Сверхпроводниковая Спинтроника

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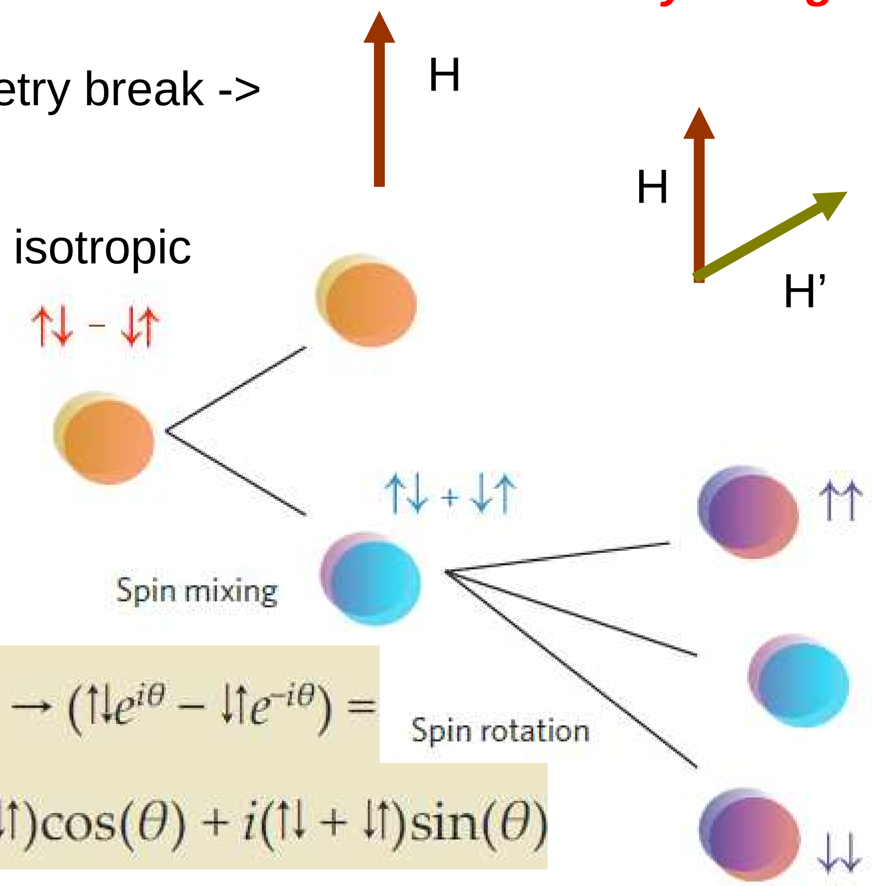
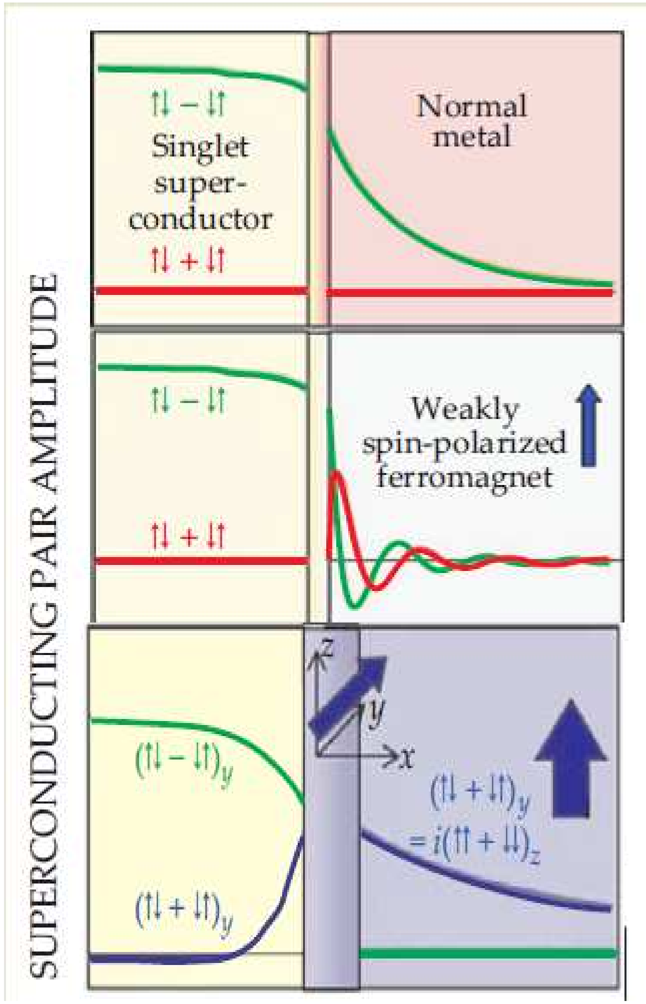
Prehistory: Long range proximity effect

Symmetry break ->



$$(\uparrow\downarrow - \downarrow\uparrow) \rightarrow (\uparrow\downarrow e^{i\theta} - \downarrow\uparrow e^{-i\theta}) =$$

$$= (\uparrow\downarrow - \downarrow\uparrow)\cos(\theta) + i(\uparrow\downarrow + \downarrow\uparrow)\sin(\theta)$$



Strong ferromagnet,

spin dependent *l*,v_{F}, *etc.*

⇒Further symmetry break

$\Rightarrow D_{\uparrow\uparrow} \neq D_{\downarrow\downarrow}$ => $\xi_{\uparrow\uparrow} \neq \xi_{\downarrow\downarrow}$

Cooper pair in the dirty limit

Normal metal

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$

$$\xi_0 = \sqrt{\hbar D_f / 2\pi k_B T_c}$$

Homogeneous magnetization

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$ triplet S_z=0: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2$

Complex coherence length

$\xi^{-1}=\xi_1^{-1} + i\,\xi_2^{-1}$:

$$\xi_f = \sqrt{\hbar D_f / h},$$

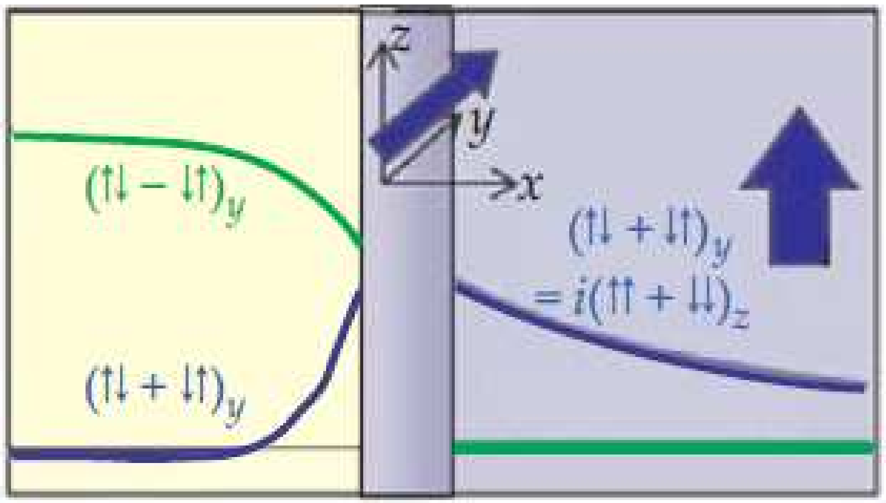
Nonhomogeneous magnetization

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$ triplet S_z=0: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2$ => ξ_f

triplet S_z=1: $|\uparrow>_1|\uparrow>_2$ triplet S_z= -1: $|\downarrow>_1|\downarrow>_2$ => ξ_0

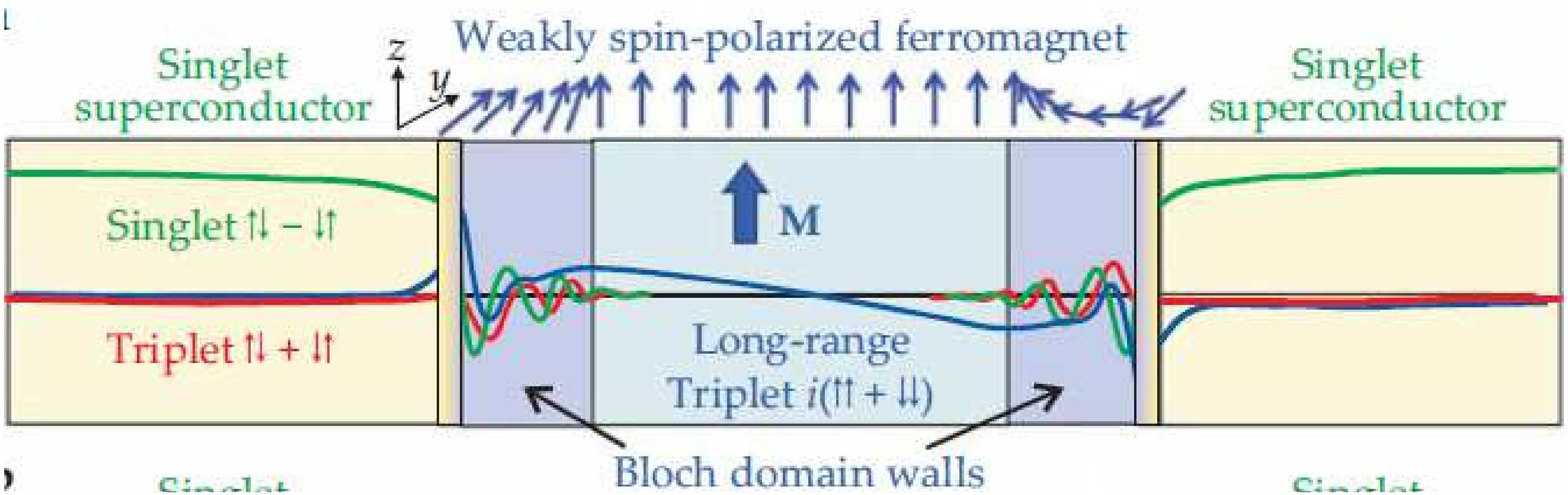
Bergeret, Volkov, Efetov (2001)
Kadigrobov, Shekhter, Jonson (2001)

Inhomogeneous magnetization: long-range triplet component



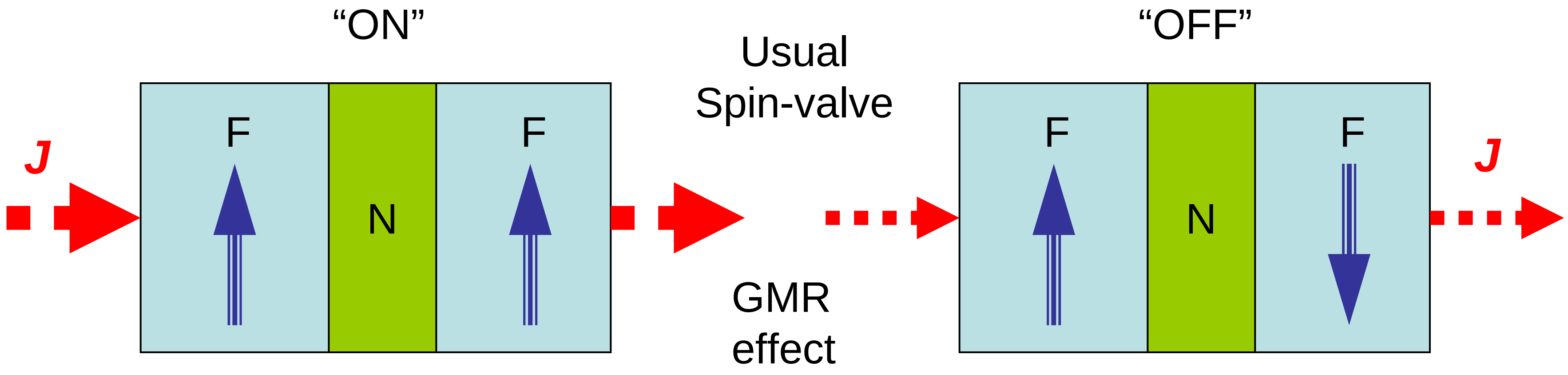
Bergeret, Volkov, Efetov (2001)

Kadigrobov, Shekhter, Jonson (2001)



short − range $\frac{1}{\xi} = \frac{1+i}{\xi_F}, \xi_F = \sqrt{\hbar D_F/H}$, long − range $\xi_0 = \sqrt{\hbar D_F/2\pi k_B T_c}$

History

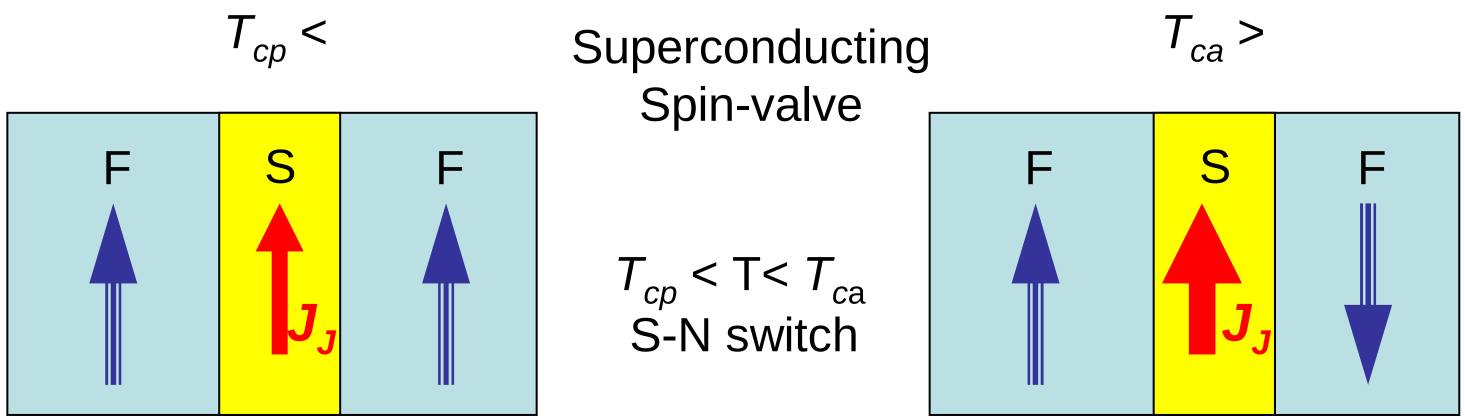


L. R. Tagirov, Phys. Rev. Lett. 83, 2058 (1999)

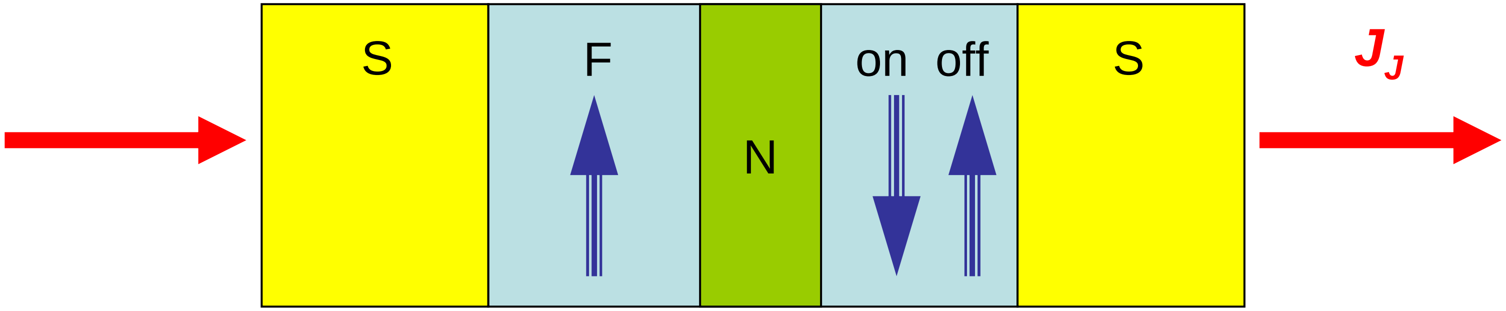
A. I. Buzdin, A. V. Vedyayev, and N. V. Ryzhanova, Eur. Phys. Lett. 48, 686 (1999)

S. Oh, D. Youm, and M. R. Beasley, Appl. Phys. Lett. 71, 2376 (1997) **SFF**

J. Y. Gu, C.-Y. You, J. S. Jiang, J. Pearson, Ya. B. Bazaliy, and S. D. Bader,
Phys. Rev. Lett. 89, 267001 (2002) **CuNi/Nb/CuNi**



Josephson spin valves



Controllable Josephson effect

A. Vedyayev, C. Lacroix, N. Pugach and N. Ryzhanova. Europhys. Lett. **71**, 679 (2005).
Spin-valve magnetic sandwich in a Josephson junction

Triplet:

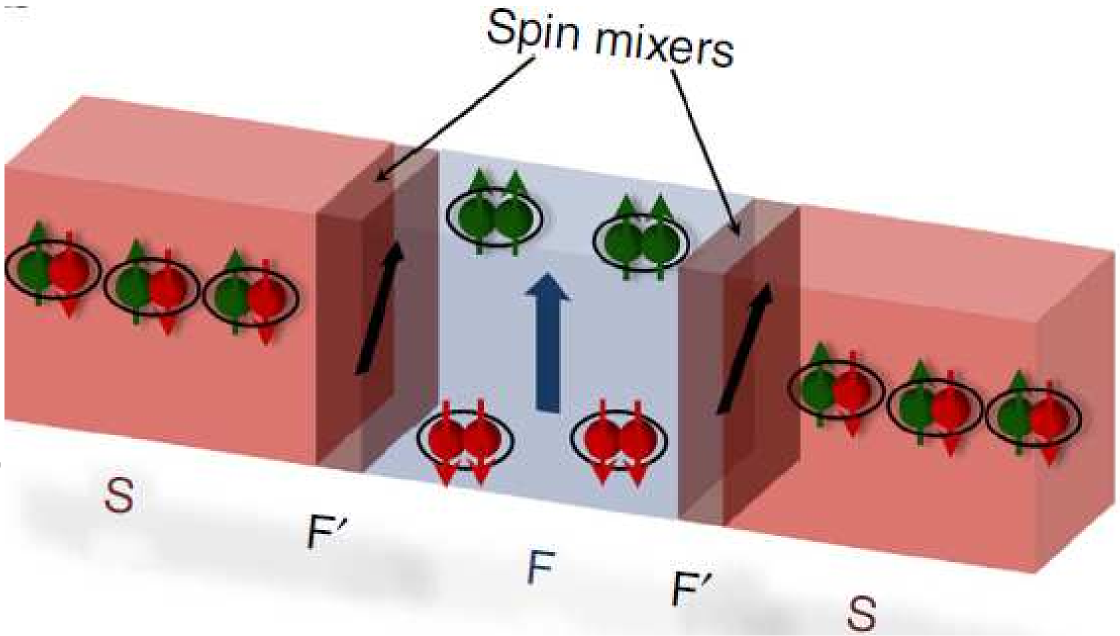
M. Houzet and A. I. Buzdin, Phys. Rev. B **76**, 060504 (2007). **SFFFS**

C. Richard, M. Houzet, and J. S. Meyer. Phys. Rev. Lett. **110**, 217004 (2013) **SFFS**

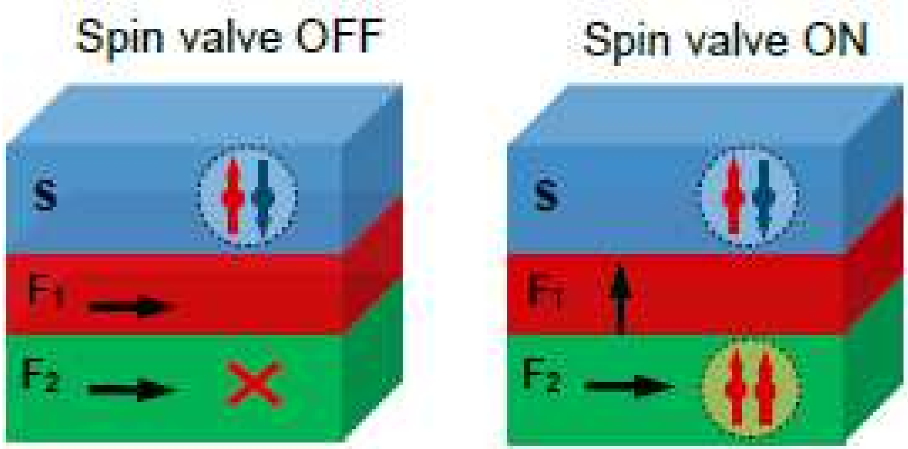
Iovan, T. Golod, and V. M. Krasnov. PRB 90, 134514 (2014) “Scissors” **SFFS**

N. Banerjee, J.W.A. Robinson, M.G. Blamire, Nature Comm. 5, 4771 (2014). **SFFFS**

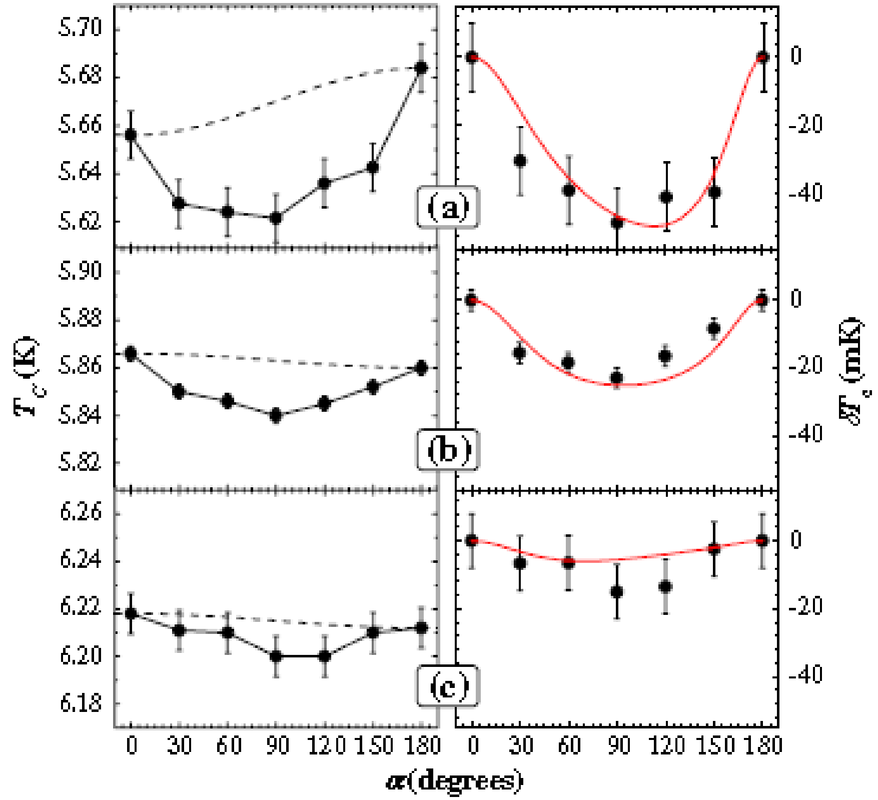
W. Martinez, W.P. Pratt, Jr., N. O. Birge, arXiv:1510.02144 (2015) **SF…F”…FS**



SFF Spin-valves



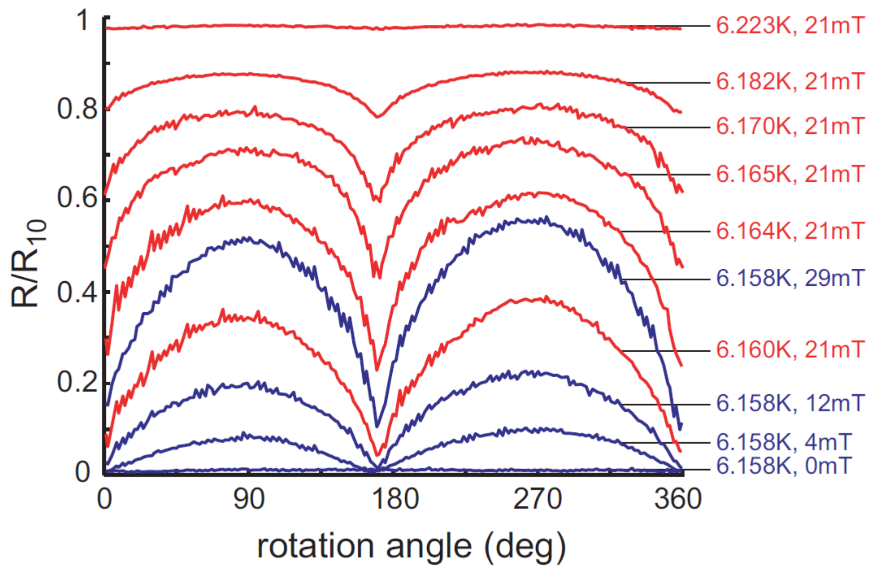
P.V. Leksin, N. N. Garif'yanov, I. A. Garifullin, et.al.,
PRL 109, 057005 (2012) **CoOx/Fe/Cu/Fe/Pb**



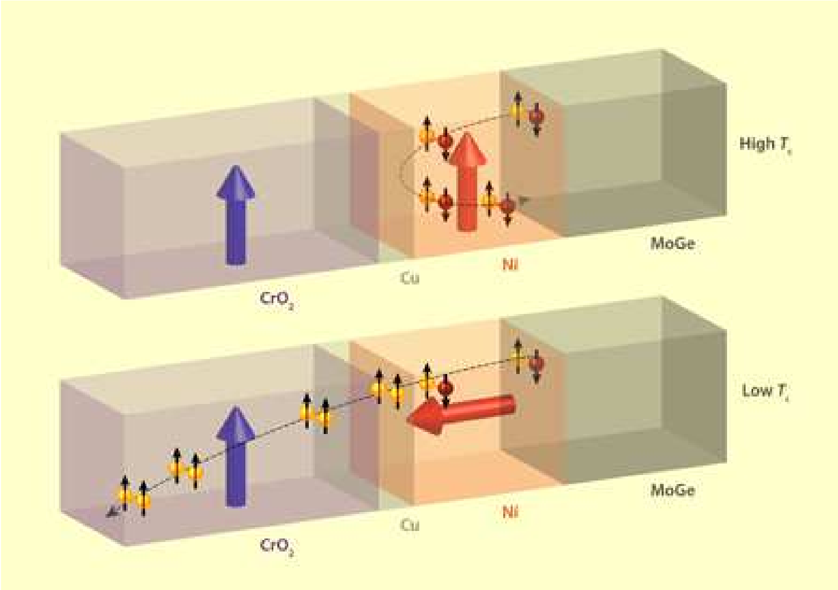
V. I. Zdravkov,1,2 J. Kehrle,1 G. Obermeier, et.al.
PRB **87**,144507 (2013) **Nb/CuNi/normalNb/Co/CoO$_x$**

X. L. Wang, M. G. Blamire, J. W. A. Robinson, et. al.
PRB 89, 140508(R) (2014) **Cu/Co/Cu/Py/Cu/Nb**

M. G. Flokstra, T. C. Cunningham, J. Ki N. Satchell, G. Burnell, P. J. Curran, S. J. Bending, C. J. Kinane, J. F. K. Cooper, S. Langridge, A. Isidori, N. Pugach, M. Eschrig, and S. L. Lee. PRB 91, 060501(R) (2015) **Nb/Co/Cu/Co**



Ya.V. Fominov, A.A. Golubov, T.Yu. Karminskaya,
M.Yu. Kupriyanov, R.G. Deminov,
L.R. Tagirov, Pis'ma ZETF 91, 329 (2010) **Theory SFF**

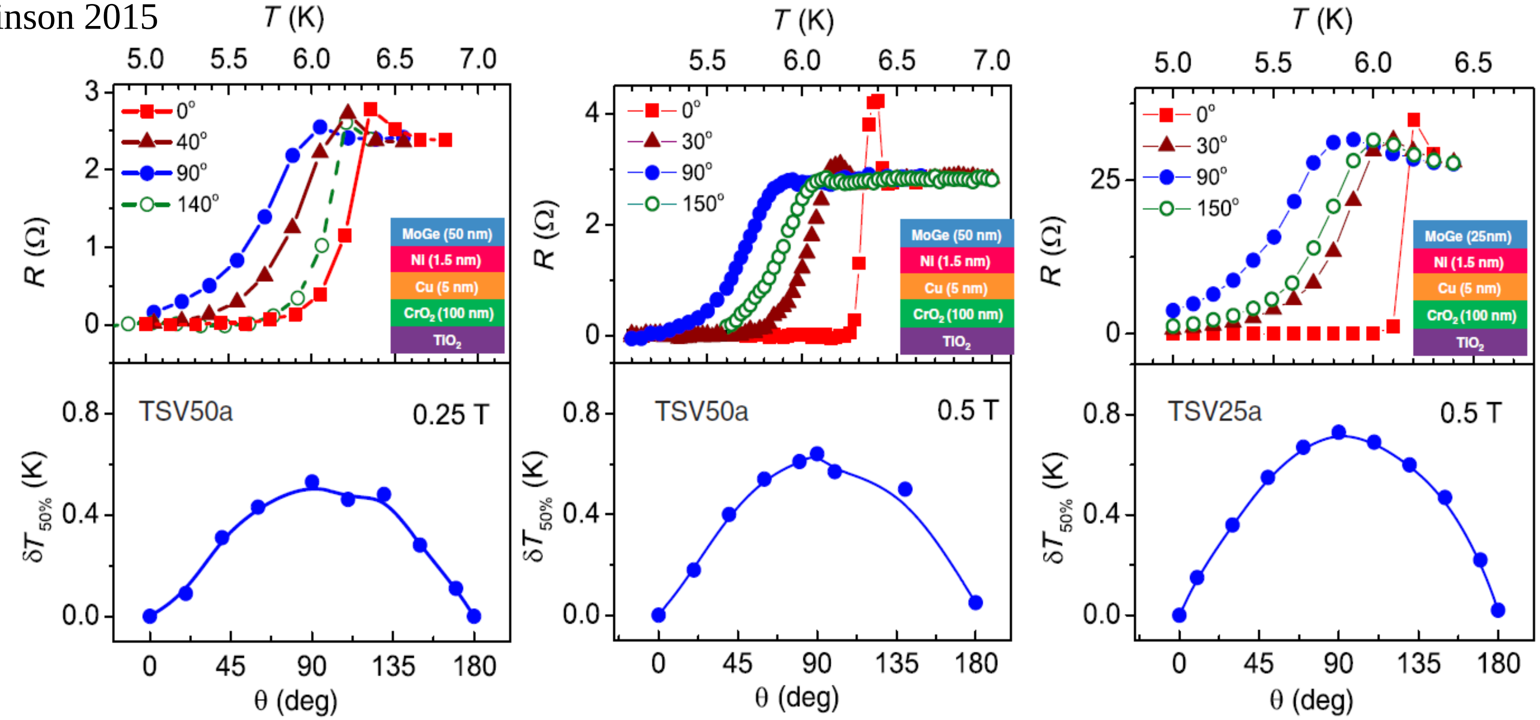


"Giant" spin-valve effect

Half-metallic ferromagnet CrO_2

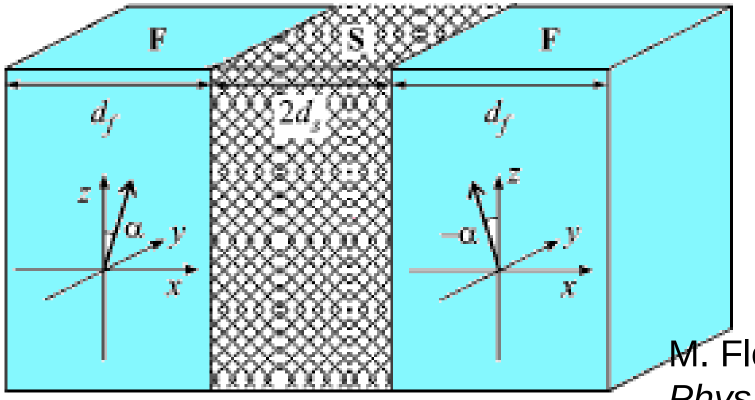
A. Singh, S. Voltan, K. Lahabi, J. Aarts,
PRX 5, 021019 (2015)

CrO_2/Cu/Ni/MoGe

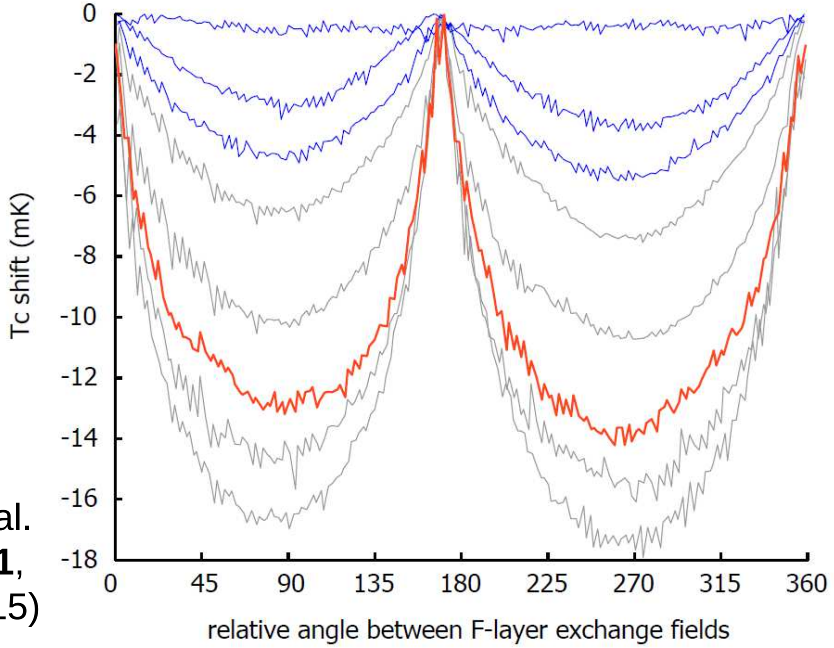


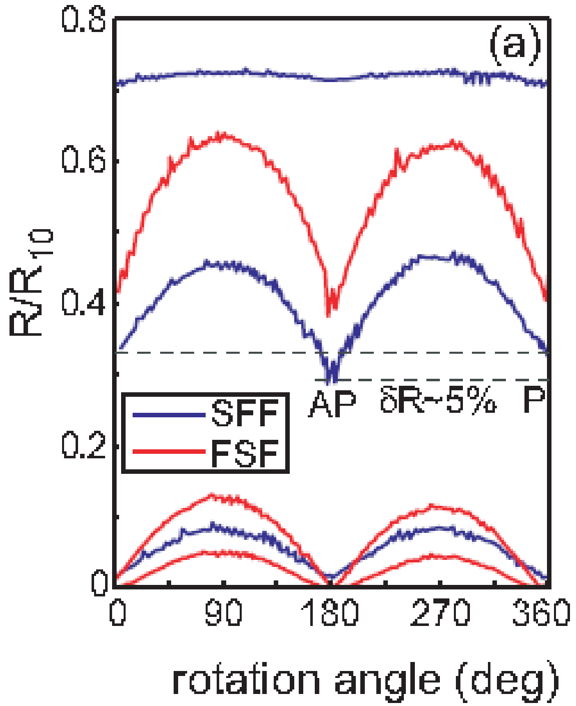
FSF spin-valves

Transport experiment: T_c for FSF and SFF structures with misaligned magnetization



M. Flokstra, et.al. *Phys. Rev. B* **91**, 060501(R) (2015)





Theory: Ya. V. Fominov, A. A. Golubov, and M. Yu. Kupriyanov (dirty limit) (2003)

Clean FSF (BDG): K. Halterman, O. T. Valls, P. H. Barsic (2008) (clean limit) give only monotonous angular dependence of T_c without any minima for weak ferromagnets

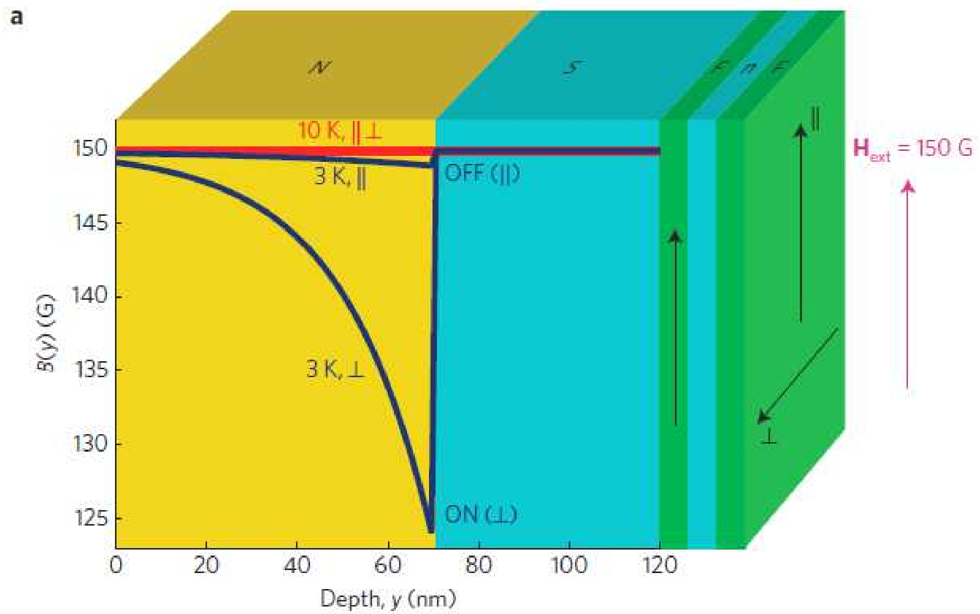
Clean and dirty FSF: S. Mironov, A. Buzdin (2014).

Clean F / dirty S: B. Vodop'yanov, L. Tagirov (2003).

We try to describe the obtained data with the theory, based on the model with strong ferromagnets.

Remote magnetization effect in NSFF spin-valve

Au(70)/Nb(50)/Co(2.4)/Nb(3)/Co(1.2) (nm)

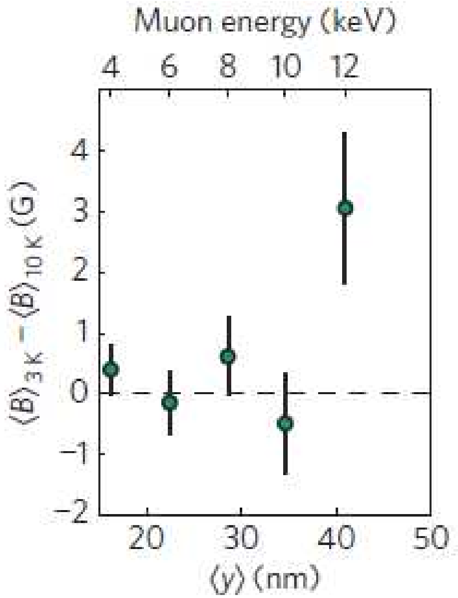


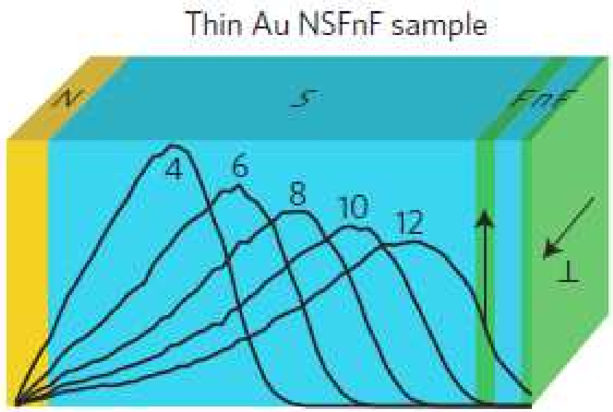
Muon scattering method
Magnetization distribution probe

Spin polarization is induced in the gold layer

• Below Tc
(superconductivity is responsible)

• Only at noncollinear magnetic configuration
(triplet spin-valve effect)





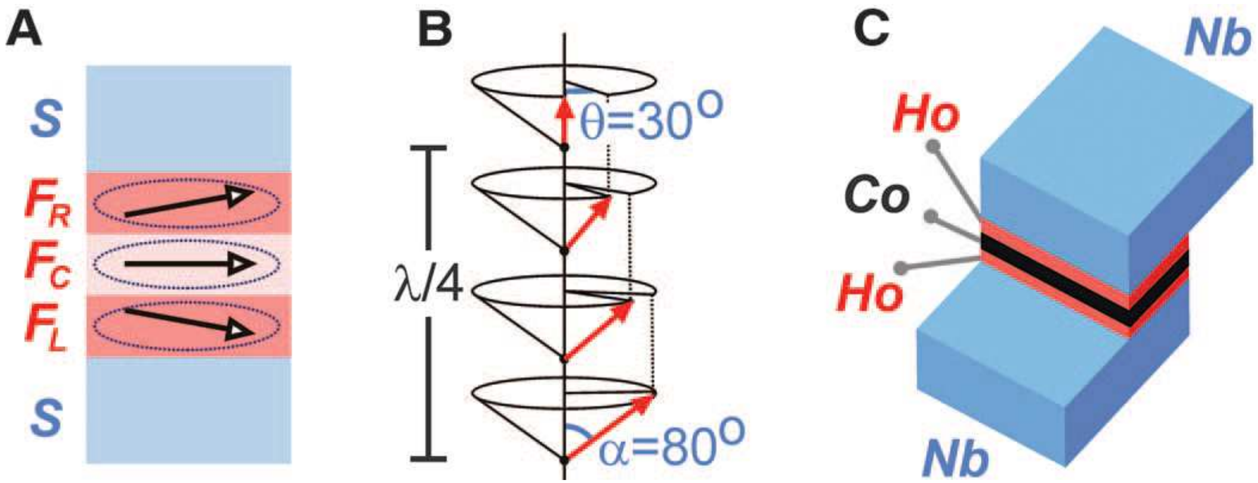
Au(5)/Nb(50)/Co(2.4)/Nb(3)/Co(1.2)

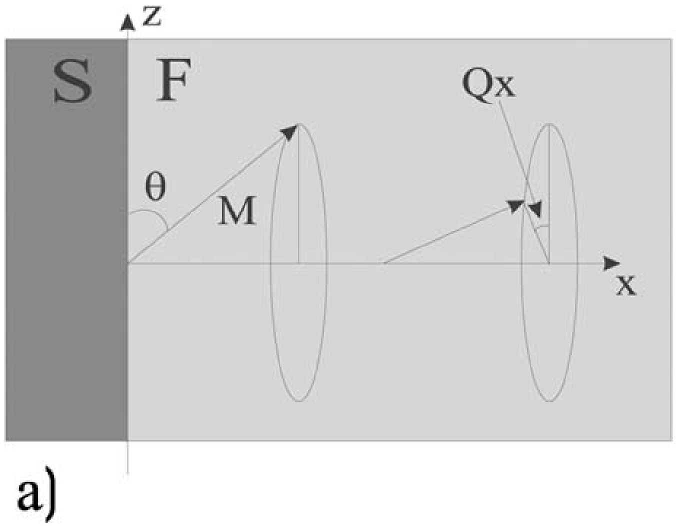
N. G. Pugach and A. I. Buzdin
Appl. Phys. Lett. 101, 242602 (2012)

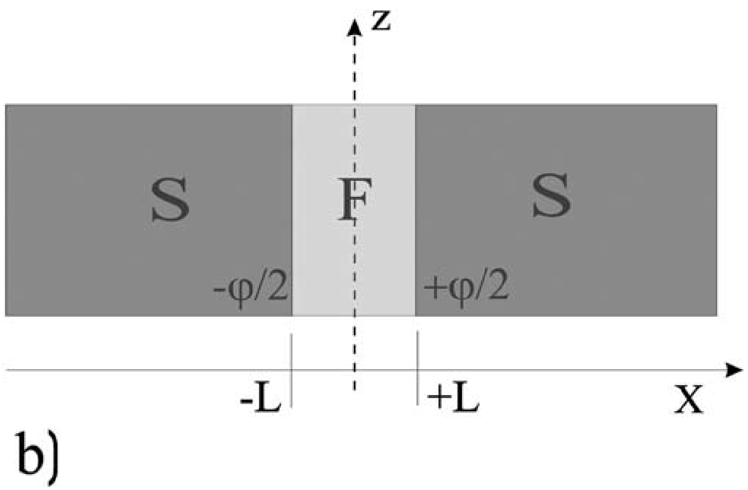
M. G. Flokstra, N. Satchell, J. Kim, G. Burnell, P. J. Curran, S. J. Bending, J. F. K. Cooper, C. J. Kinane, S. Langridge, A. Isidori, N. Pugach, M. Eschrig, H. Luetkens, A. Suter, T. Prokscha and S. L. Lee
Nature Phys. 12, 57 (2016).
Appl. Phys. Lett. 107, 262602 (2015)

Helical magnets based SSV

Spiral magntization in Ho
J. W. A. Robinson,
J. D. S. Witt, M. G. Blamire
Science 329, 59 (2010)







Spiral superconducting spin valve

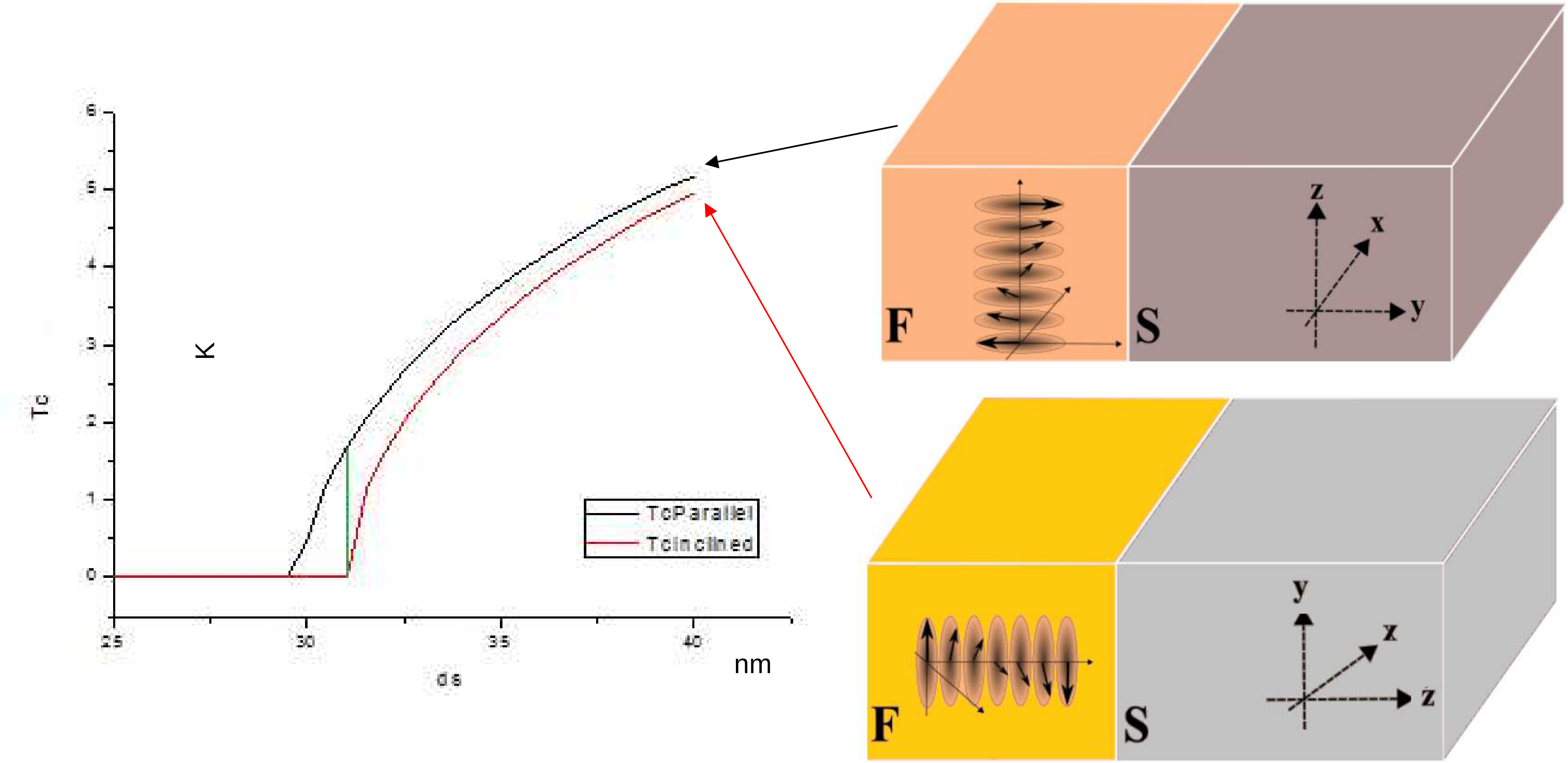
MnSi family compounds (CoSi, FeCoSi, MnGe, FeGe, MnFeGe)

Cubic and complex noncentrosymmetric crystal lattice => DM SO interaction

Magnetic spiral may be realized in 3 equivalent directions (111), (1-11), (-1-11)

λ~18nm (MnSi)>>ξ_f

The spiral direction may be switched => LRTC switch => T_c change

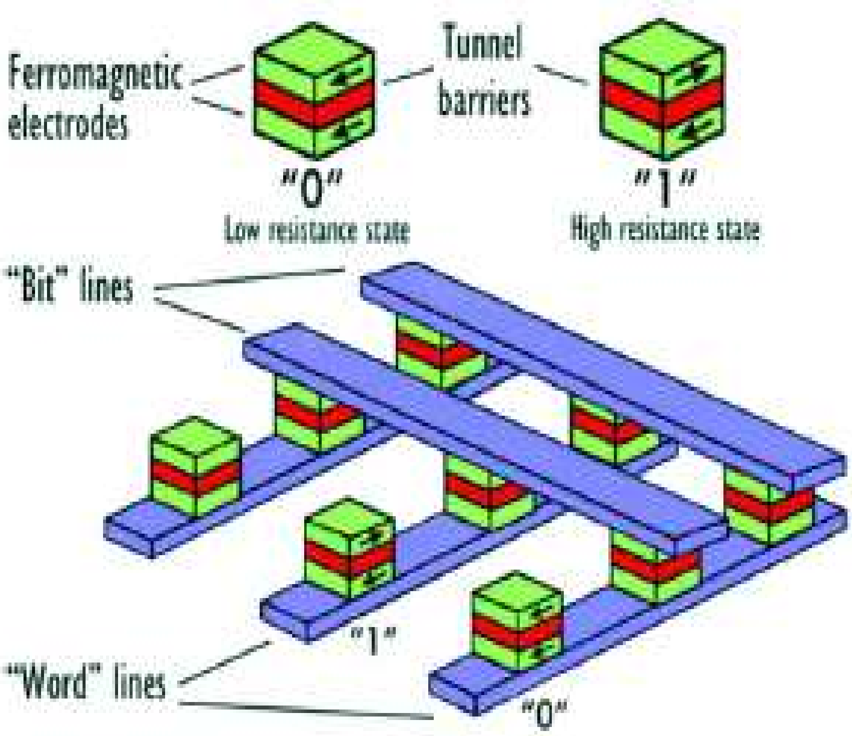


Advantages of spiral SSV as a memory element

• simple structure (bilayer with a bulk magnetic material)

•T_c change may be appreciable ~ 1K

• **half-select problem** solution



Savchenko scheme
In production from 2006

Conclusion

- Superconducting spin-valves may be of few types:
  - Josephson
  - SFF
  - FSF

- For both sample types (SFF and FSF) a large suppression of T_c may be realized when the magnetizations are orthogonal (triplet effect). We have found this effect in experiment, it may be explained by the theory.

- The new effect of “remote” magnetization in NSFF spin-valve was found.

- The new type of the superconducting spin valve based on the magnetic spiral reorientation in a spiral magnet is proposed. Its work based on the control of the long range triplet superconducting correlations appearance.

Спасибо за внимание!