In-plane FFLO instability in multilayered S/F systems

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Outline

1. Proximity effect in S/F systems

2. Can Meissner response become paramagnetic?

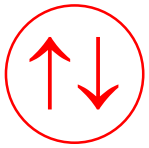
3. In-plane FFLO states in S/F systems

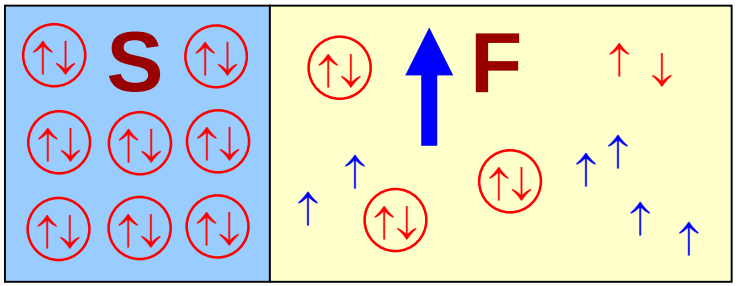
4. How experimentally observe the FFLO states?

S. Mironov, A. Mel'nikov and A. Buzdin, Phys. Rev. Lett. **109**, 237002 (2012)

Proximity effect in S/F systems

Exchange field (energy) in the ferromagnet: $\hat{H} = \ldots + \vec{h}\,\hat{\vec{\sigma}}$





$\uparrow\downarrow$ **no coupling**

$\uparrow\uparrow$ **exchange field**

Singlet: $\uparrow\downarrow - \downarrow\uparrow$

$S = 0$

Triplet:

$\uparrow\downarrow + \downarrow\uparrow \quad S_z = 0$

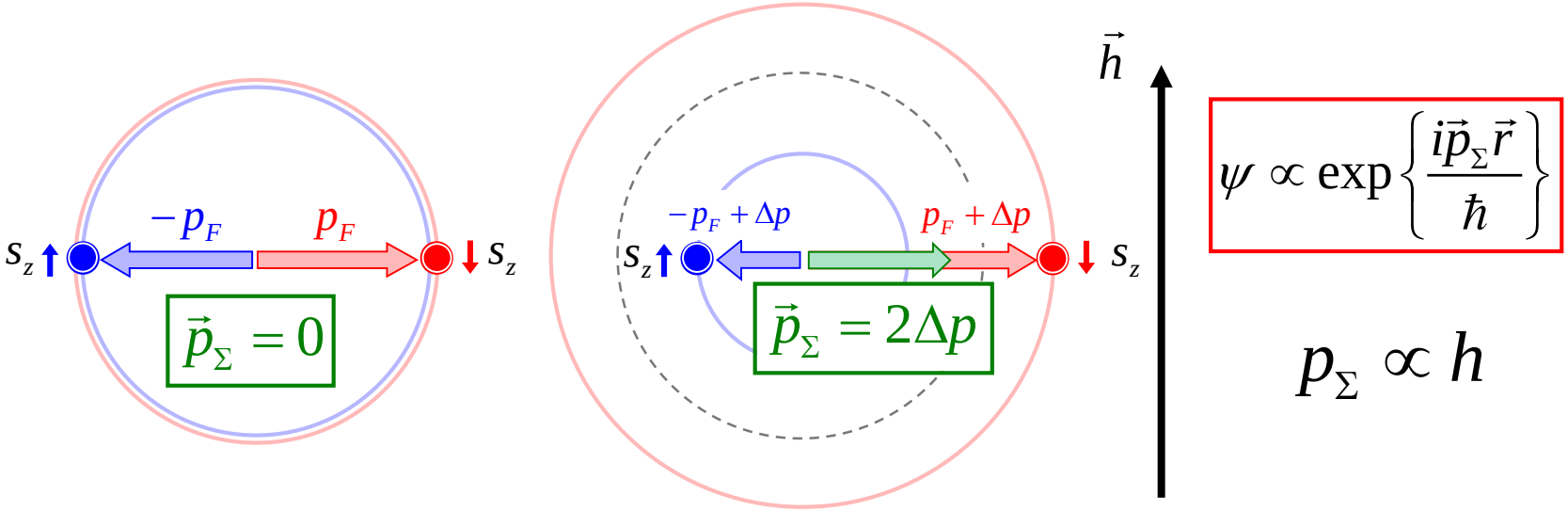
$\uparrow\uparrow$

$\downarrow\downarrow$

$S_z = \pm 1$

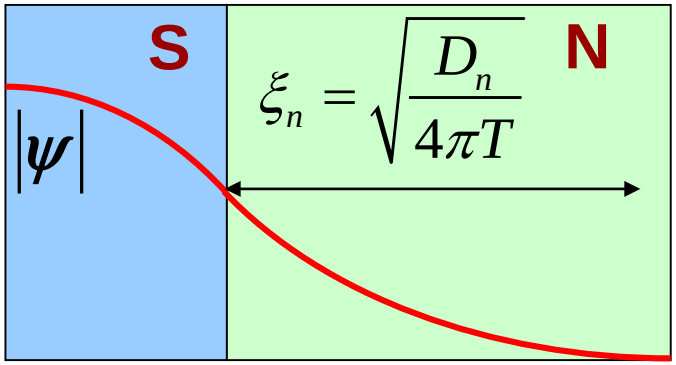
Proximity effect in S/F systems

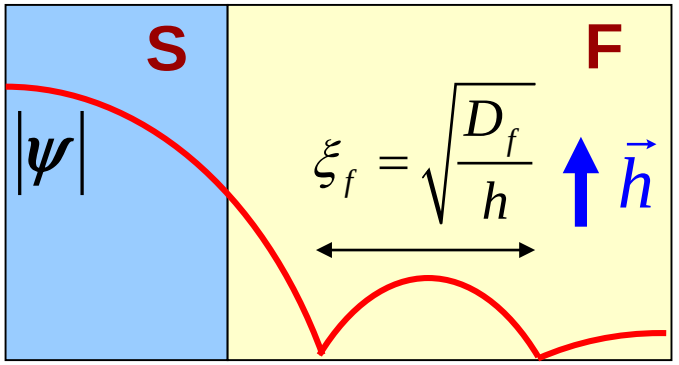
Exchange field (energy) in the ferromagnet: $\hat{H} = \ldots + \vec{h}\,\hat{\vec{\sigma}}$



P. Fulde and R. A. Ferrell, Phys. Rev. (1964).

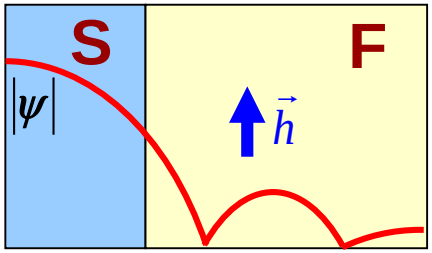
A. I. Larkin and Yu. N. Ovchinnikov, JETP (1964).

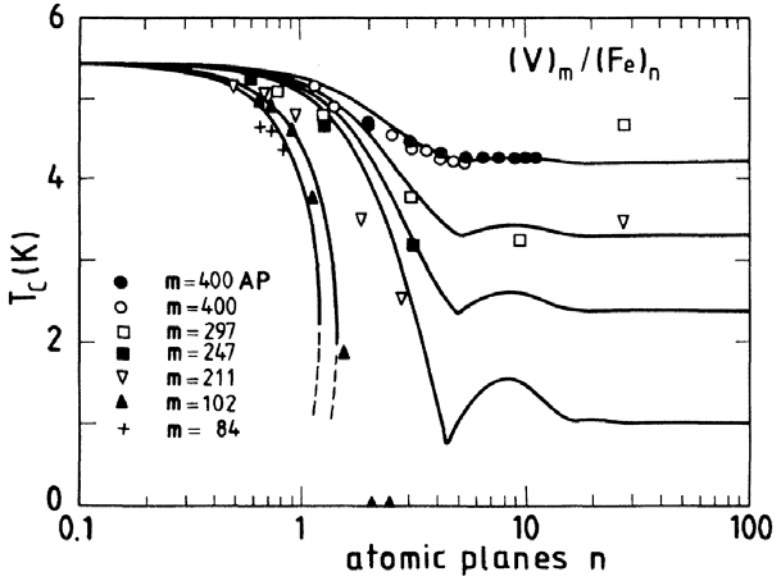


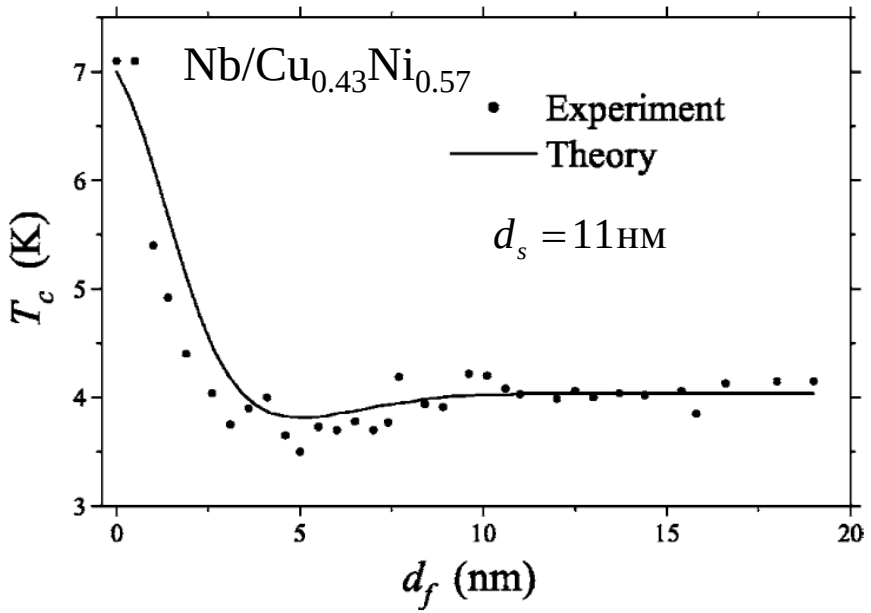


Transversal FFLO states

Dependence of the critical temperature on the thickness of the F layer







A.I. Buzdin and M.Yu. Kupriyanov, JETP Lett. (1990)

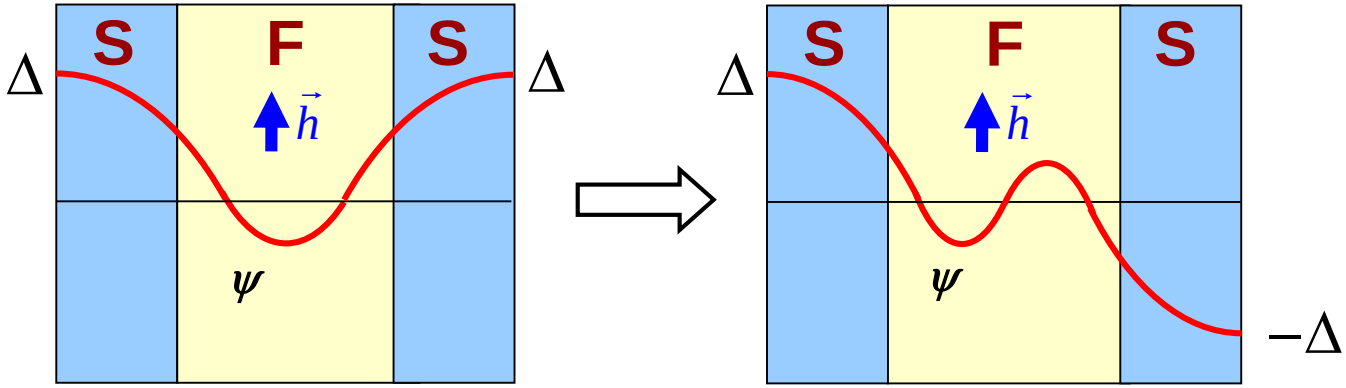
Z.Radović, A.I. Buzdin, J.R. Clem, Phys. Rev. B (1991)

H.K. Wong *et al.*, Journ. Low Temp. Phys. (1986)

V.V. Ryazanov, V.A. Oboznov, A.S. Prokof'ev and S.V. Dubonos, JETP Lett. (2003)

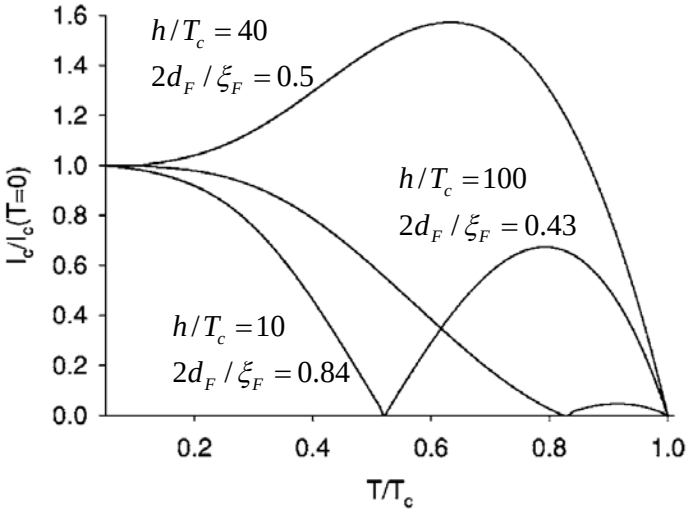
Ya.V. Fominov, N.M. Chtchelkatchev, A.A. Golubov, Phys. Rev. B (2002)

Formation of π-junctions

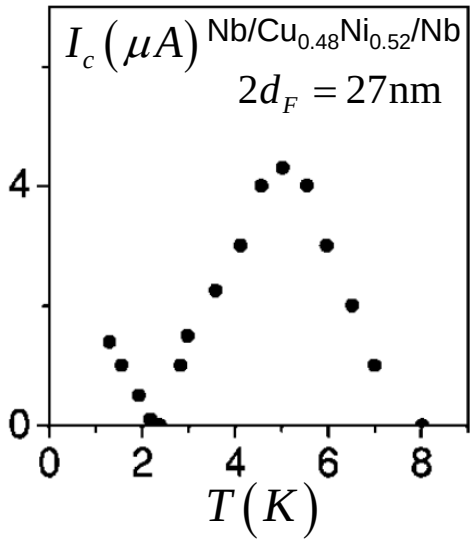


«0-junction» «π-junction»

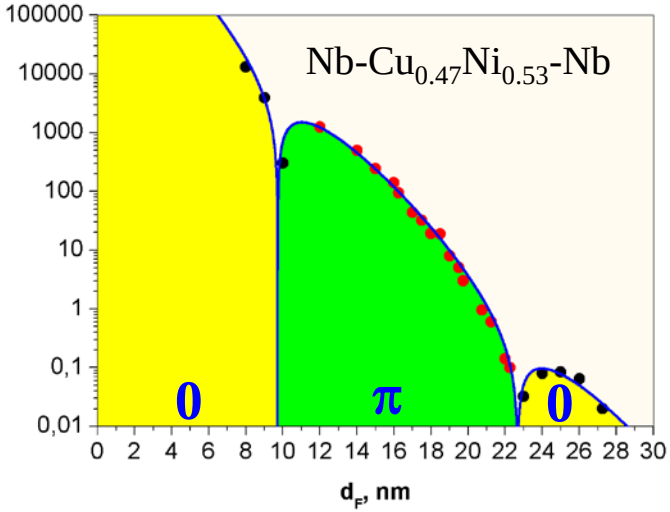
A.I. Buzdin and M.Yu. Kupriyanov, JETP Lett. (1990)



A.I. Buzdin, Rev. Mod. Phys. (2005)



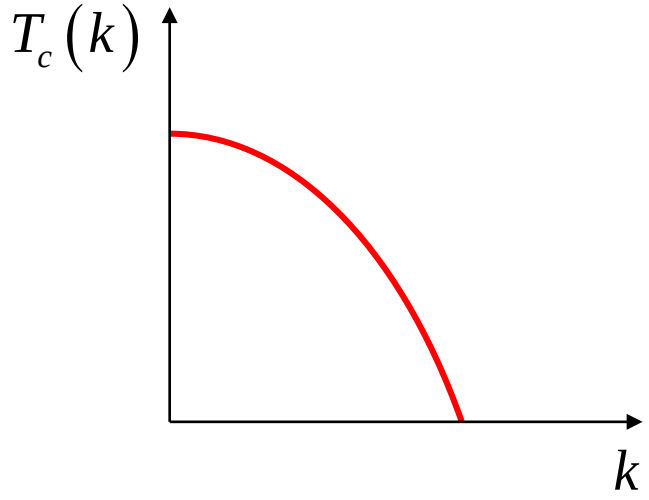
V.V. Ryazanov *et al.*,
Phys. Rev. Lett (2001)



V.A. Oboznov, V.V. Bol'ginov,
A.K. Feofanov, V.V. Ryazanov,
A. I. Buzdin, Phys. Rev. Lett. (2006)

Phenomenological description of FFLO states

$$\psi \propto \exp\left(i\vec{k}\,\vec{r}\right)$$

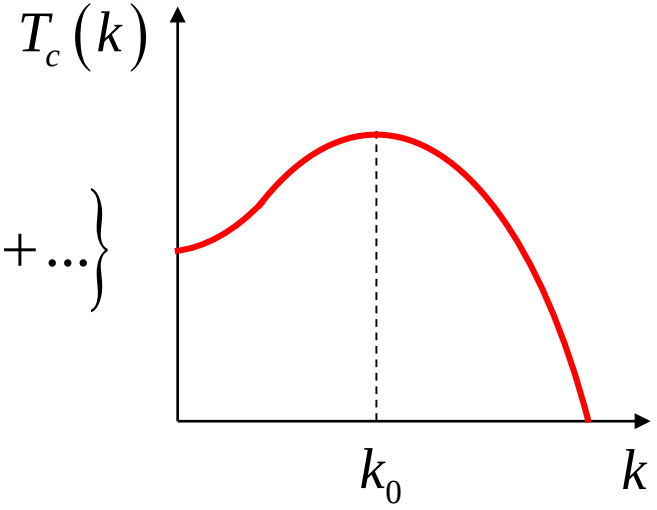


$$m > 0$$

$$F[\psi] = \int dV \left\{ \alpha \left(T - T_{c0}\right) |\psi|^2 + \frac{\hbar^2}{4m} |\nabla \psi|^2 + \ldots \right\}$$

$$m < 0$$

$$F[\psi] = \int dV \left\{ \alpha \left(T - T_{c0}\right) |\psi|^2 - \gamma |\nabla \psi|^2 + \eta |\nabla^2 \psi|^2 + \ldots \right\}$$



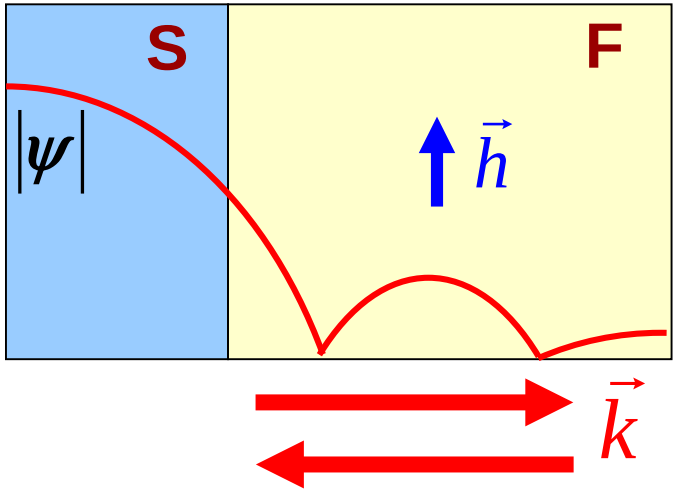
$$\psi_0(\vec{r}) = \sum_{|\vec{k}|=k_0} C_{\vec{k}} \exp\left(i\vec{k}\vec{r}\right)$$

A.I. Buzdin and H. Kachkachi, Phys. Lett. **A225**, 341 (1997)

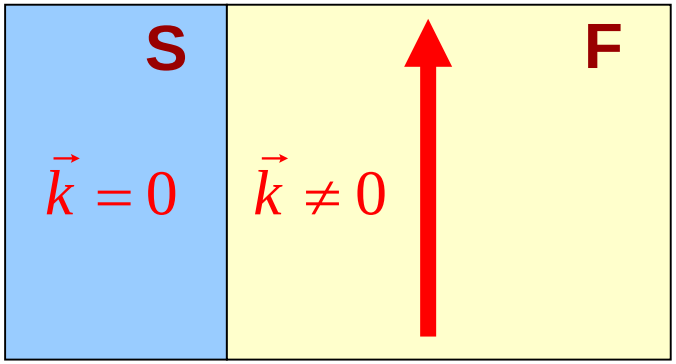
Transversal FFLO states

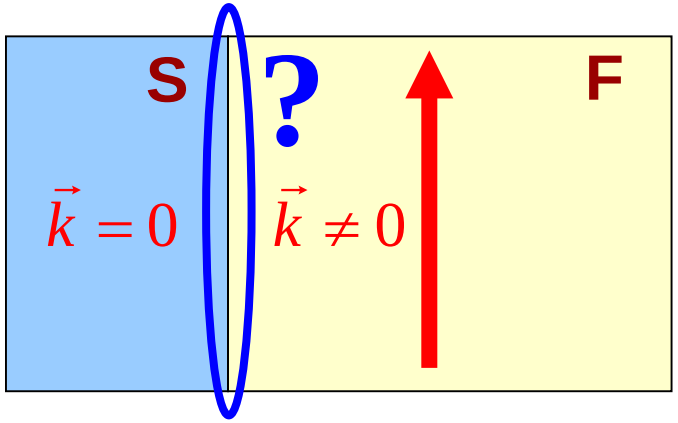
$$\psi_0(\vec{r}) = \sum_{|\vec{k}|=k_0} C_{\vec{k}} \exp\left(i\vec{k}\vec{r}\right)$$

+ in-plane homogeneity



Can in-plane FFLO states exist?

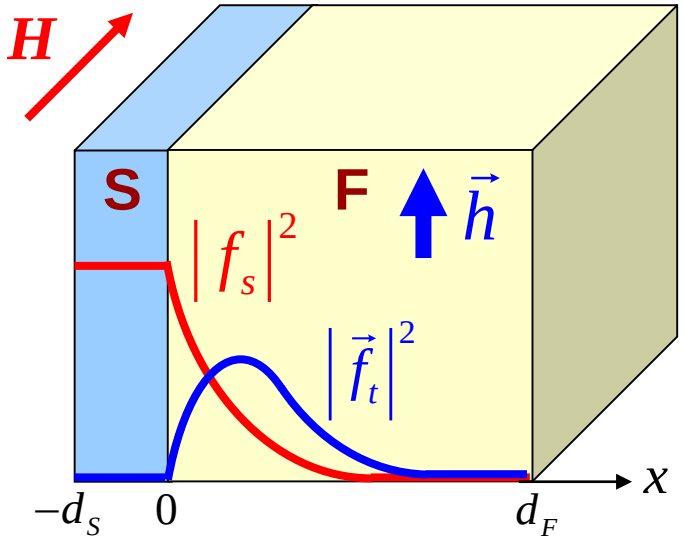




Yu. A. Izumov, Yu. N. Proshin and
M. G. Khusainov, UFN **172**, 113 (2002)

Ya.V. Fominov, M.Yu. Kupriyanov and
M.V. Feigelman, UFN **173**, 113 (2003)

Paramagnetic Meissner effect in dirty S/F bilayers



$$\vec{j} = -\frac{1}{4\pi}\lambda^{-2}\vec{A}$$

$\uparrow\downarrow - \downarrow\uparrow$

$\uparrow\downarrow + \downarrow\uparrow$

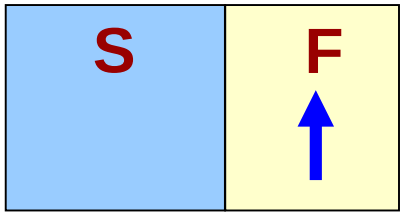
$\uparrow\uparrow, \downarrow\downarrow$

$$\lambda^{-2} = \frac{16\pi^2 T_c}{d_0}\sum_{n=0}^{\infty}\int\sigma\left(|f_s|^2 - |\vec{f}_t|^2\right)dx$$

$|\vec{f}_t|^2 > |f_s|^2 \Rightarrow \lambda^{-2}(x) < 0$

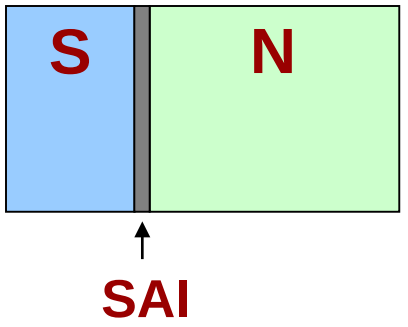
Local paramagnetic response

Global paramagnetic Meissner effect

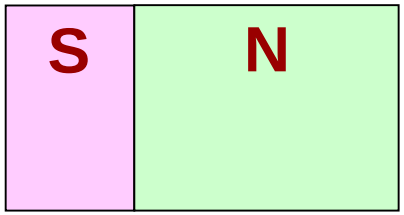


$\lambda_S^{-2} > 0 \quad \lambda_F^{-2} < 0$

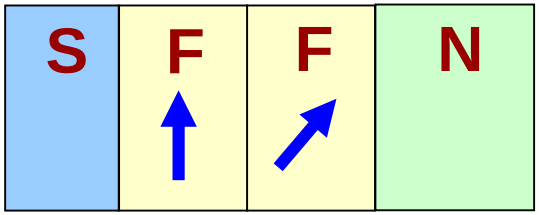
F.S. Bergeret, A.F. Volkov, K.B. Efetov,
Phys. Rev. B **64**, 134506 (2001)



T. Yokoyama, Y. Tanaka, N. Nagaosa,
Phys. Rev. Lett. **106**, 246601 (2011)



Y. Asano et al., A. A. Golubov,
Y. V. Fominov, Y. Tanaka,
Phys. Rev. Lett. **107**, 087001 (2011)



M. Alidoust, K. Halterman, J. Linder,
Phys. Rev. B **89**, 054508 (2014)

Paramagnetic Meissner effect and FFLO instability

$$\vec{j} = -\frac{1}{4\pi}\lambda^{-2}\vec{A} = -\frac{\delta F_A}{\delta \vec{A}} \quad \Longrightarrow \quad F_A = \frac{1}{8\pi}\int \lambda^{-2}\vec{A}^2 dV$$

$$F_A = \frac{1}{8\pi}\int \lambda^{-2}\left(\vec{A} - \frac{\Phi_0}{2\pi}\nabla\varphi\right)^2 dV$$

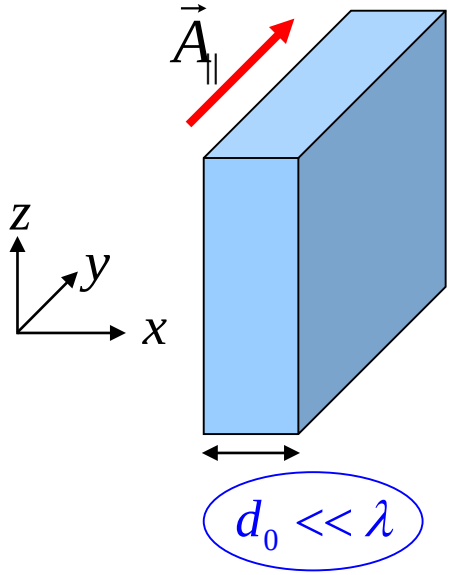
$$\Downarrow \quad \vec{A} = 0$$

$$F_A = \frac{\Phi_0^2}{32\pi^3}\int \lambda^{-2}\left(\nabla\varphi\right)^2 dV \qquad \lambda^{-2} = \frac{4\pi e^2 n_s}{m}$$

1. Uniform superconducting state can become unstable

2. Meissner response can not be paramagnetic

In-plane FFLO states in film-film S/F structures



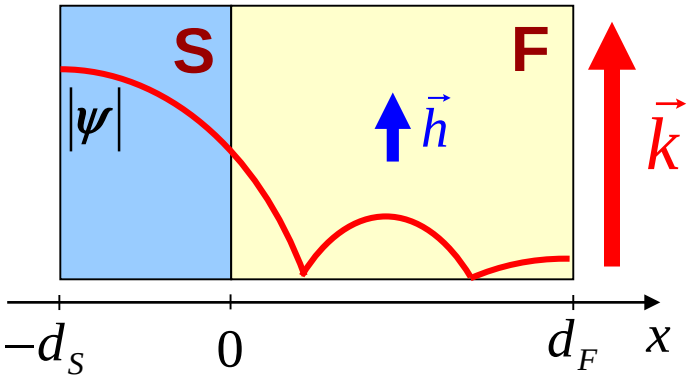
$$\hat{f} = \hat{f}(x)\exp\left\{i\vec{k}\vec{r}_{\parallel}\right\}$$

$$F_A = \left(\vec{A}_{\parallel} - \frac{\Phi_0}{2\pi}\vec{k}\right)^2 \frac{S}{8\pi}\int \lambda^{-2}dx$$

The criterion of instability: vanishing of the Meissner response

$$\lambda^{-2} = \frac{1}{d_0}\int \frac{e^2 n_s}{2m}dx < 0 \quad \Longrightarrow \quad \textbf{In-plane FFLO state}$$

Inhomogeneous FFLO states in thin S/F bilayers



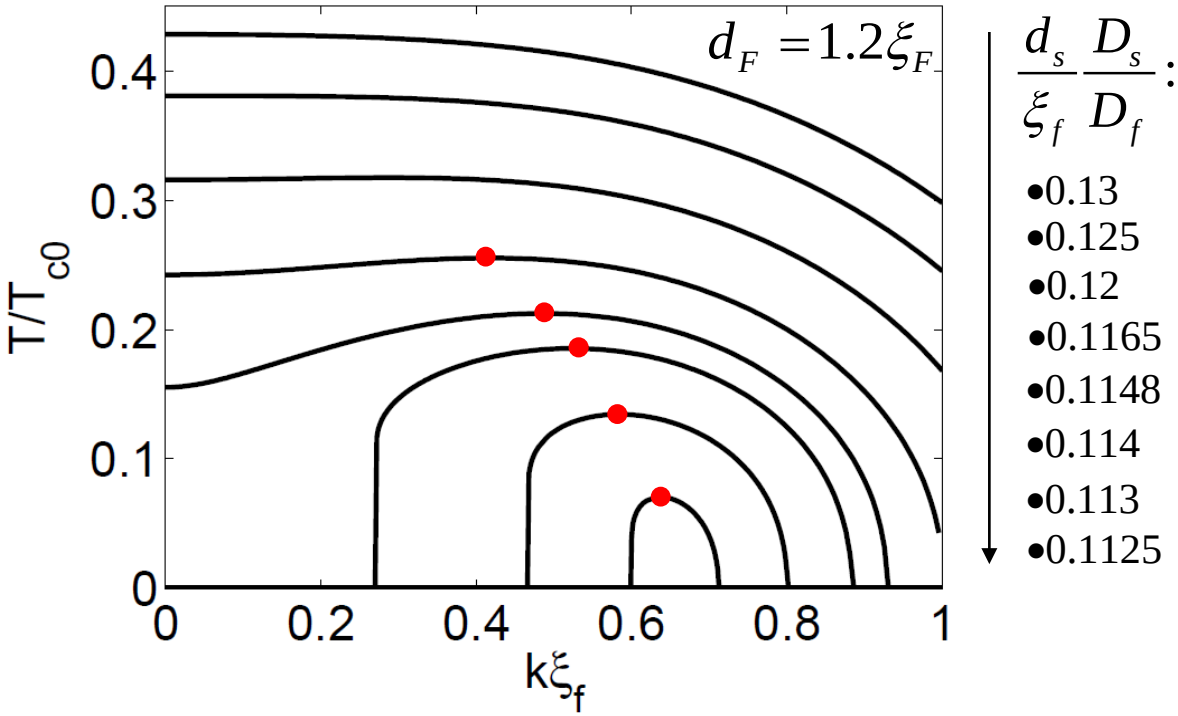
$$\begin{cases} \dfrac{D}{2}\dfrac{\partial^2 \hat{f}}{\partial x^2} - \left(\omega_n + \dfrac{D}{2}k^2\right)\hat{f} - \dfrac{i}{2}\left(\vec{h}\hat{\vec{\sigma}}\,\hat{f} + \hat{f}\,\vec{h}\hat{\vec{\sigma}}\right) + \hat{\Delta} = 0 \\ \Delta \ln\dfrac{T_c(k)}{T_{c0}} + \sum_{n=-\infty}^{\infty}\left(\dfrac{\Delta}{n+\frac{1}{2}} - 2\pi T_c(k) f_{12}^S\right) = 0 \end{cases}$$

$$\Delta = \Delta(x)\exp\left\{i\vec{k}\vec{r}_{\parallel}\right\}$$

$$\hat{f}(k) = \left(f_s + \vec{f}_t\hat{\vec{\sigma}}\right)i\hat{\sigma}_y$$

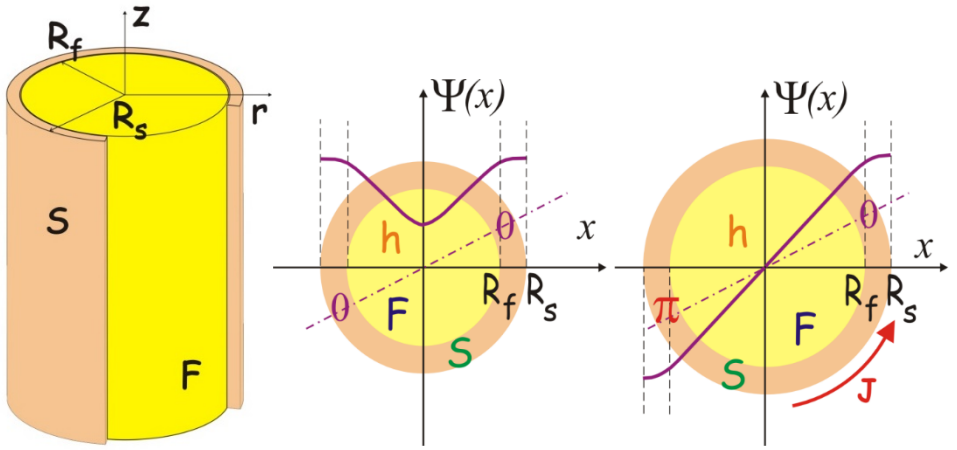
$$T_c = \max\left\{T_c(k)\right\}$$

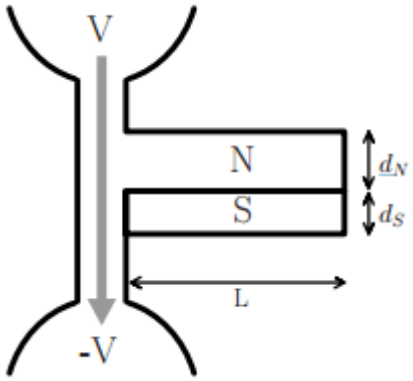
$$T_c << T_{c0}$$

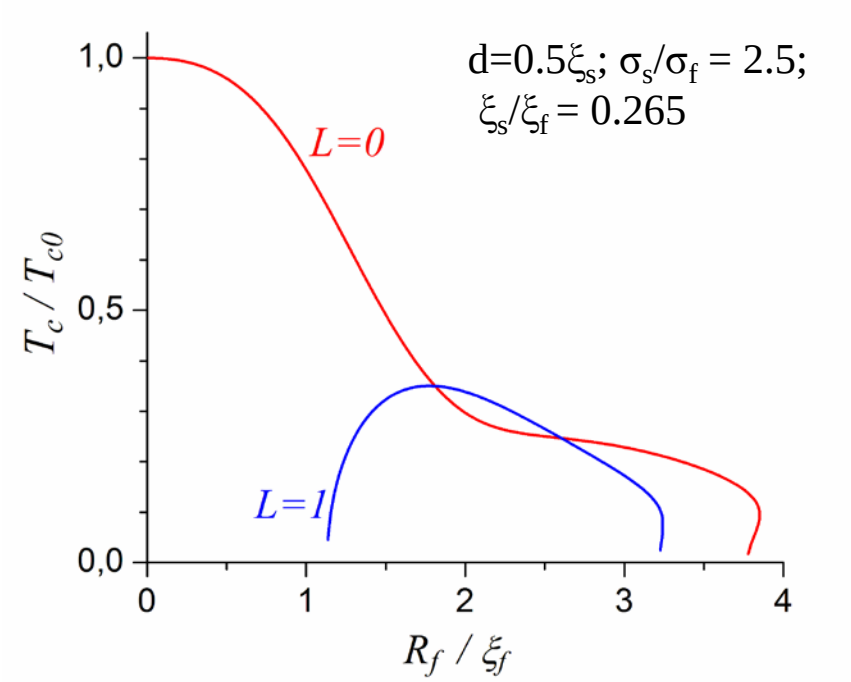


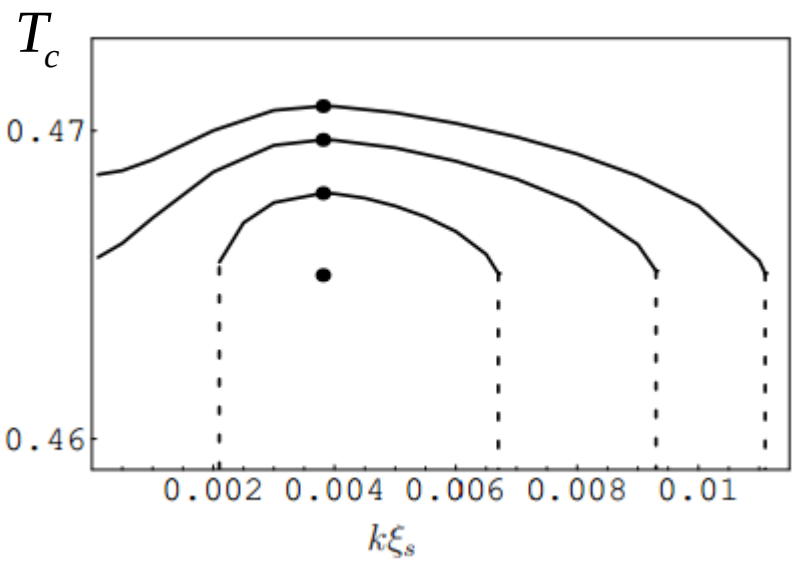
$$\frac{D_f}{D_s} >> \frac{h}{T_{c0}} \qquad d_F \sim \xi_f \qquad \frac{h}{T_{c0}}\xi_f \le d_S \le \frac{D_f}{D_s}\xi_f$$

Other systems with in-plane FFLO instability





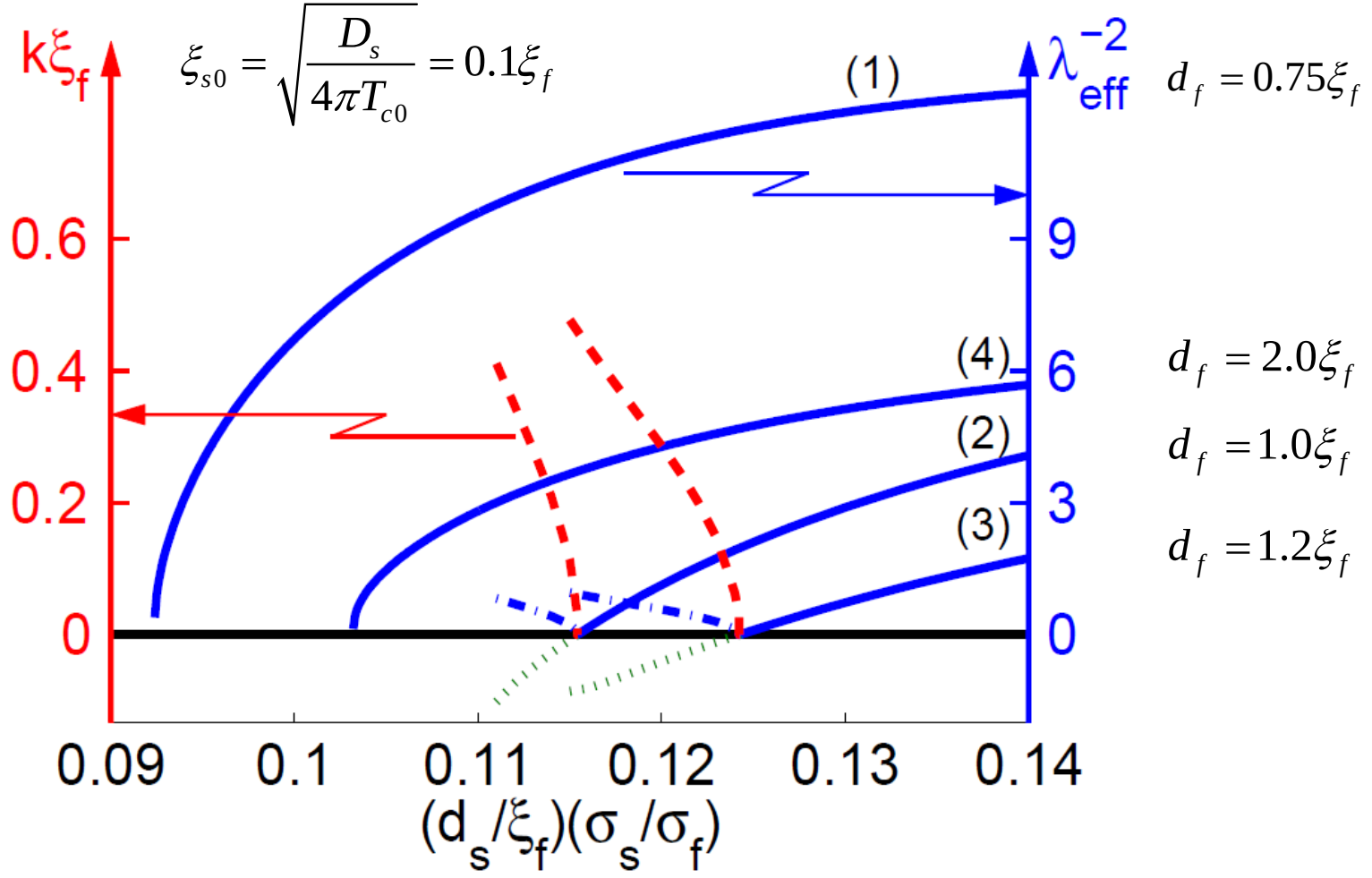




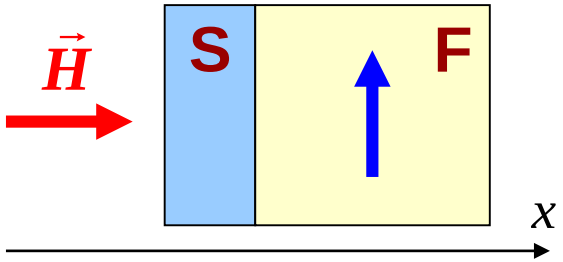
A.V. Samokhvalov, A.S. Mel'nikov and A.I. Buzdin, Phys. Rev. B **76**, 184519 (2007)

I.V. Bobkova and A.M. Bobkov, Phys. Rev. B **88**, 174502 (2013)

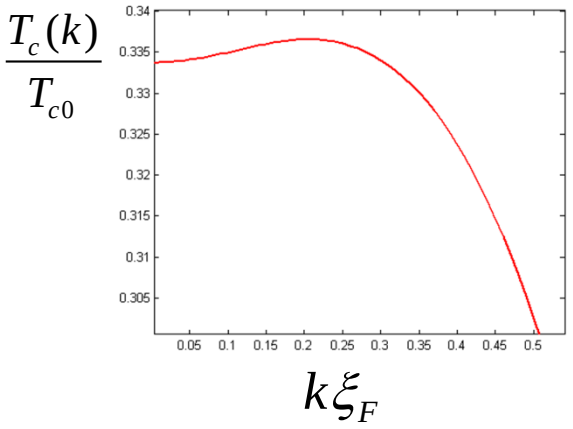
Inhomogeneous FFLO states in S/F bilayers

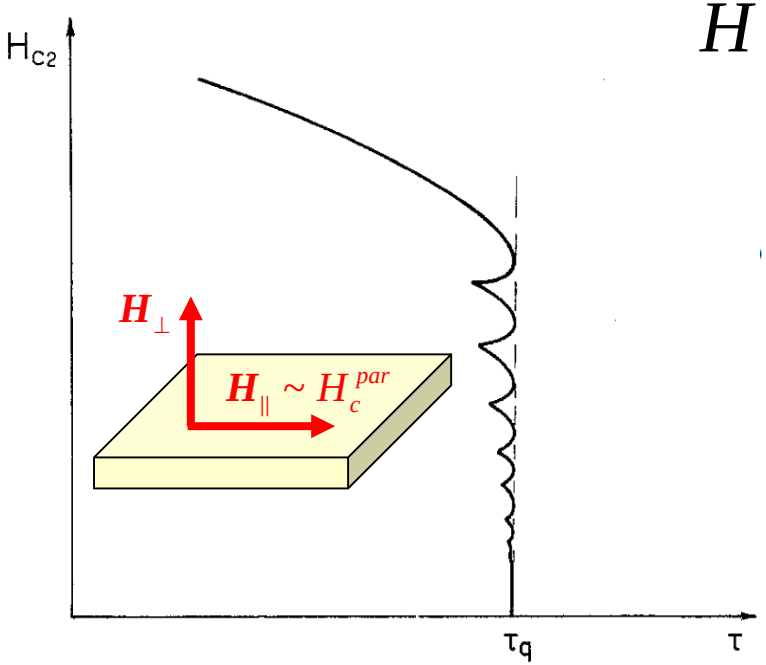


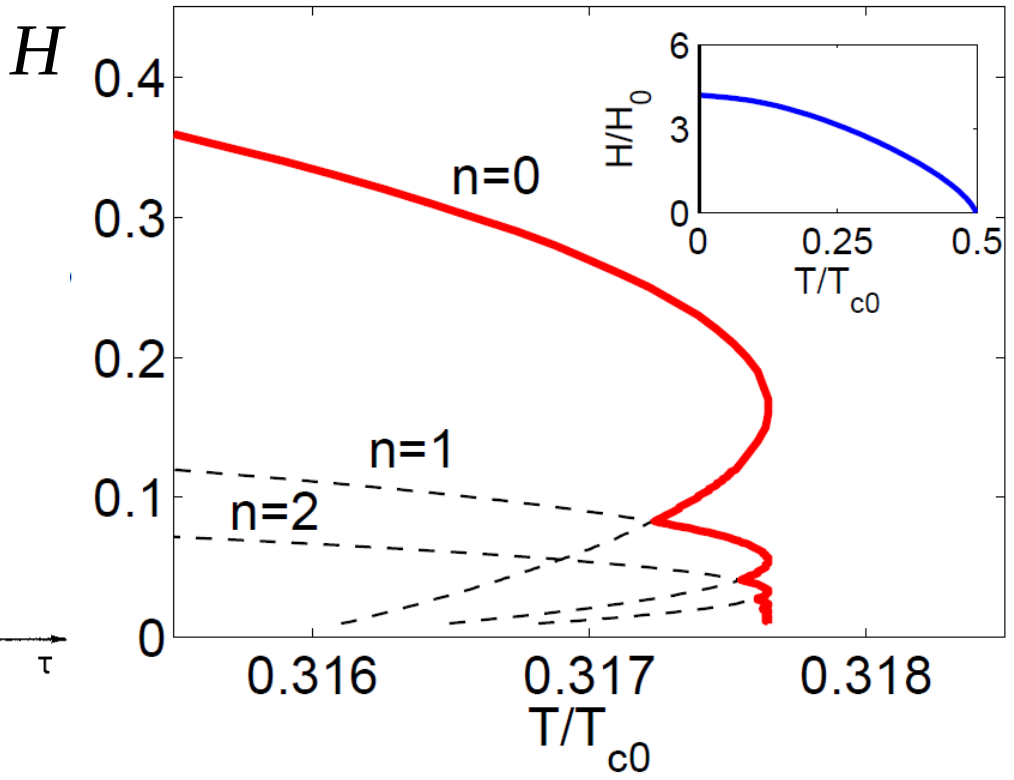
Phase diagram of S/F bilayers in the in-plane FFLO state



$$k^2 \to 4eH\left(n+\frac{1}{2}\right)$$



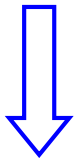




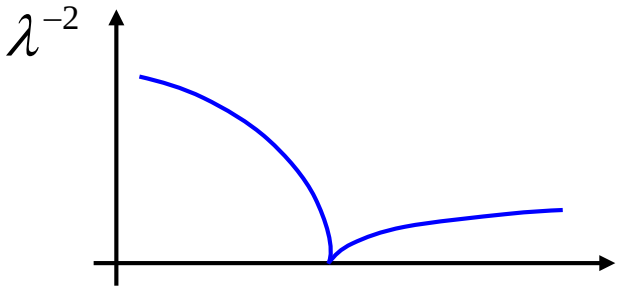
A.I. Buzdin and M.L. Kulić,
J. Low Temp. Phys. (1984)

Summary

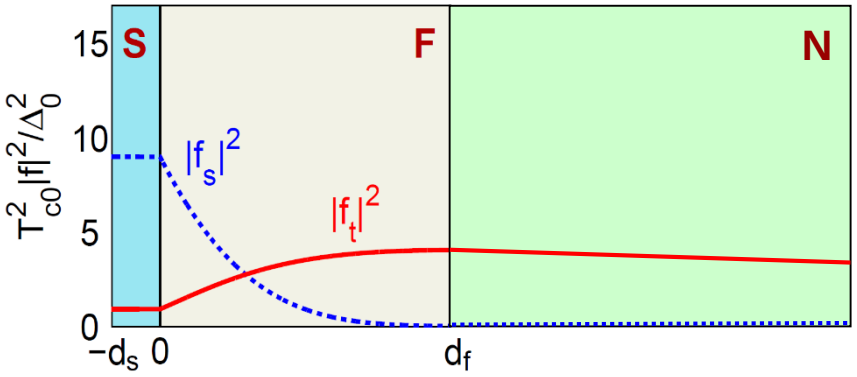
~~Paramagnetic~~
~~Meissner effect~~



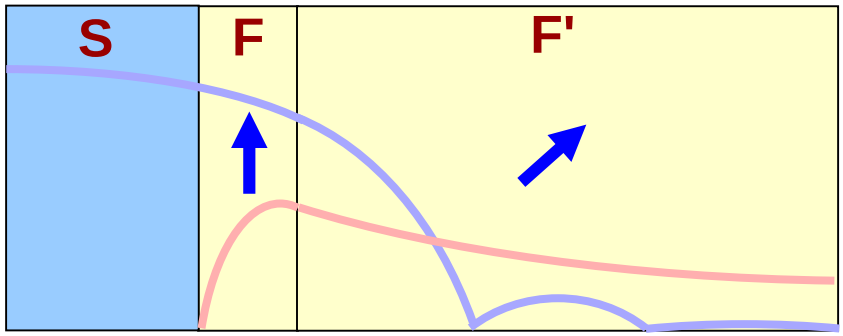
In-plane FFLO states



In-plane FFLO states in S/F/N and S/F/F' systems



FFLO states at $T \approx T_{c0}$



$\theta < \theta_c \Longrightarrow$ **Uniform state**

$\theta > \theta_c \Longrightarrow$ **FFLO state**

Thank you for attention!