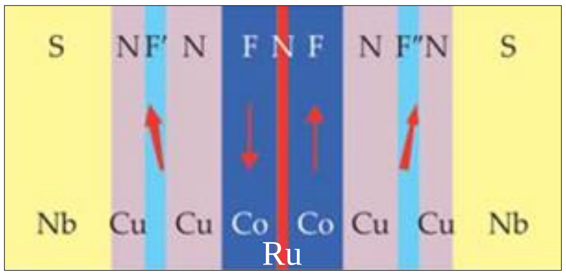


Wakamura et al., Nat. Mater. **14,** 675 (2015)

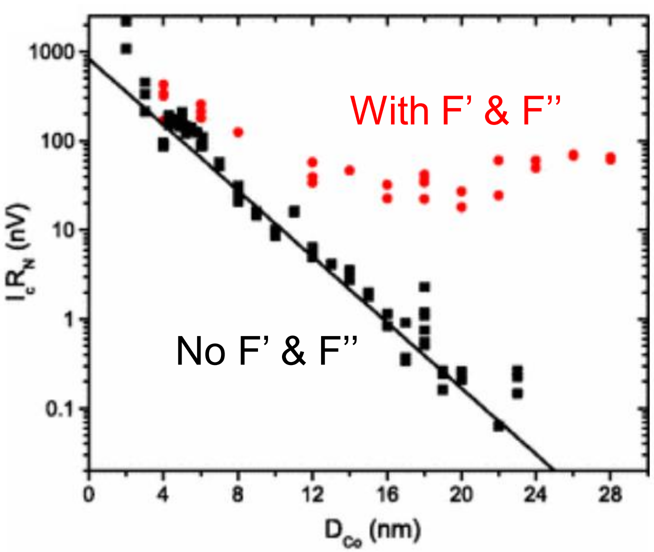
- Long-range spin-triplet supercurrents in ferromagnets

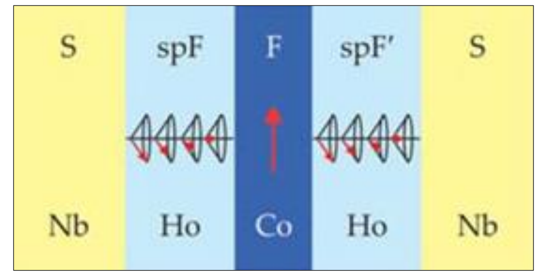
[*probed mostly by indirect means under equilibrium condition*]

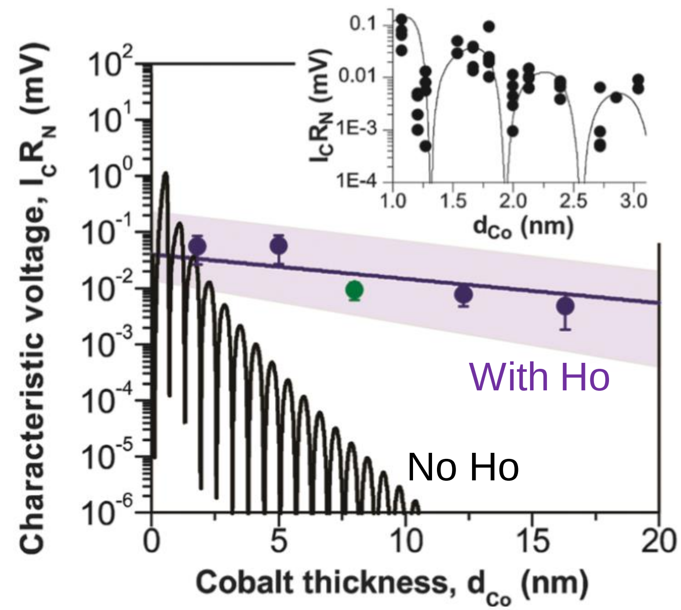
➢ *Josephson effect*



F’ = F’’ = PdNi or CuNi







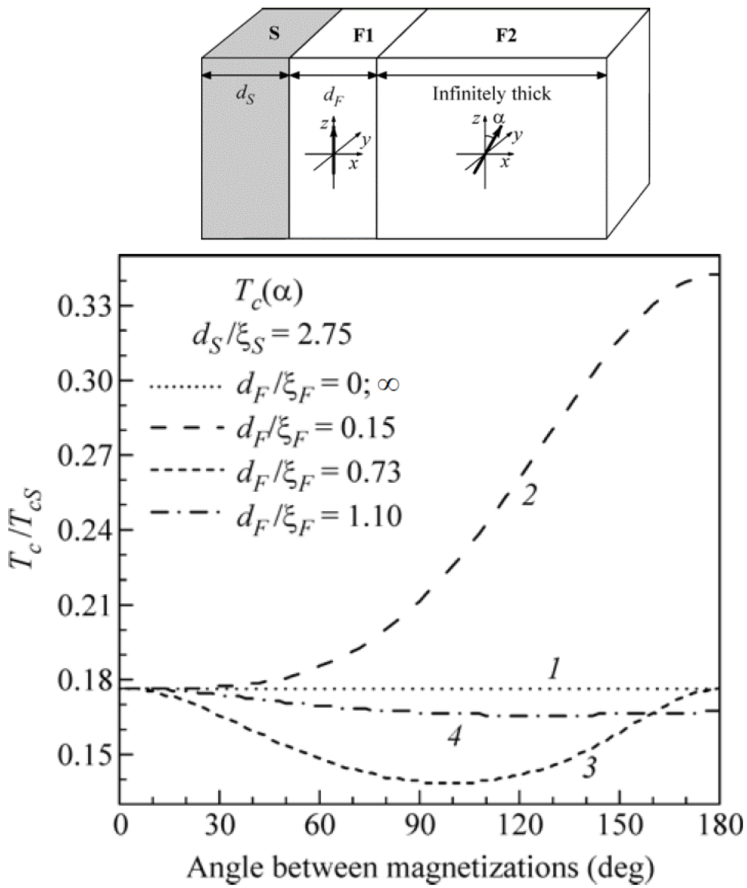
Khaire *et al., Phys. Rev. Lett.* **104,** 137002 (2010)

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

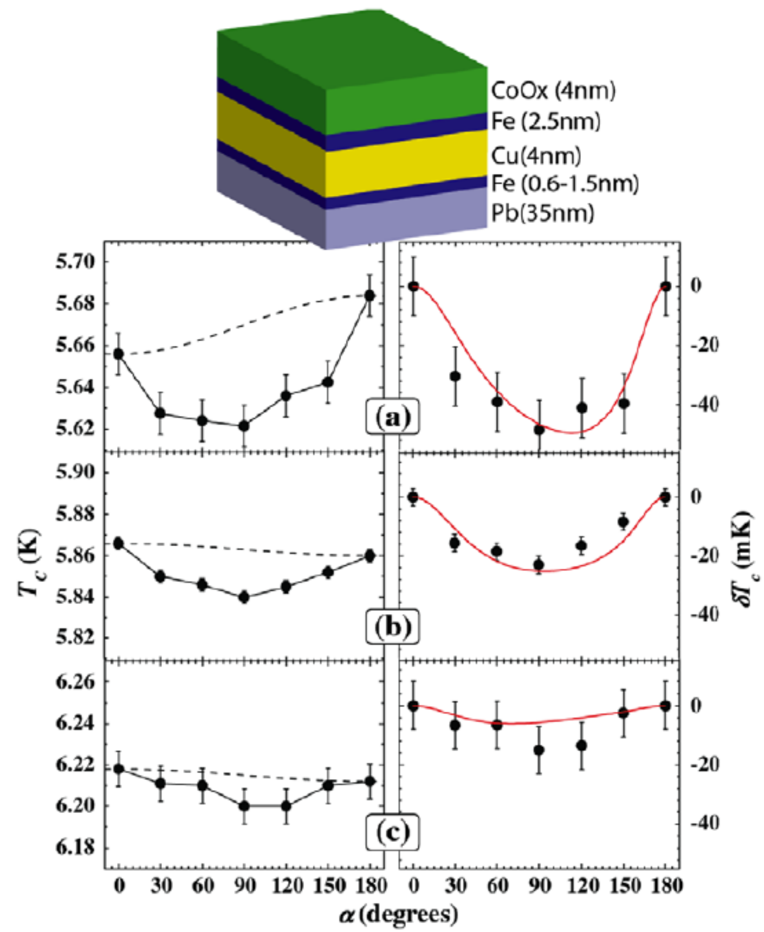
- Long-range spin-triplet supercurrents in ferromagnets

[*probed mostly by indirect means under equilibrium condition*]

➢ T_c *modulation*



Fominov *et al., JETP Lett.* **91,** 308 (2010)



Leksin *et al., Phys. Rev. Lett.* **109,** 057005 (2012)

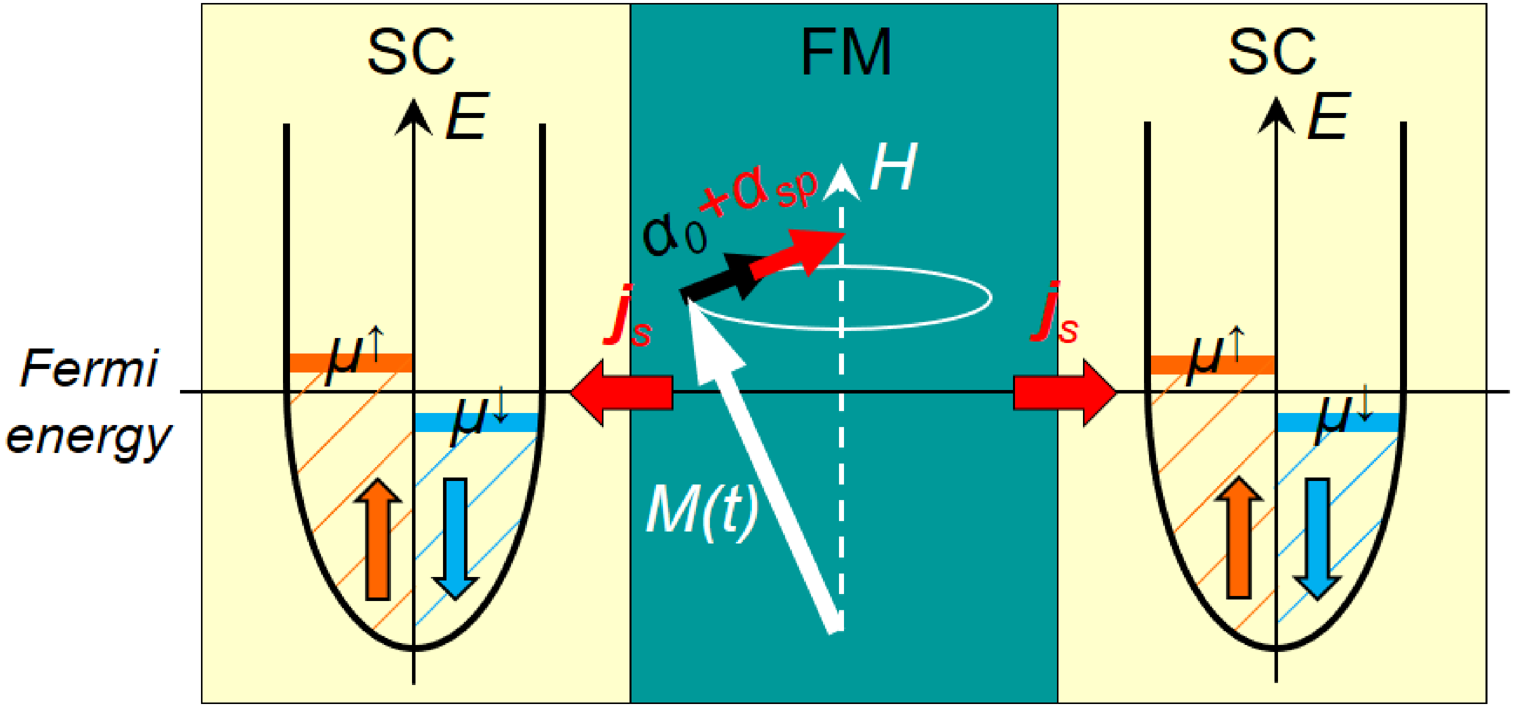
Aim

- *Ferromagnetic resonance (FMR) driven*

spin-polarized transport via spin-triplet states

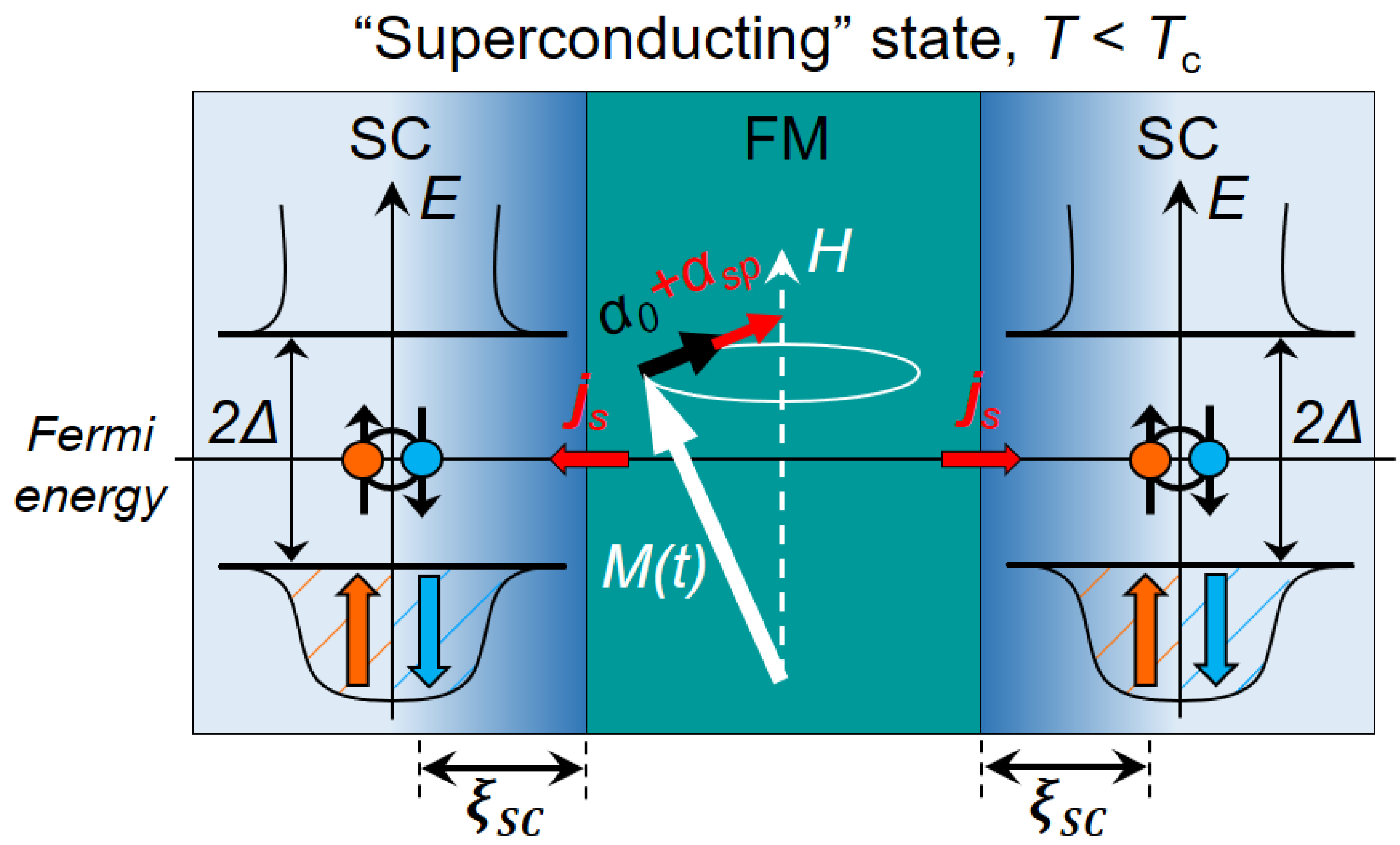
induced by spin-orbit coupling (SOC)

“Normal” state, $T > T_c$



$$\frac{\partial \vec{M}}{\partial t} = -\gamma\mu_0 \vec{M} \times \vec{H}_{eff} + \frac{(\alpha_0 + \alpha_{sp})}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t}$$

Tserkovnyak *et al., Rev. Mod. Phys.* **77,** 1375 (2005); *Phys. Rev. Lett.* **88,** 117601 (2002)

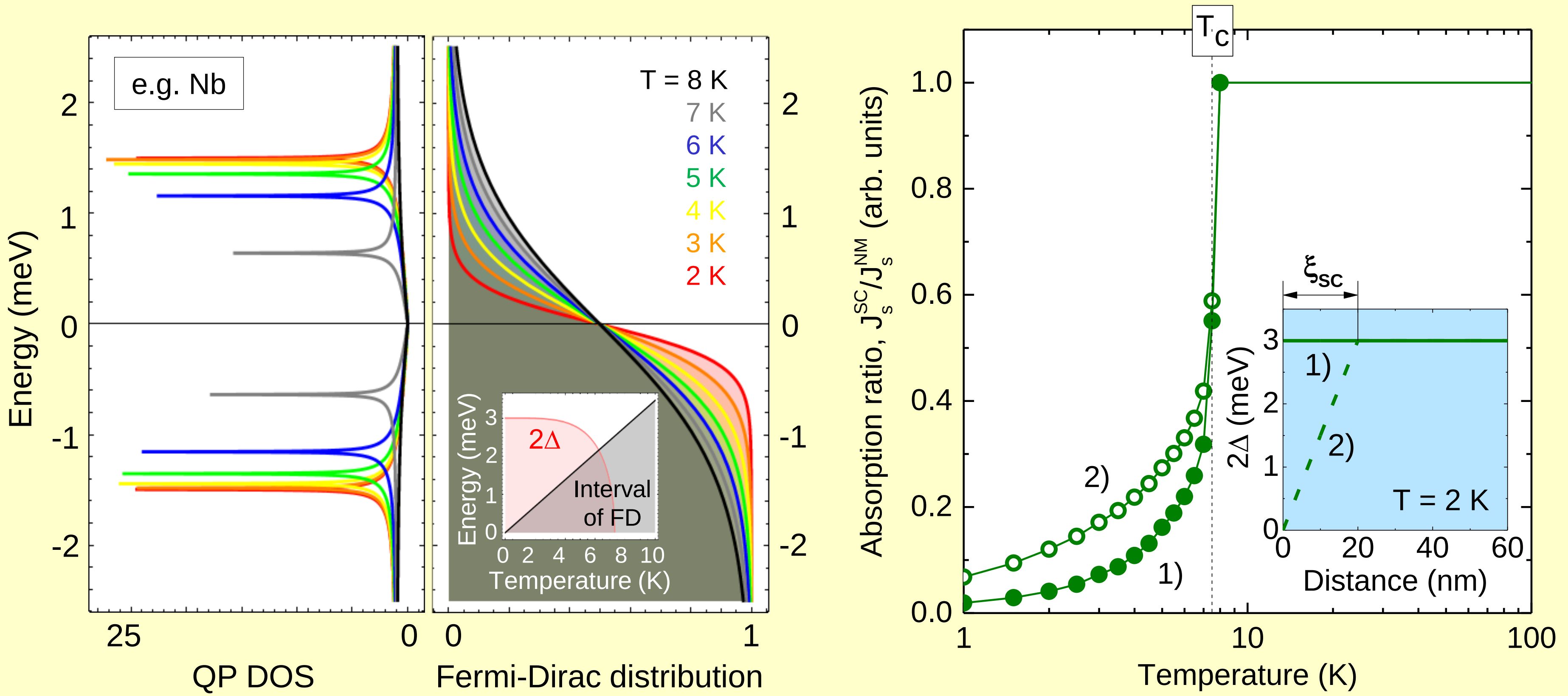


Bell *et al., Phys. Rev. Lett.* **100,** 047002 (2008), Morten *et al., Eur. Phy. Lett.* **84,** 57008 (2008)

Suppression of Diffusive Spin-Polarized QPs

$$\frac{J_S^{SC}}{J_S^{NM}} \approx \int_{-\infty}^{+\infty} \frac{N_{SC}(E)}{N_{NM}(E)} \left(-\frac{\partial f(E)}{\partial E}\right) dE$$

Spin absorption across T_c: Model calculation



Bell *et al.*, *Phys. Rev. Lett.* **100,** 047002 (2008), Morten *et al.*, *Eur. Phy. Lett.* **84,** 57008 (2008)
Wakamura *et al.*, *Phys. Rev. Lett.* **112**, 036602 (2014)

Ferromagnetic Josephson structures:

Type I: Cu(5 nm)/Nb(t_{Nb})/Py(6 nm)/Nb(t_{Nb})/Quartz

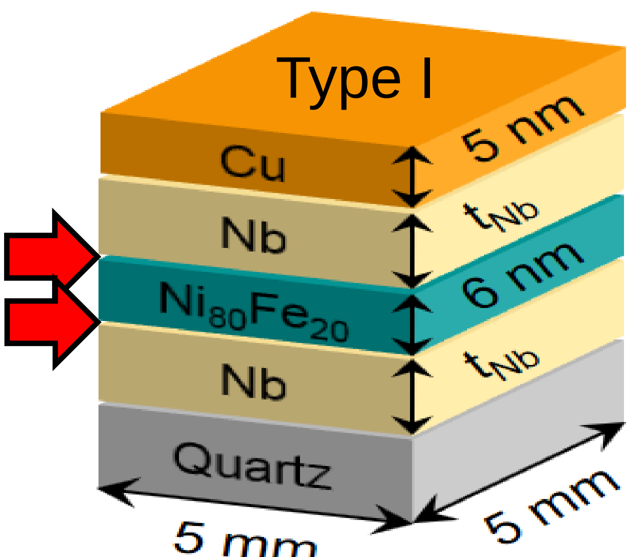
Type II: Cu(5 nm)/Pt(5 nm)/Nb(t_{Nb})/Py(6 nm)/Nb(t_{Nb})/Pt(5 nm)/Quartz

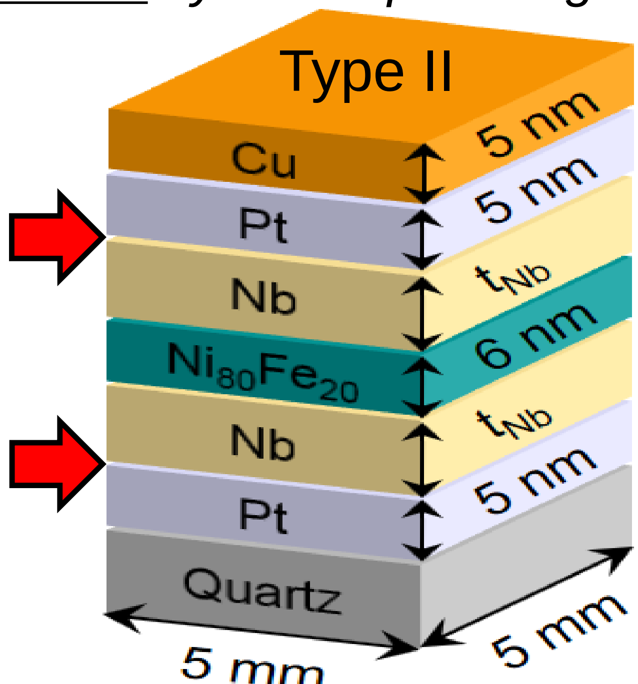
t_{Nb} = 7.5, 15, 30, 45, 60 nm ($\lambda_L(0)$ > 100 nm for thin Nb films)

Cu capping layer: long spin diffusion length (a few hundred nm)

Quartz (silicon oxide) substrate: low MW loss at GHz

Grown in a single deposition run by UHV sputtering





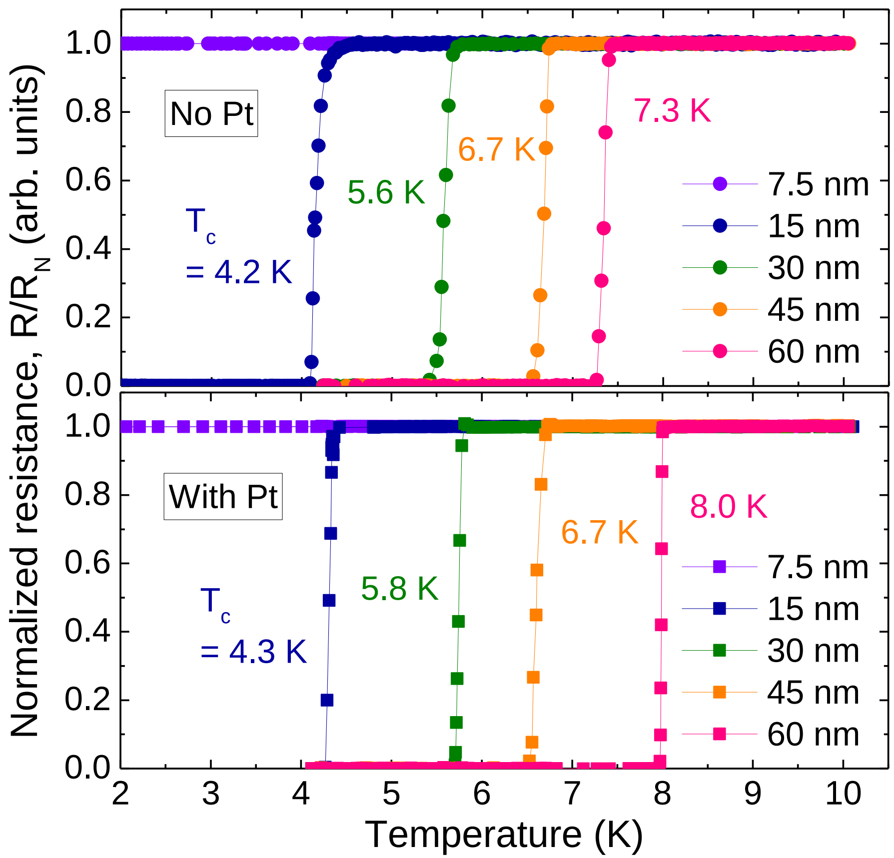
Sample Structure & Property

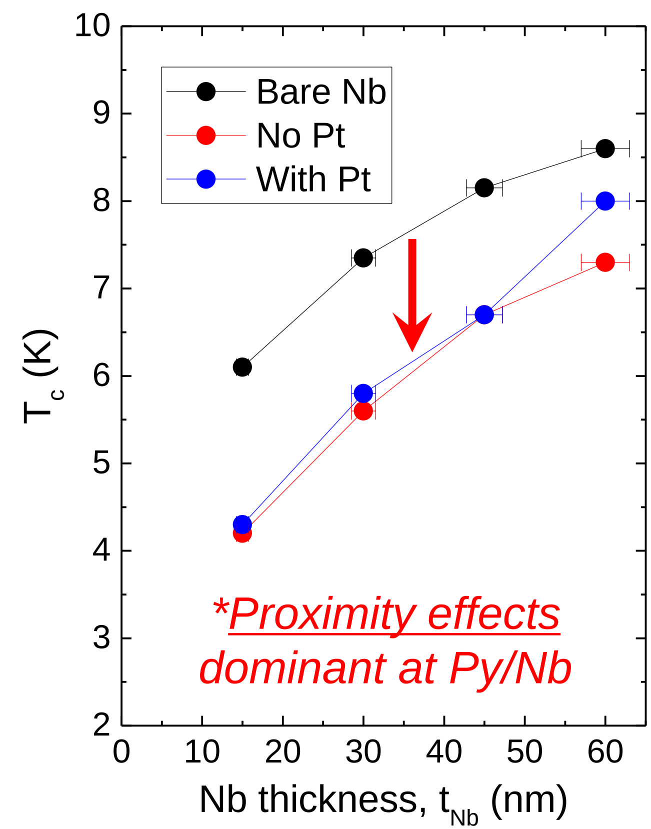
Ferromagnetic Josephson structures:

Type I: Cu(5 nm)/Nb(t_{Nb})/Py(6 nm)/Nb(t_{Nb})/Quartz

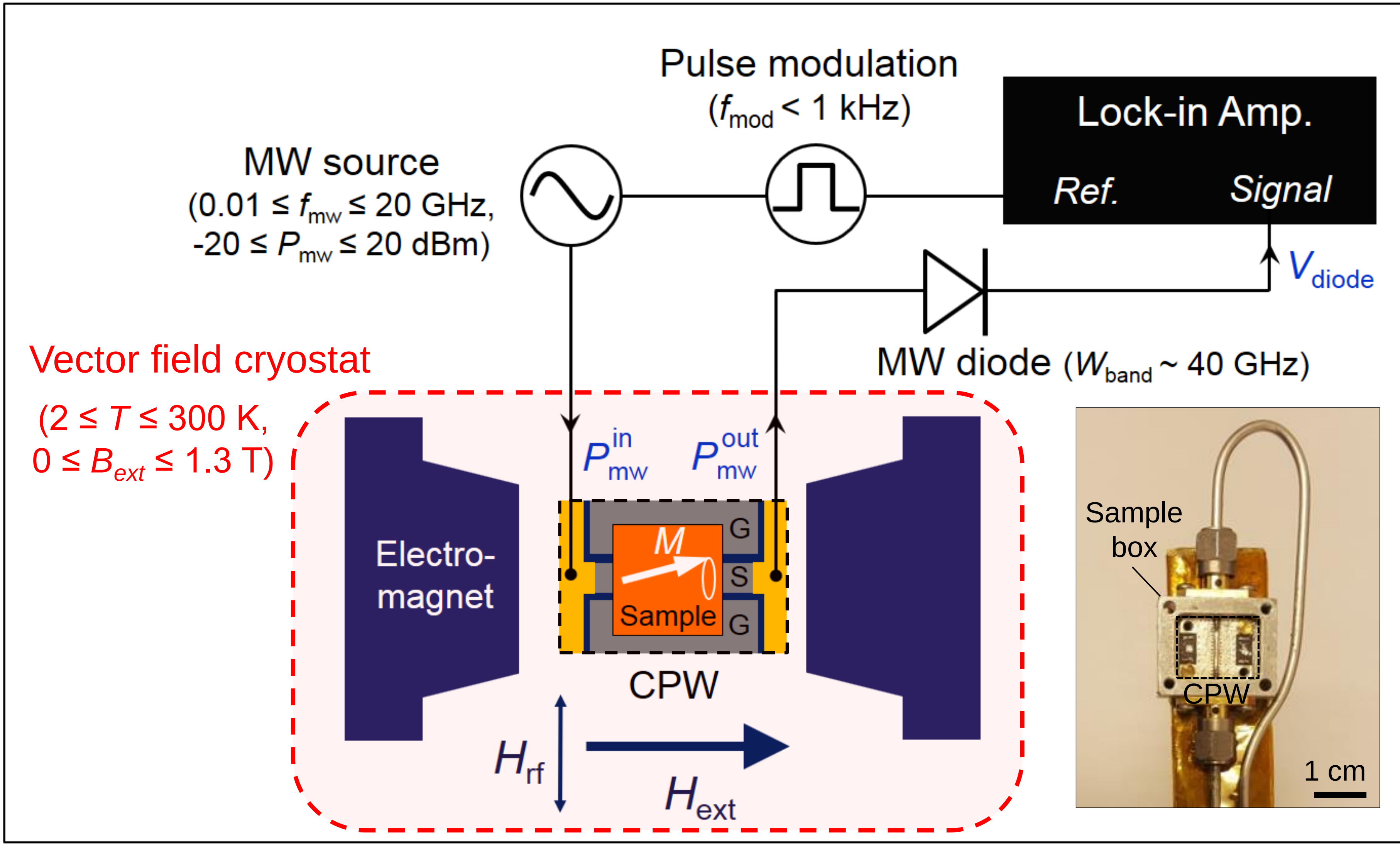
Type II: Cu(5 nm)/Pt(5 nm)/Nb(t_{Nb})/Py(6 nm)/Nb(t_{Nb})/Pt(5 nm)/Quartz

Systematically controlled T_c by Nb thinckness





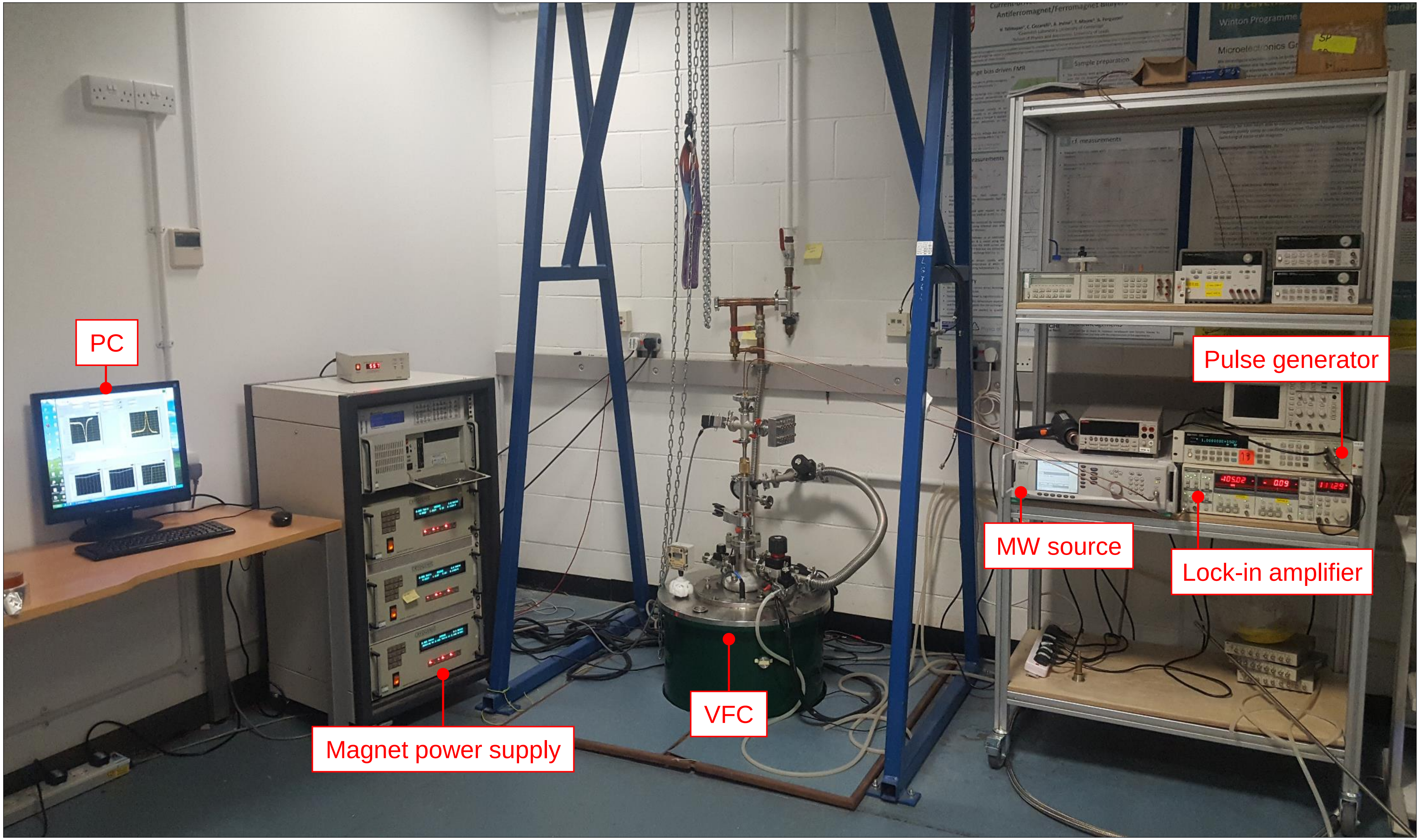
Schematic diagram of FMR spectroscope



ME group (Cavendish)

*Thanks to Chiara & Andrew

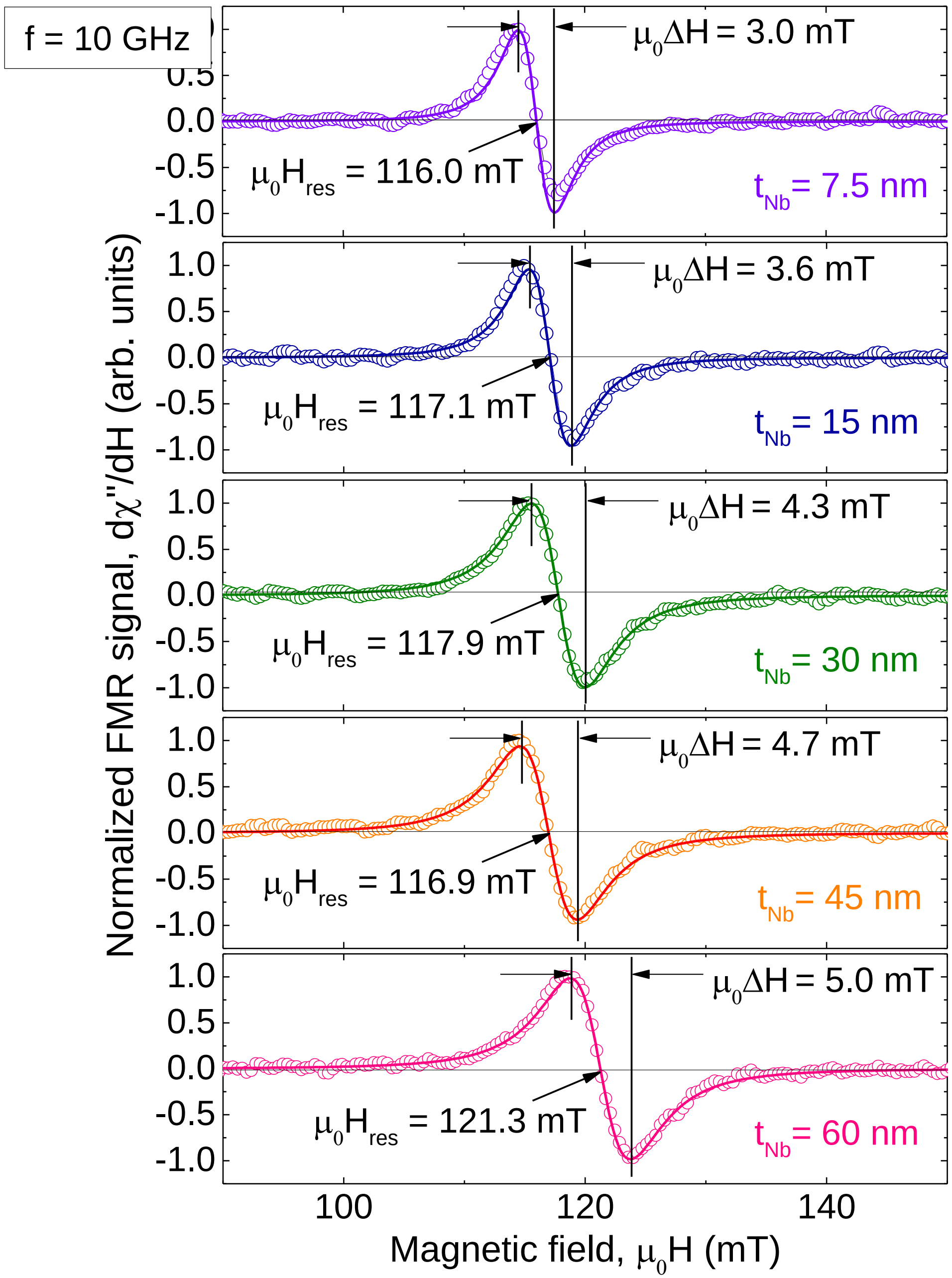
FMR Setup with Vector Field Cryostat (VFC)

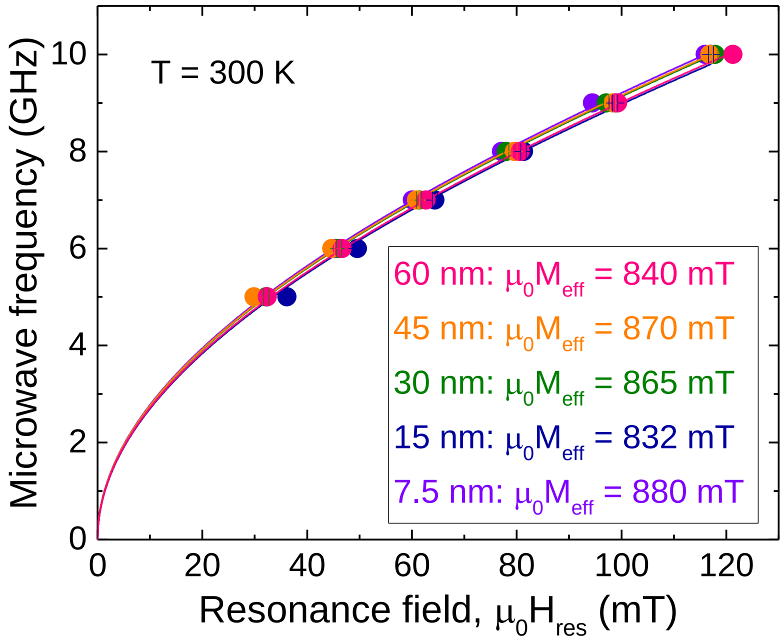


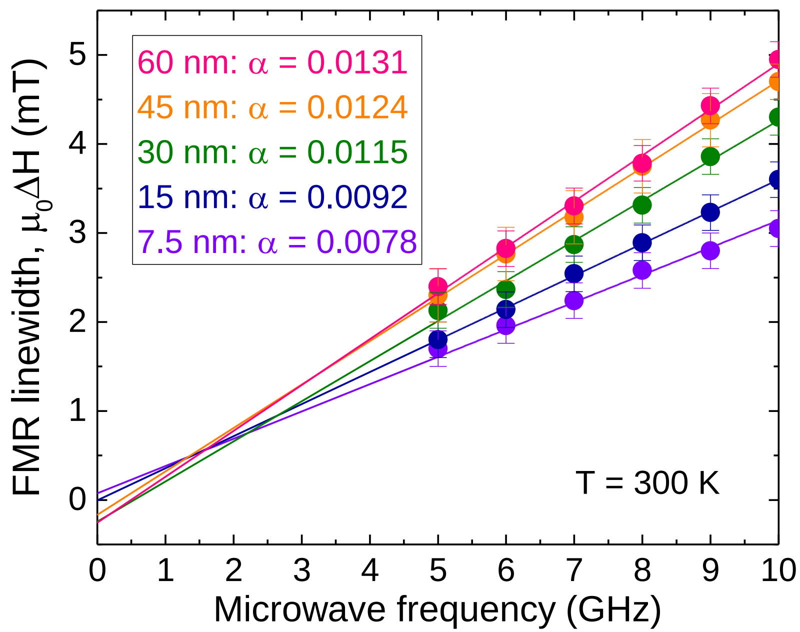
ME group (Cavendish)

**Thanks to Chiara & Andrew*

Nb Thickness Dependence of FMR Spectra at 300 K





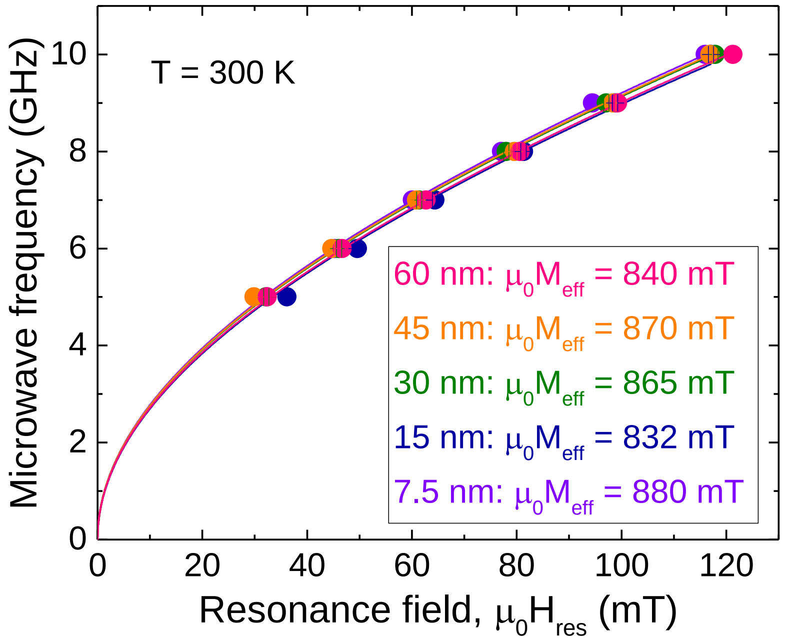


Nb Thickness Dependence of FMR Spectra at 300 K

Resonance field

$$f = \frac{\gamma}{2\pi}\sqrt{[\mu_0(H_{res} + M_{eff}) \cdot \mu_0 H_{res}]}$$

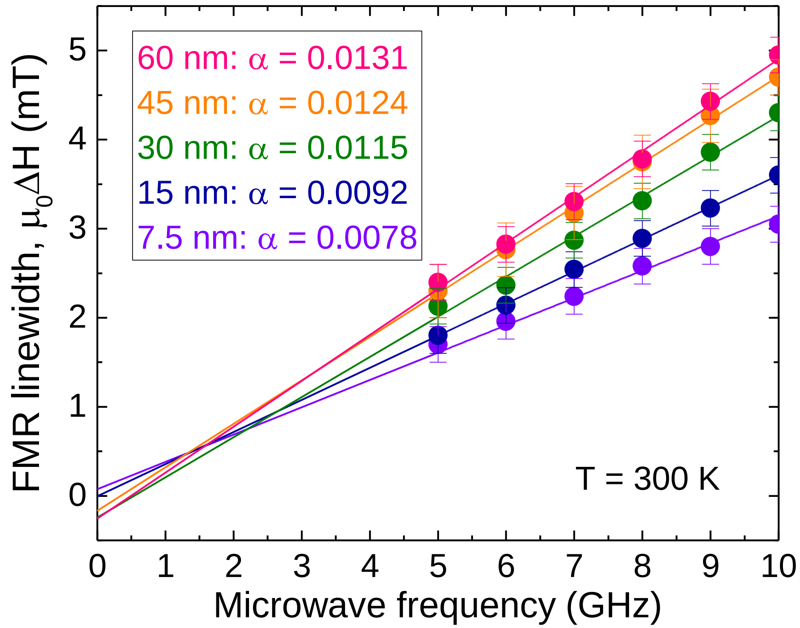
$\gamma (= g_L \mu_B / \hbar)$: *gyromagnetic ratio*



Linewidth

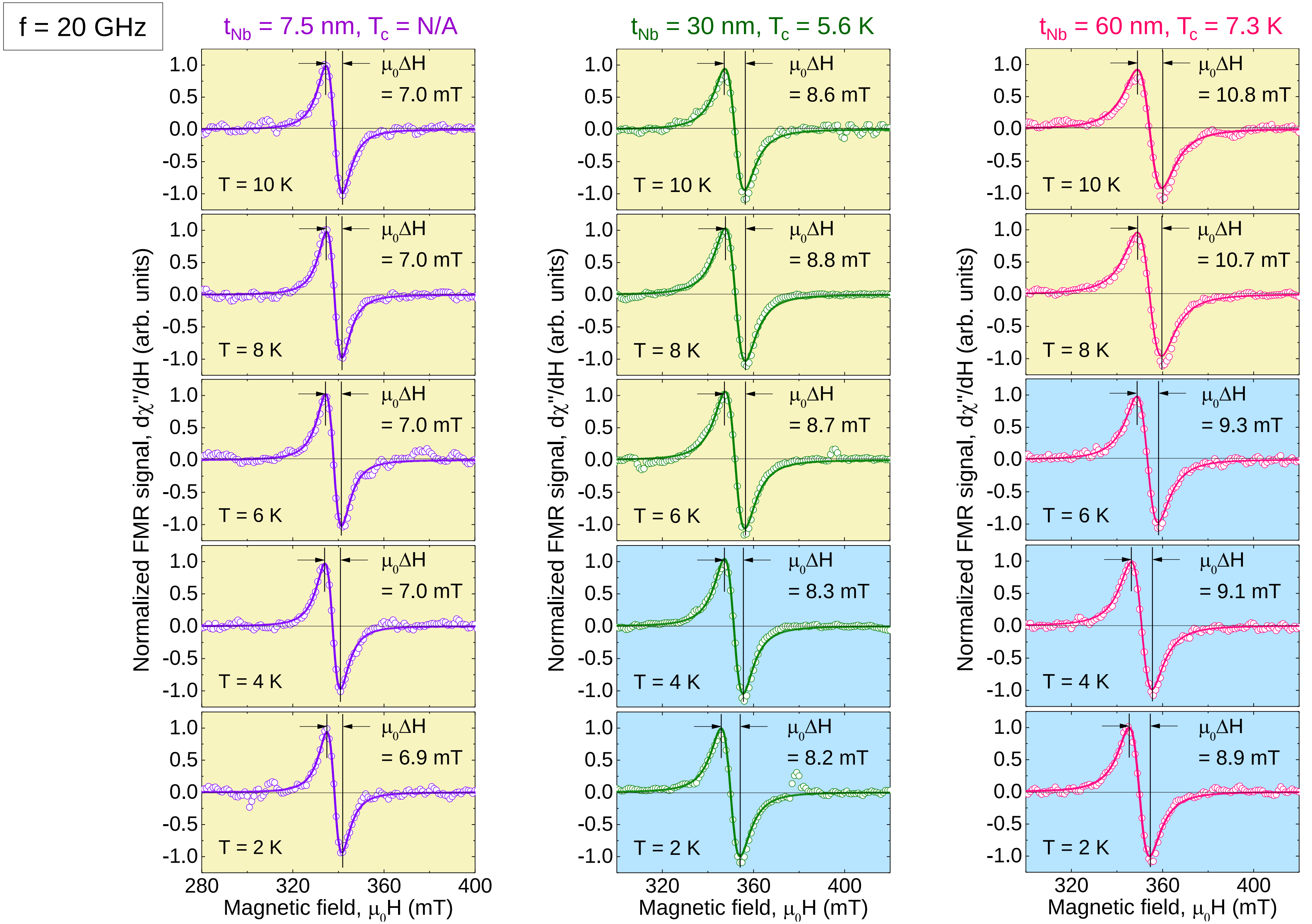
$$\mu_0 \Delta H(f) = \mu_0 \Delta H_0 + \frac{4\pi\alpha f}{\sqrt{3}\gamma}$$

α: *Gilbert damping constant*



Mizukami *et al.*, *PRB* **66**, 104413 (2002)
Tserkovnyak *et al.*, *PRL* **88**, 117601 (2002)

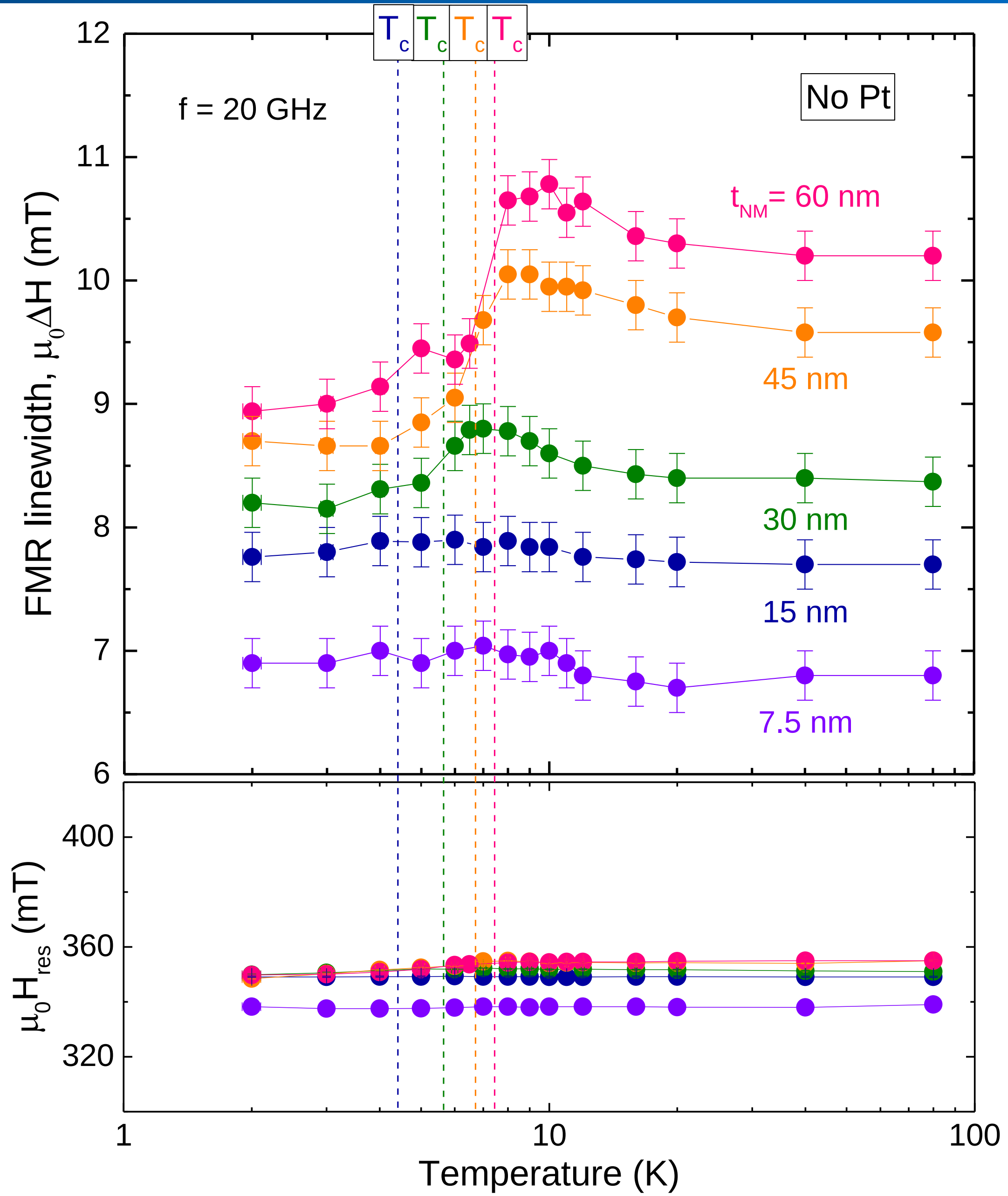
Effect of Superconducting Correlation on FMR Spectra



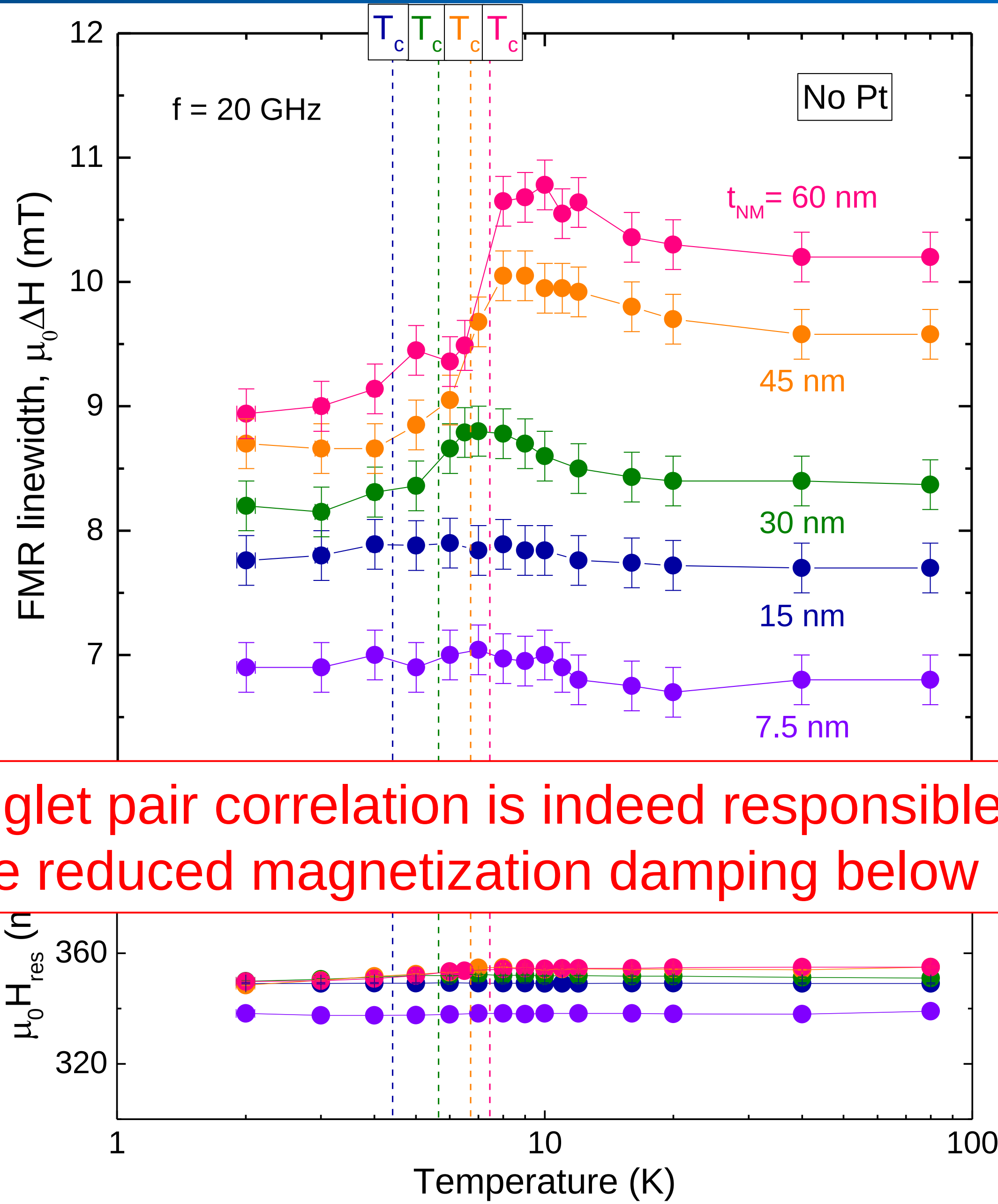
Normal state

Superconducting state

Sudden Reduction in FMR Linewidth across T_c



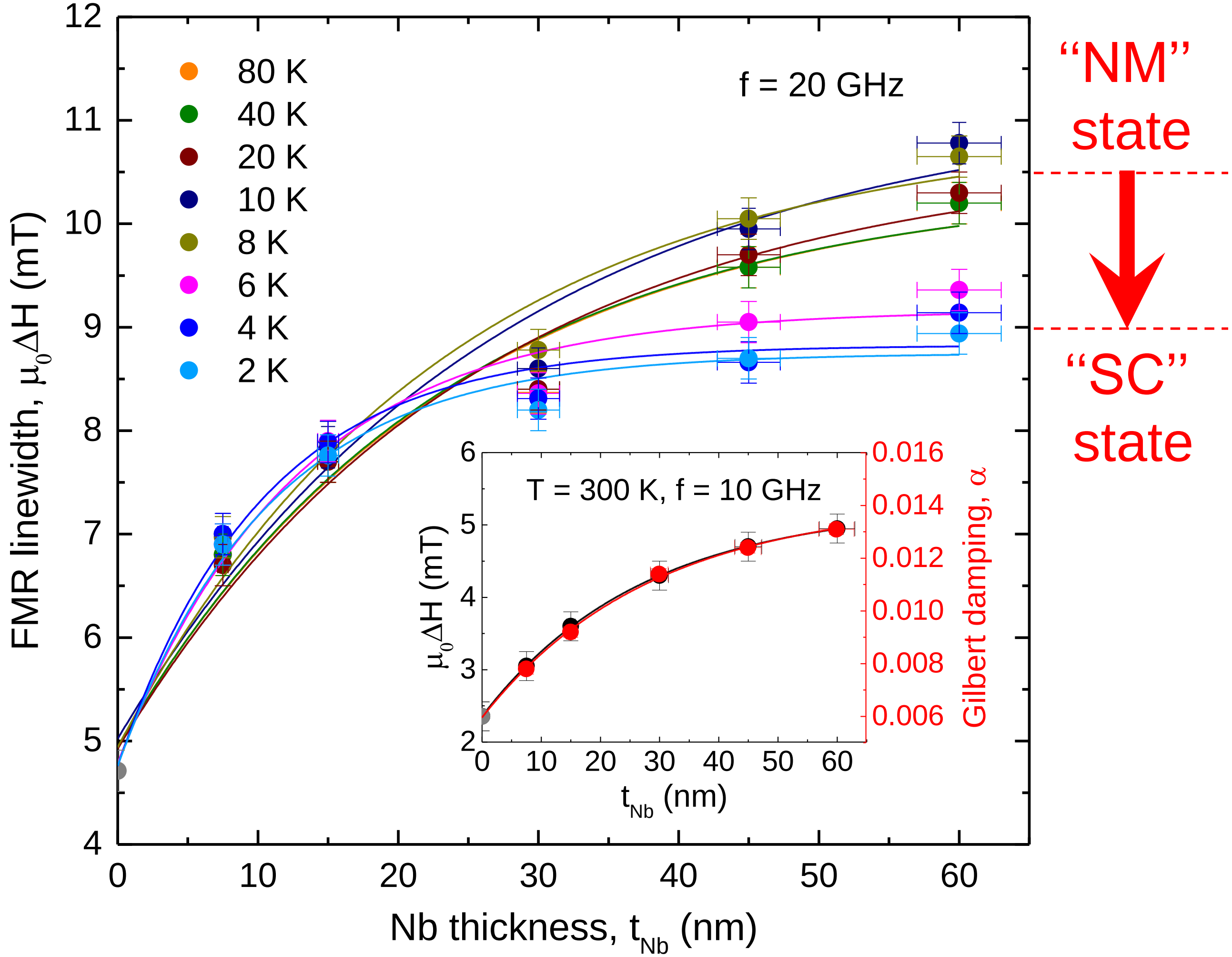
Sudden Reduction in FMR Linewidth across T_c



Singlet pair correlation is indeed responsible for the reduced magnetization damping below T_c.

Characterizing Diffusive Penetration of Spin-Polarized QPs

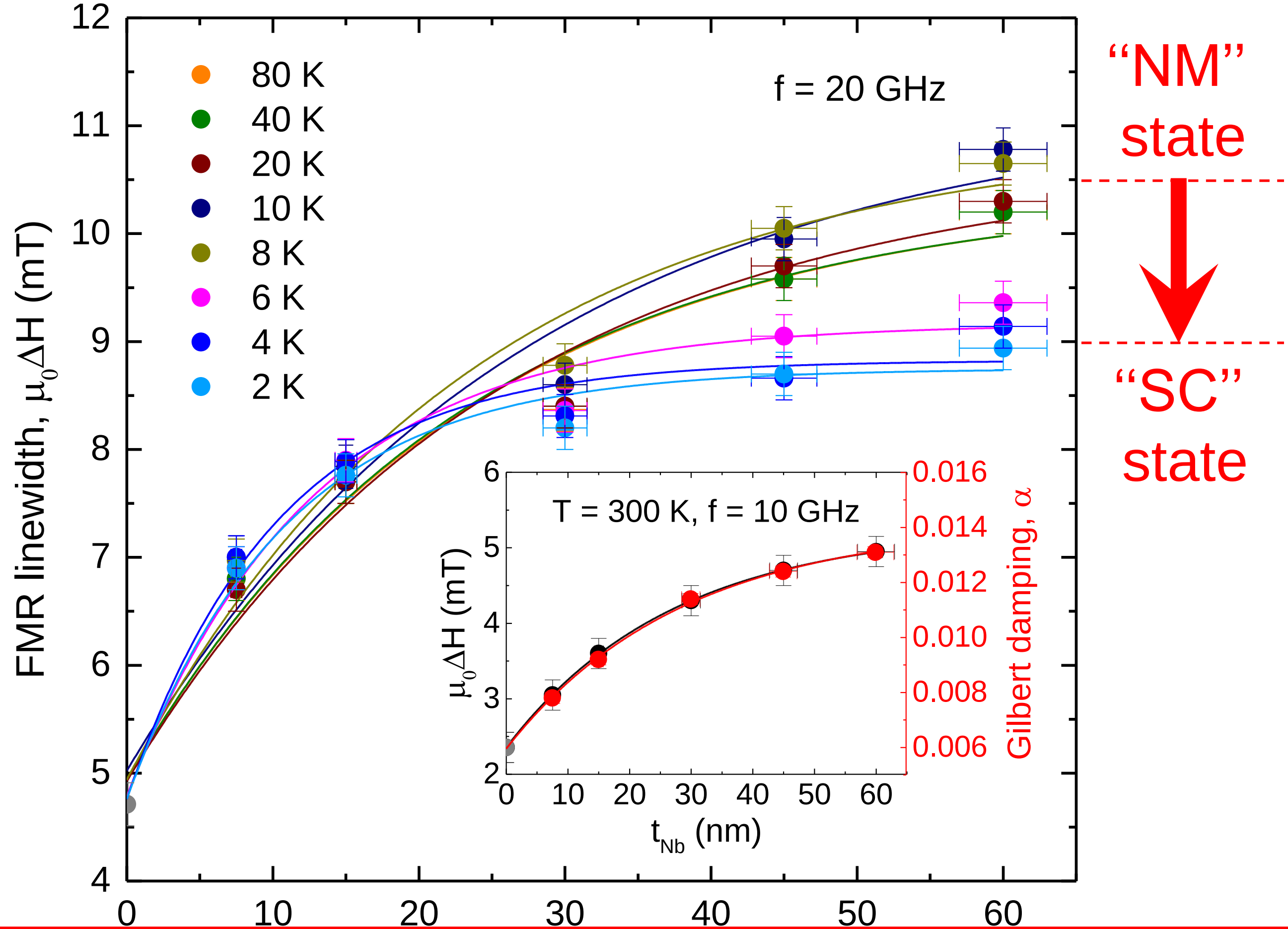
Tserkovnyak *et al.*, *Rev. Mod. Phys.* **77,** 1375 (2005); *Phys. Rev. Lett.* **88,** 117601 (2002)



Below T_c, 1) the spin transfer efficiency diminishes
as well as 2) the characteristic length of spin transport gets shorter.

Characterizing Diffusive Penetration of Spin-Polarized QPs

Tserkovnyak *et al., Rev. Mod. Phys.* **77,** 1375 (2005); *Phys. Rev. Lett.* **88,** 117601 (2002)

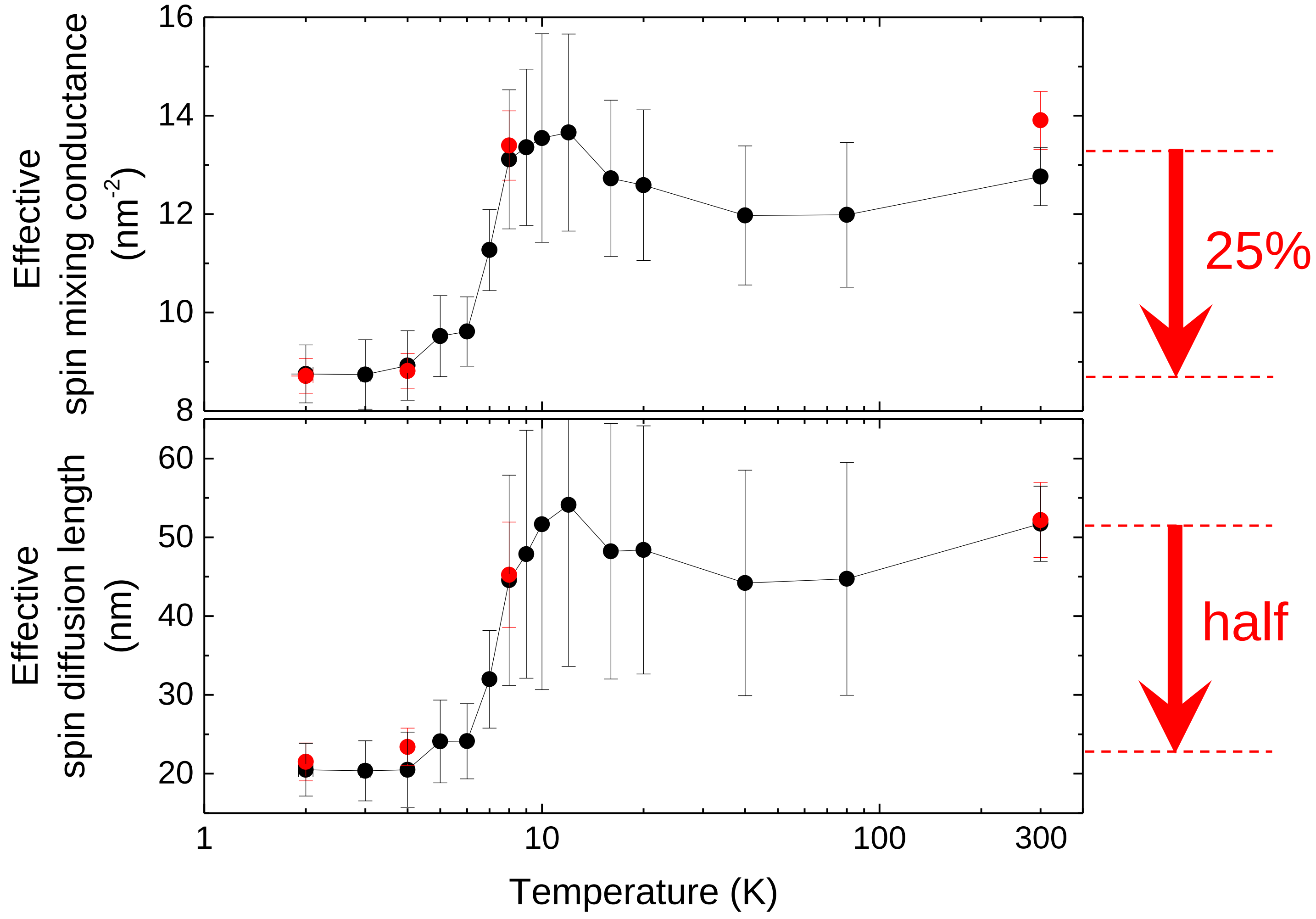


Spin mixing conductance & spin diffusion length

$$\alpha_{sp}(t_{SC}) = 2 \cdot \left(\frac{g_L \mu_B g_r^{\uparrow\downarrow}}{4\pi M_s t_{FM}} \right) \cdot \left[1 + \frac{g_r^{\uparrow\downarrow} \rho_{SC} l_{sd}^{SC}\, e^2/2\,\pi\hbar}{\tanh(t_{SC}/l_{sd}^{SC})} \right]^{-1}$$

Spin Mixing Conductance & Spin Diffusion Length

Bell *et al., Phys. Rev. Lett.* **100,** 047002 (2008), Morten *et al., Eur. Phy. Lett.* **84,** 57008 (2008)



In the SC state, the spin injection efficiency becomes lower (25%) as well as the spin transport length gets shorter (half).

Interface Transparency & Andreev Reflection

Interface spin transparency

$$\mathcal{T} = \frac{g_0^{\uparrow\downarrow}}{g_0^{\uparrow\downarrow} + (2\pi\hbar\,/\rho_{FM}\, l_{sd}^{FM} e^2)\cdot \tanh(t_{FM}/l_{sd}^{FM})},$$

$$g_0^{\uparrow\downarrow} = \frac{g_r^{\uparrow\downarrow}\cdot (2\pi\hbar\,/\rho_{FM}\, l_{sd}^{FM} e^2)\cdot \tanh\left(t_{FM}/l_{sd}^{FM}\right)}{(2\pi\hbar\,/\rho_{FM}\, l_{sd}^{FM} e^2)\cdot \tanh(t_{FM}/l_{sd}^{FM}) - g_r^{\uparrow\downarrow}}$$

l_{sd}^{FM}*: spin diffusion length of FM,* ρ_{FM}*: resistivity of FM,*
$g_0^{\uparrow\downarrow}$ *(*$g_r^{\uparrow\downarrow}$*): actual (effective) spin mixing conductance*

Zhang *et al.*,
Nat. Phys. **11,** 496 (2015)

Temp.	2 K	4 K	8 K	300 K
$\mathcal{T}$	0.34	0.34	0.51	0.59

Andreev reflection & spin relaxation

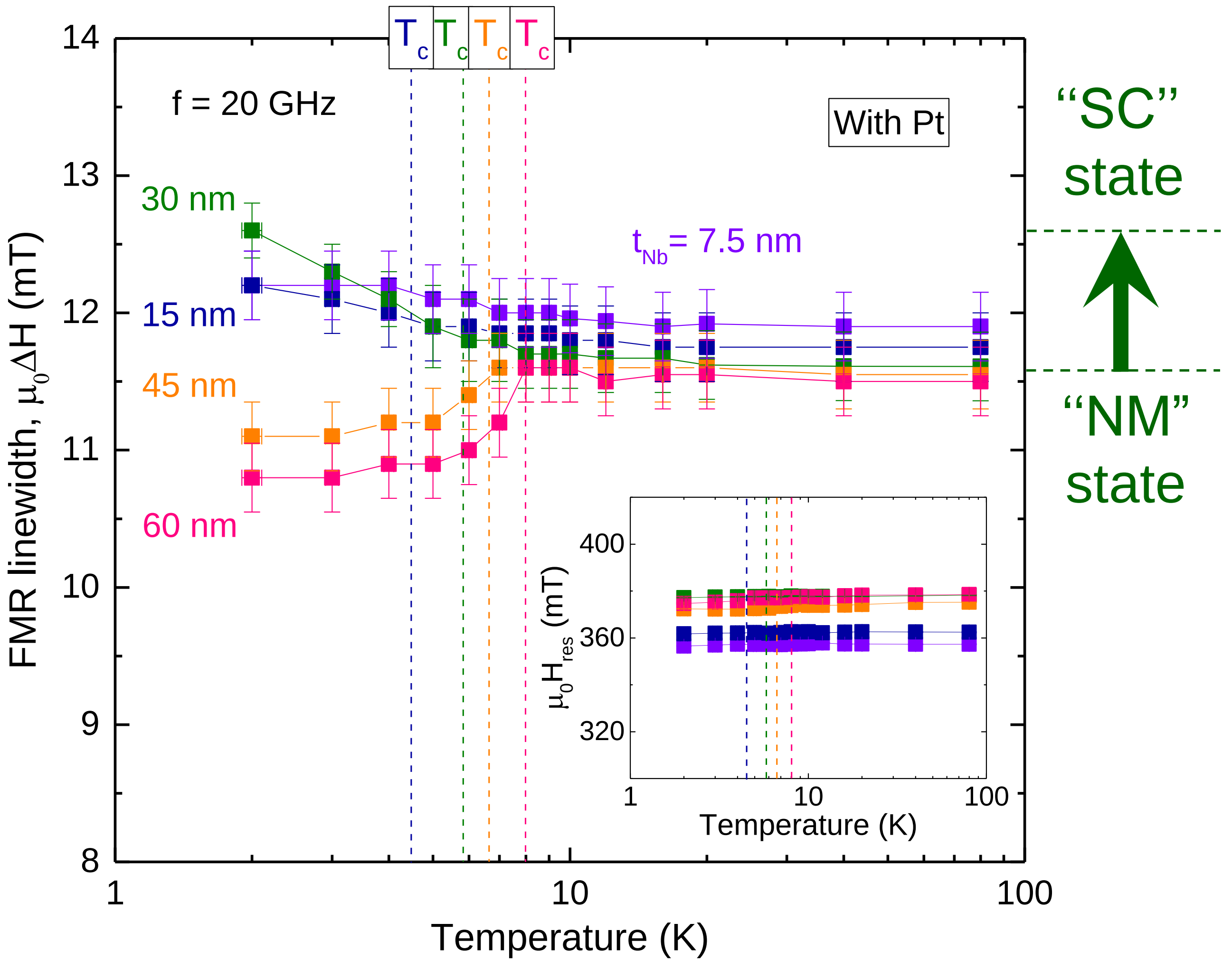
$$l_{qp}^{sp} = \sqrt{D\cdot\left(1/\tau_{AR} + 1/\tau_{sf}\right)^{-1}} \approx \sqrt{D\tau_{AR}}$$

τ_{AR}*: conversion time into (singlet) Cooper pairs*
τ_{sf}*: spin lifetime of QPs*

Gu *et al.*,
Phys. Rev. B **66,** 140507 (2002)

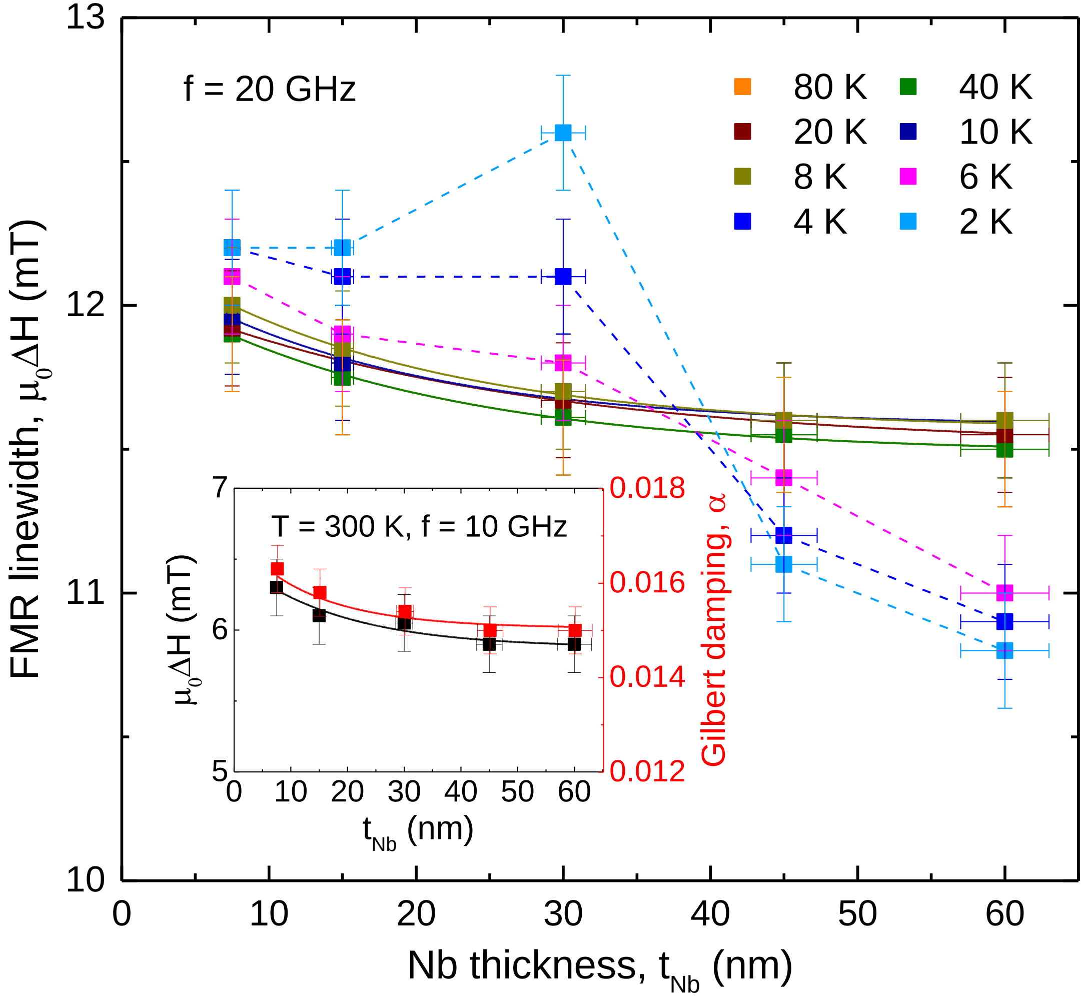
Zero-temperature ξ_{sc} of Nb (13 nm)
in the dirty limit

Anomalous Increase of FMR Linewidth below T_c



When coupled with Pt, the anomalous increase of FMR linewidth appears for intermediate Nb thicknesses (15 & 30 nm) below T_c.

Enhanced Transport/Dissipation of Spin Currents at low T

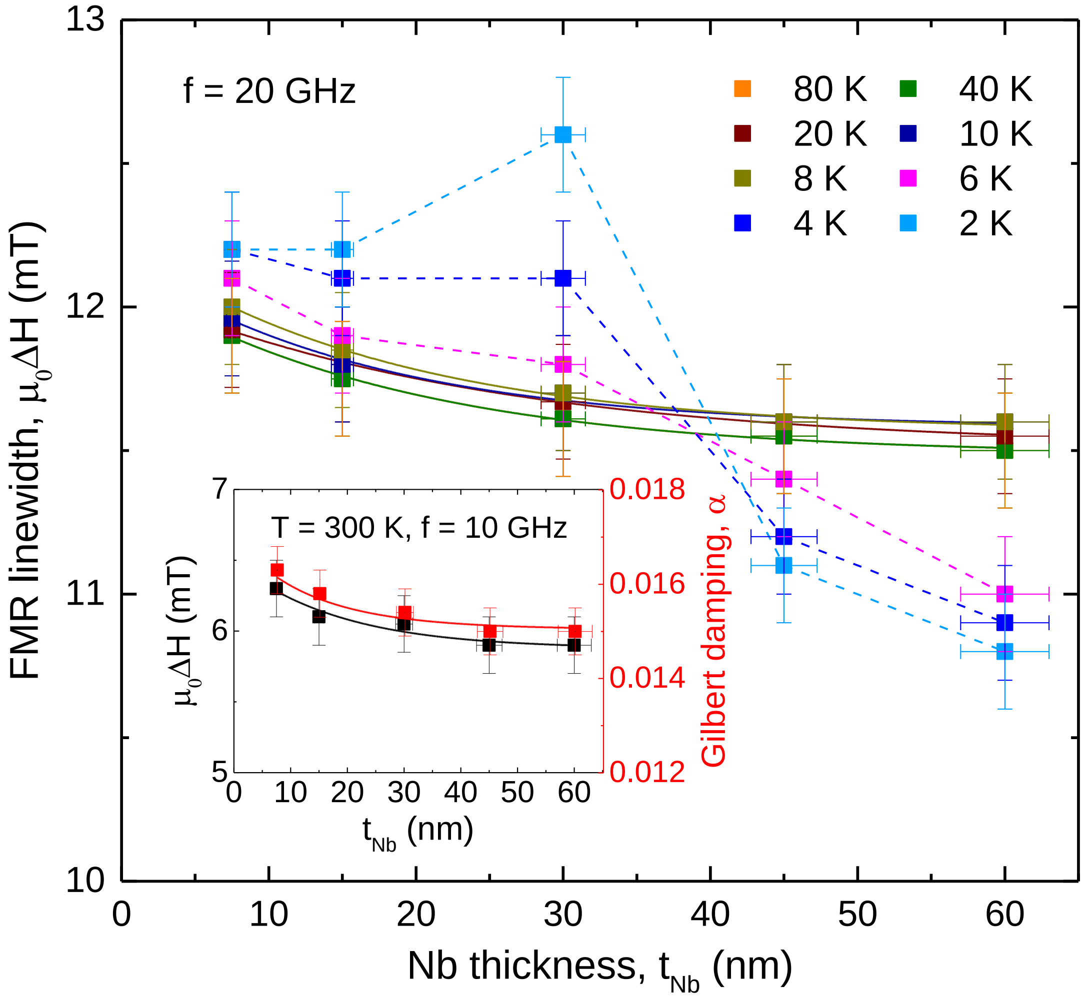


In contrast to "NM" state, FMR linewidth as a function of t_{Nb} below T_c cannot be described by (standard) spin pumping model.

Rev. Mod. Phys. **77,** 1375 (2005);
Phys. Rev. Lett. **88,** 117601 (2002)

Spin mixing conductance & spin diffusion length

$$\alpha_{sp}^{c}(t_{SC}) = 2 \cdot \left(\frac{g_L \mu_B g_r^{\uparrow\downarrow}}{4\pi M_s t_{FM}}\right) \cdot \left[1 + \frac{g_r^{\uparrow\downarrow} \rho_{SC} l_{sd}^{SC} e^2}{2\pi\hbar} \cdot \left(\frac{1 + g\rho_{SC} l_{sd}^{SC} e^2/2\pi\hbar \cdot \tanh(t_{SC}/l_{sd}^{SC})}{\tanh(t_{SC}/l_{sd}^{SC}) + g\rho_{SC} l_{sd}^{SC} e^2/2\pi\hbar}\right)\right]^{-1}$$



Notably different spin transfer mechanism at play in "SC" state.

When coupled with Pt, the remarkably enhanced spin current flow occurs for intermediate Nb thicknesses at low *T*.

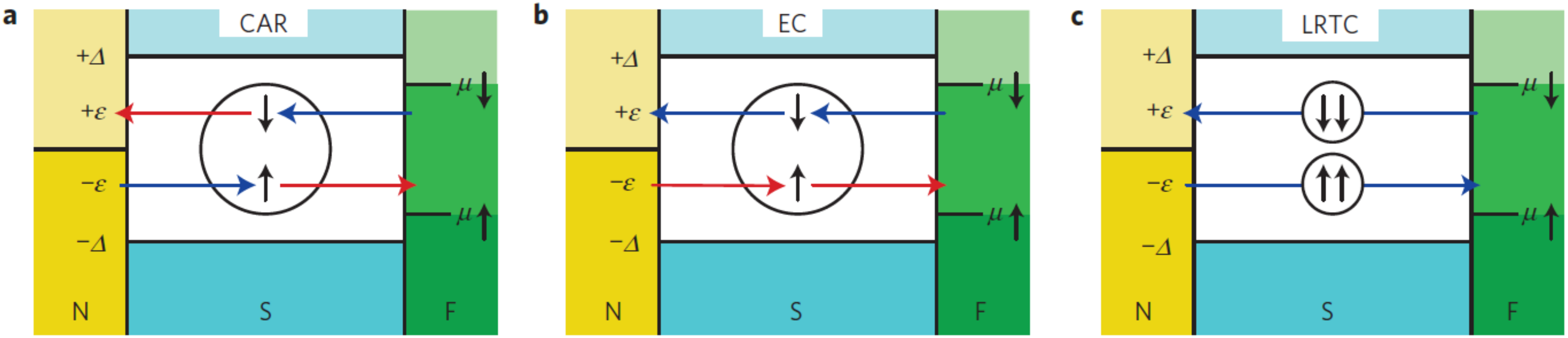
- Spin transfer mechanisms

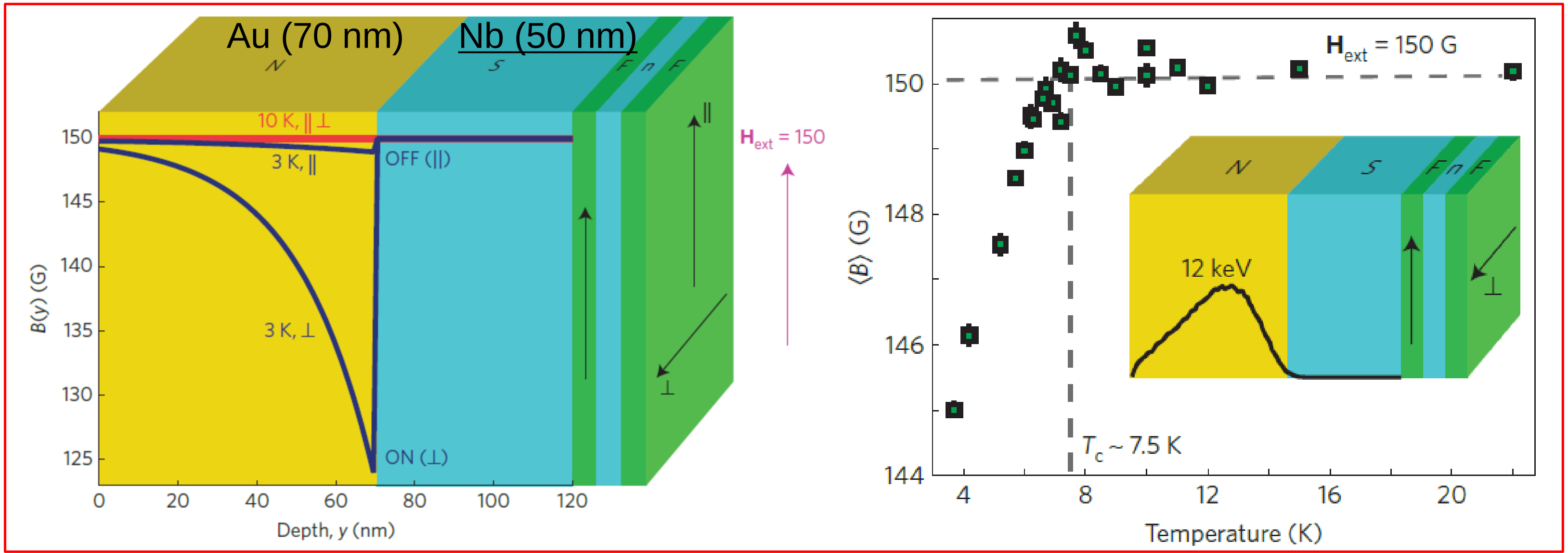
Flokstra *et al.*, *Nat. Phys.* **12,** 57 (2016)

➢ *Crossed Andreev reflection*

➢ *Elastic co-tunnelling*

➢ *Long-range triplet components*



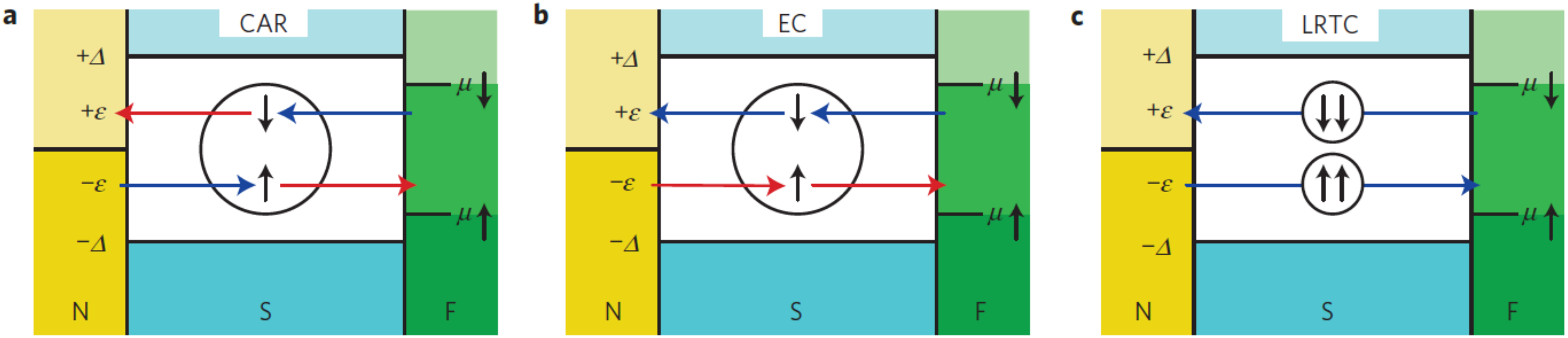


“Singlet Pair” vs. “Triplet Pair”: Open Question

- Spin transfer mechanisms

Flokstra *et al.*, *Nat. Phys.* **12**, 57 (2016)

- ➢ *Crossed Andreev reflection*
- ➢ *Elastic co-tunnelling*
- ➢ *Long-range triplet components*



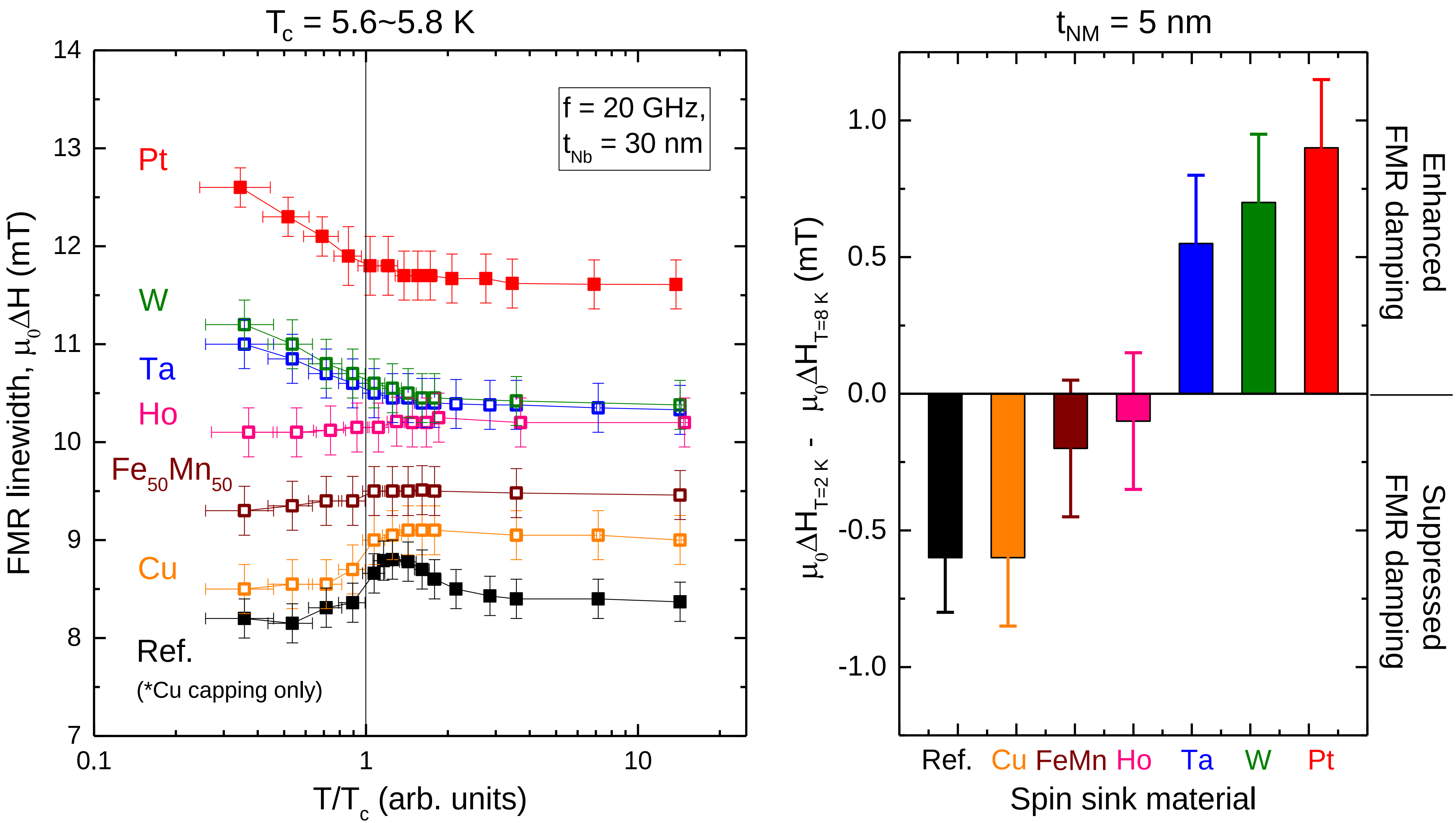
Spin-singlet pairs either being formed from electrons originating from the interfaces at opposite sides of the S layer (CAR) or being used to effectively transfer an electron from one of the interfaces to the other interface (EC).

Flows of spin-triplet where a net flow of spin-up electron pairs moving from one side of the S layer to the other side is cancelled by an opposing flow of spin-down electron pairs.

**No spin current* in S

**Pure spin current* in S

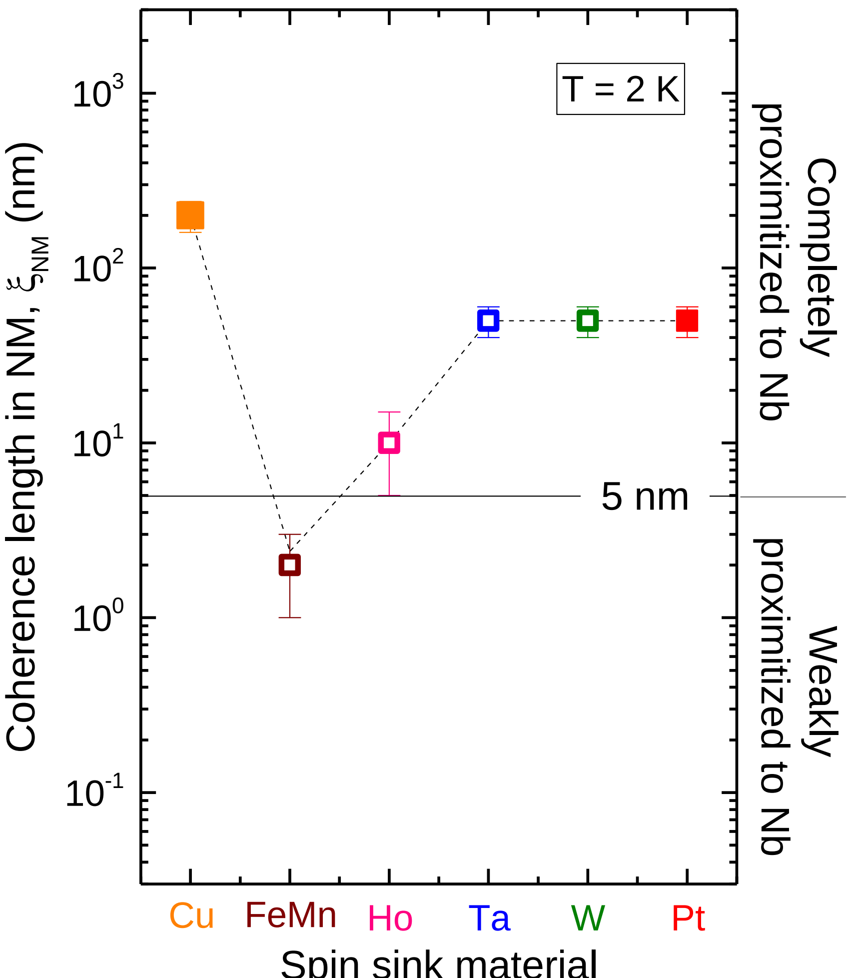
Spin-Sink Material Dependence of Damping Change across T_c

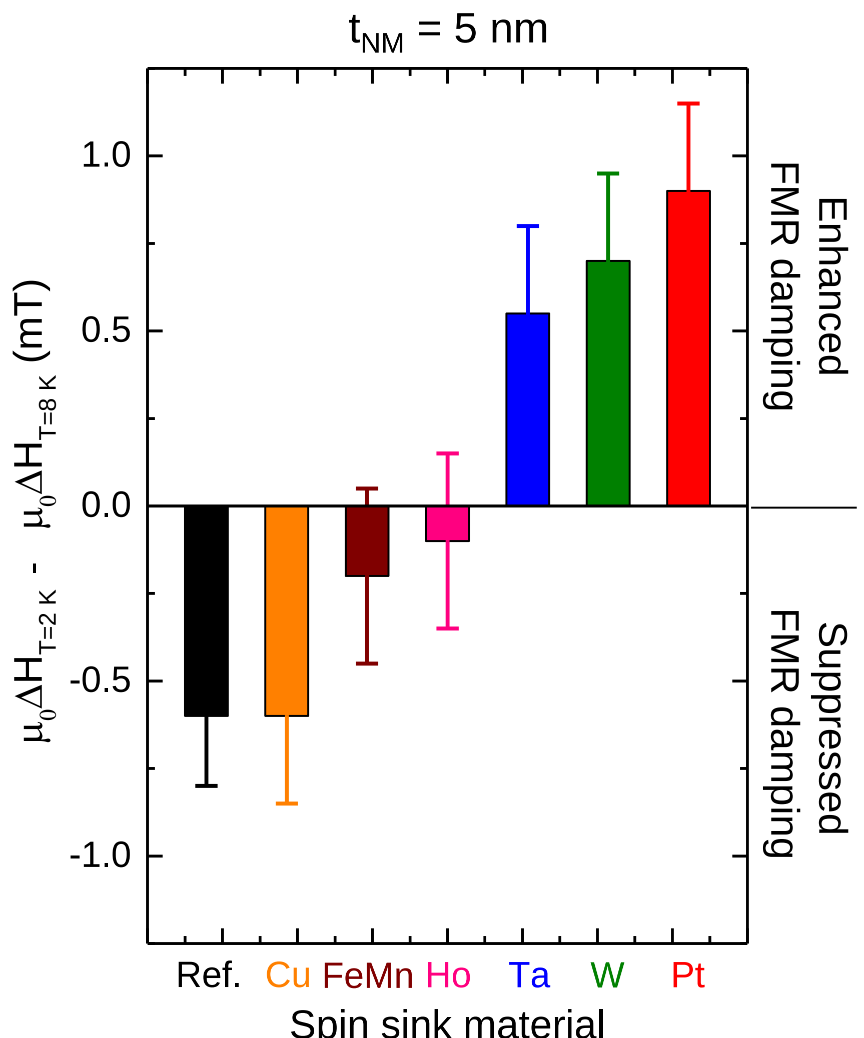


Note that $\mu_0 H_{res}$ ≥ 350 mT induces a homogeneous M in Ho(5 nm), enabling to focus on SOC rather than M inhomogeneity.

Spin Transfer Mechanism: “Singlet Pair” vs. “Triplet Pair”

Ta: PRB **34**, 217 (1986)
$Fe_{50}Mn_{50}$: PRB **69,** 109903 (2003)





“SC” spin transport strongly enhanced (suppressed) by Ta ($Fe_{50}Mn_{50}$) relative to “NM” state are incompatible with CAR & EC.

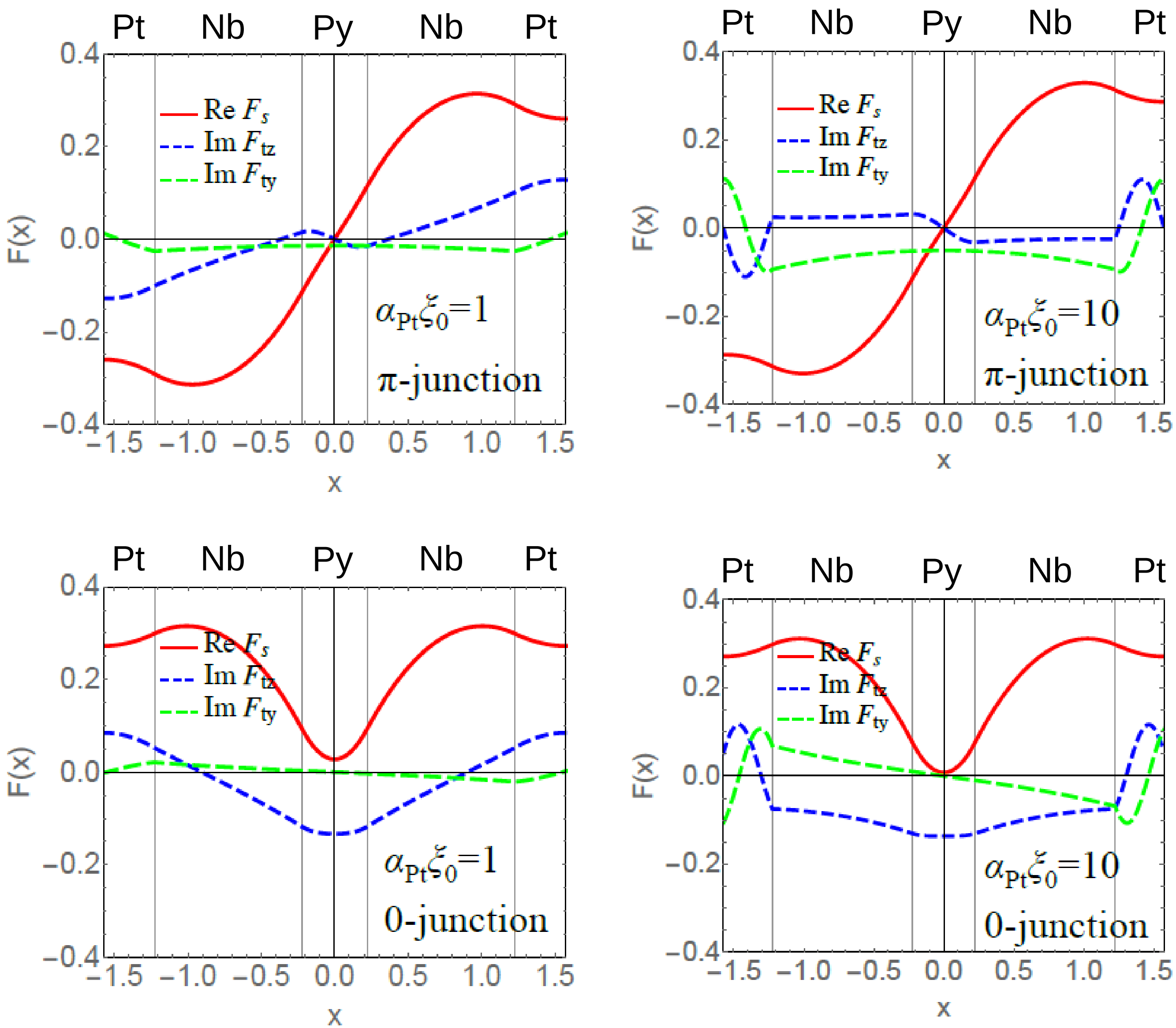
Mechanisms for Generating Triplet Pair Correlation

➢ Static magnetic-inhomogeneity	➢ Spin-orbit coupling in concert with exchange field	➢ Magnetization precession
Theory: *PRB* ***76,*** 060504(R) (2007), *Nat. Phys.* **4,** 138 (2008). *Experiment:* *PRL***104,** 137002 (2010), *Science* **329,** 59 (2010).	*Theory:* *PRB* **89,** 134517 (2014), *PRB* **92,** 024510 (2015), *Sci. Rep.* **6**, 23926 (2016).	*Theory:* *PRL* **99**, 057003 (2007), *PRL* **101,** 057009 (2008), *PRB* **83**, 104521 (2011).
N/A (due to a single FM, precessing coherently)	Possible	Possible

**In all cases, long-ranged triplet pairs (generated on the FM side) should also penetrate into the SC and decay on the length scale of ξ_{sc}.*

**Courtesy of Xavier & Matthias*

α: SOC strength



$\alpha_{Nb}=\alpha_{Py}=0$

$\xi_0^2=D/2\pi T_c$

$h_{Py}/2\pi T_c=10$

$h_{Pt}/2\pi T_c=1$

$\gamma_{b,Nb|Pt}=0,\ \gamma_{Nb|Pt}=1$

$\gamma_{b,Py|Nb}=0,\ \gamma_{Py|Nb}=1$

$d_{Py}=0.45\xi_0$

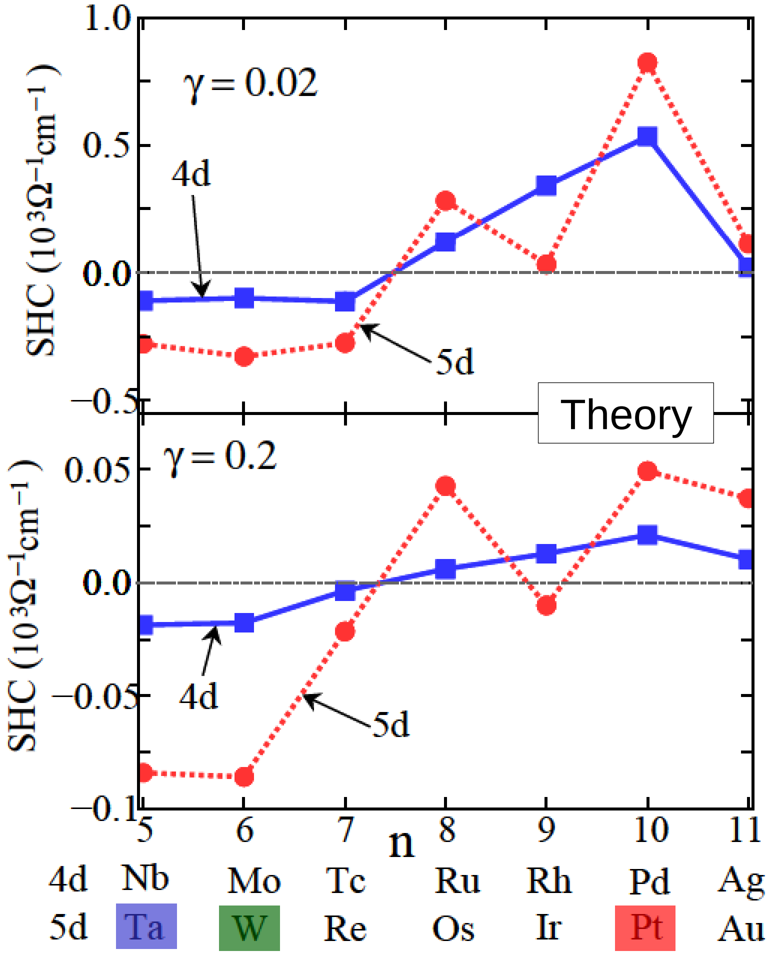
$d_{Nb}=\xi_0$

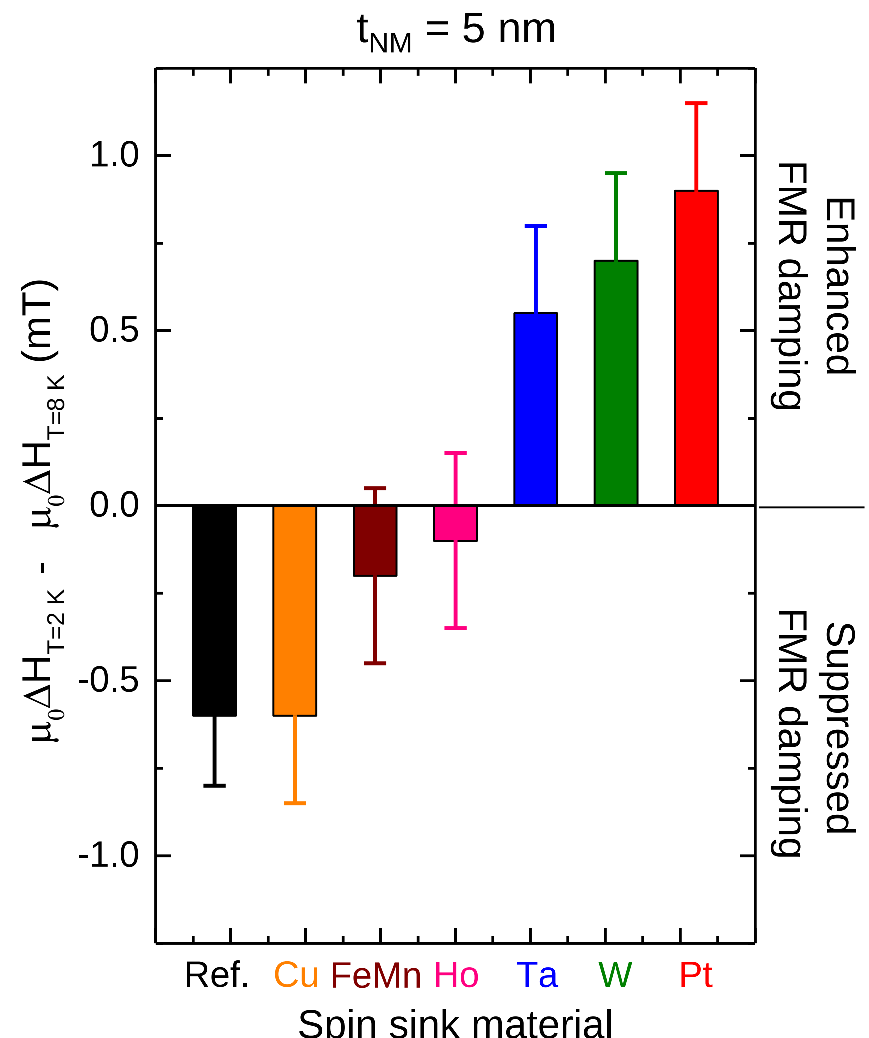
$d_{Pt}=0.35\xi_0$

Large α <-> High density of triplet pair (Im F_{ty})

Superconducting Spin Currents by SOC with *M* precession

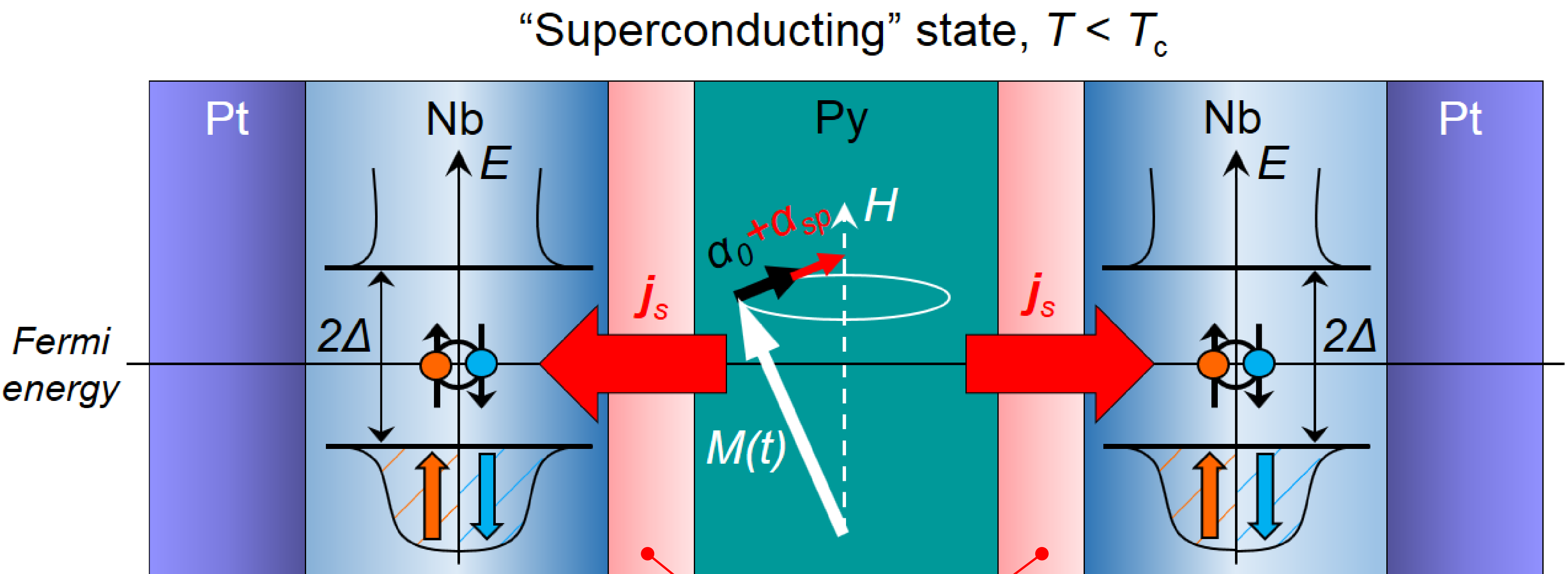
Tanaka *et al.*, *PRB* **77,** 165117 (2008)





Our results imply that SOC, possibly acting in conjunction with precessing *M* may provide the underlying explanation.

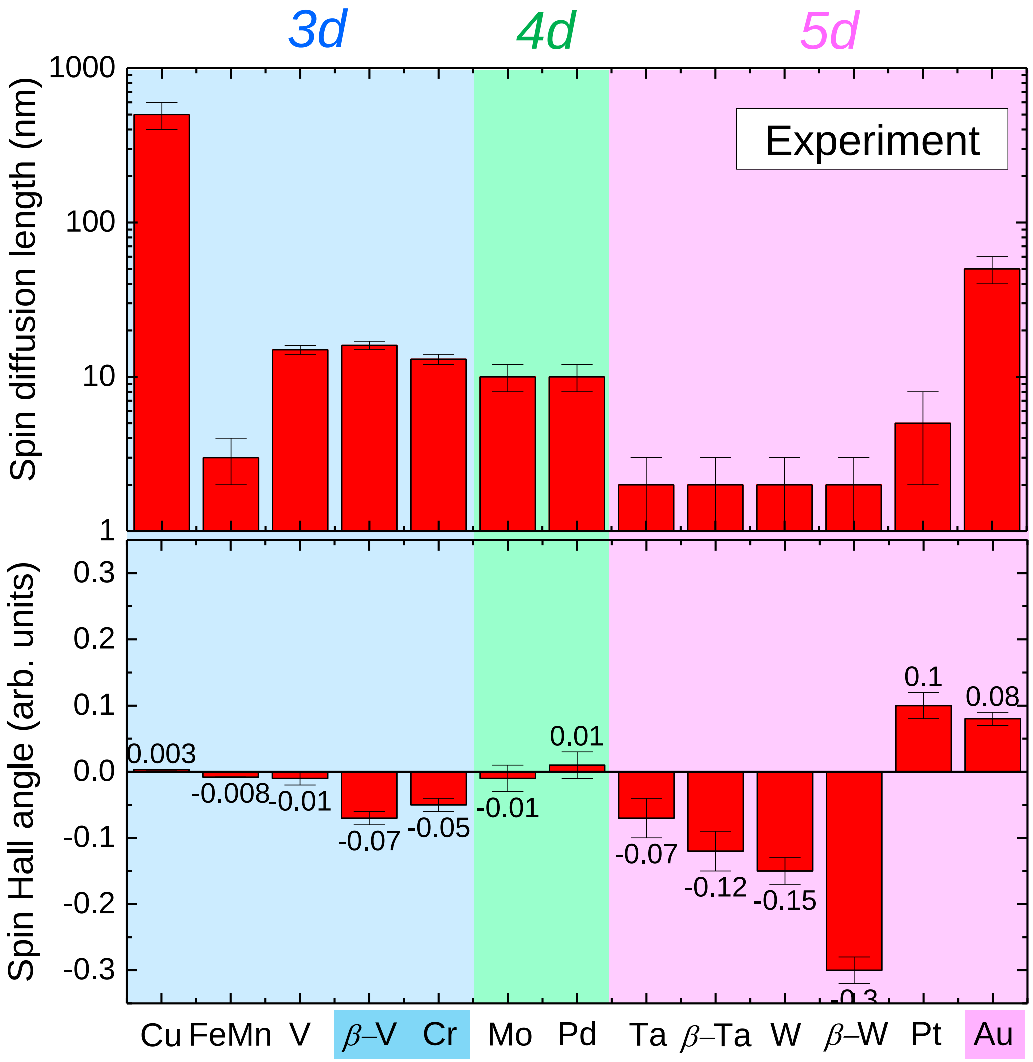
- Spin-orbit-coupled interface (a few nm)



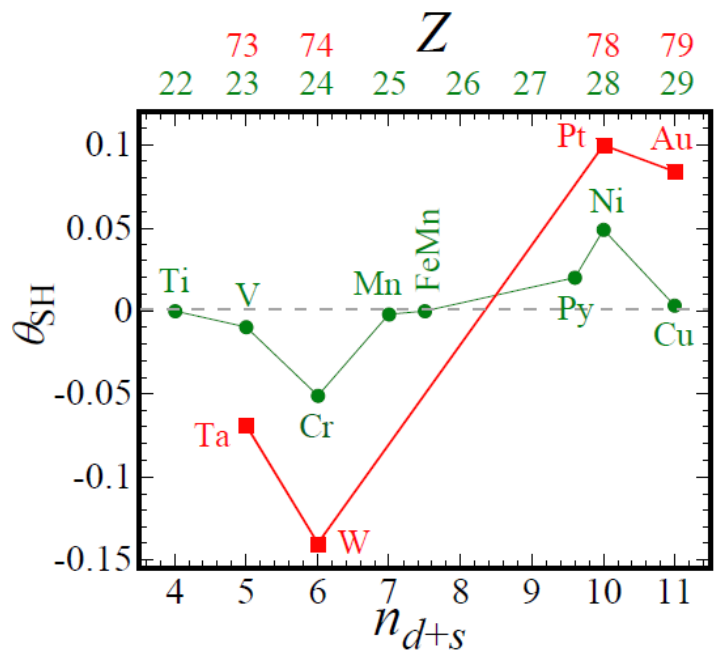
1) Strong spin-orbit coupling: Enhance the triplet pair density

2) Modest spin diffusion length: Avoid the additional spin relaxation

Spin Diffusion Length & Spin Hall Angle in 3d, 4d, & 5d TMs

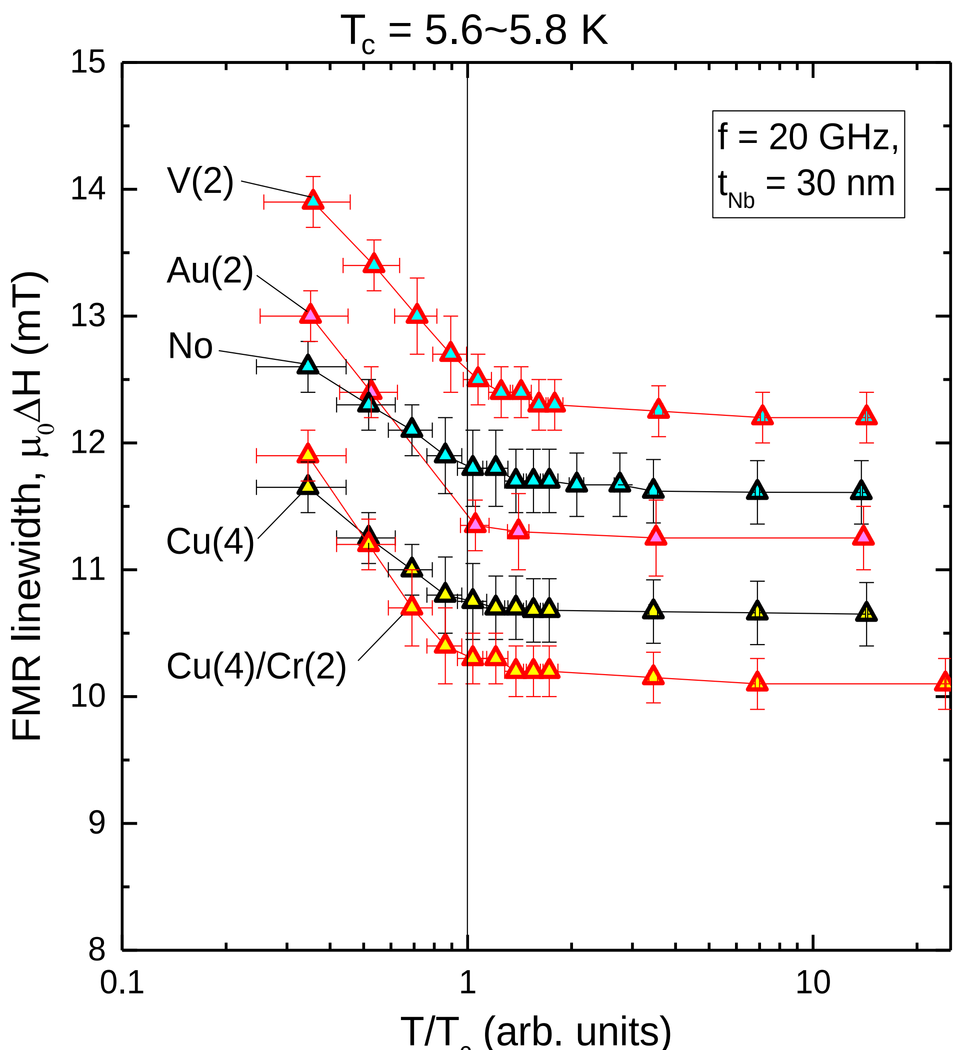


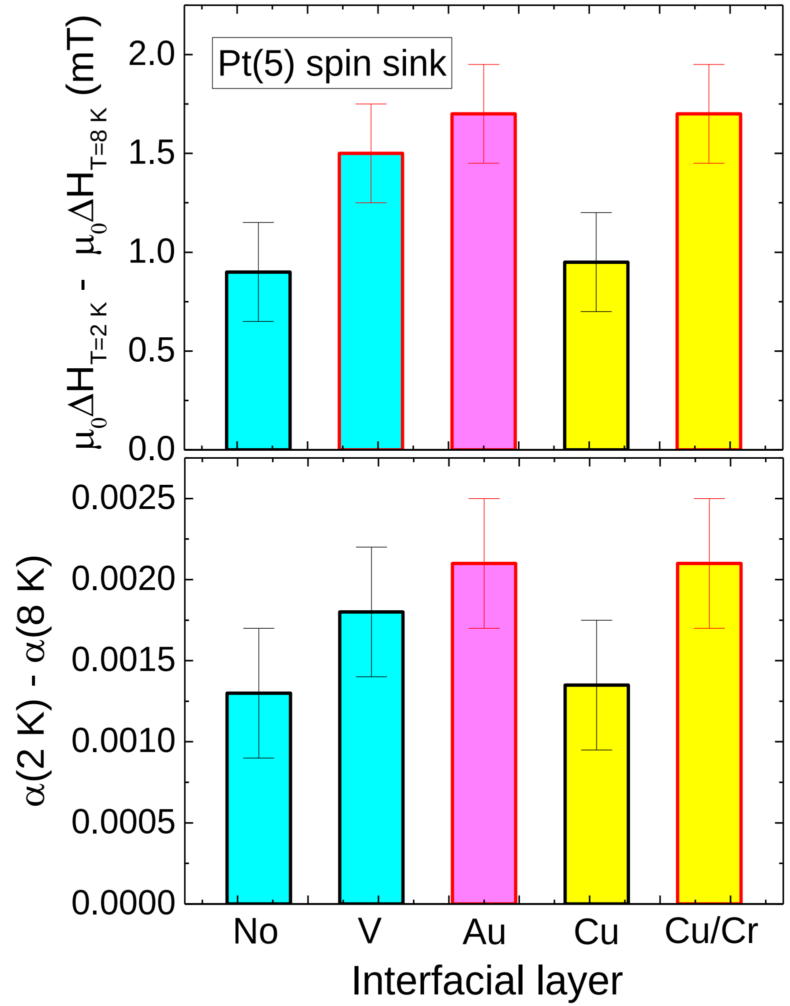
For spin-orbit coupling:
Both Z^4 & *d*-count are important;
Z^4 & *d*-count are additive, not multiplicative.



Liu *et al.*, *PRL* **106,** 036601 (2011)
Liu *et al.*, *Science* **336,** 55 (2012)
Mosendz *et al.*, *PRB* **82,** 214403 (2010)
Pai *et al.*, *APL* **101,** 122404 (2012)
Zhang *et al.*, *PRB* **90,** 140407(R) (2014)
Zhang *et al.*, *PRL* **113,** 196602 (2014)
Wang *et al.*, *Sci. Rep.* **7,** *1306* (2017)
Wang *et al*. *PRL* **112**, 197201 (2014)
Wang *et al. APL* **104**, 202405 (2014)
Du *et al. PRB* **90**, 140407(R) (2014)

Effect of Spin-orbit-coupled Interface on FMR Damping





This suggests that "SC" spin transport can be further enhanced by SO-coupled interface engineering (*e.g.* triplet pair density).

Summary

- *Demonstrated the superconducting spin transport via spin-triplet states induced by SOC*

- *Decreased spin pumping efficiency below T_c due to the development of (spin-zero) singlet pairing*

- *Significantly increased FMR damping for SC layers of the order of ξ_{sc} when coupled to a large SOC spin sink*

- *Spin-sink material dependence: Superconducting spin currents enabled by SOC with M precession*

- *SO-coupled interface: Boosting up the superconducting spin transport*

Jeon *et al., submitted for publication (2017)*