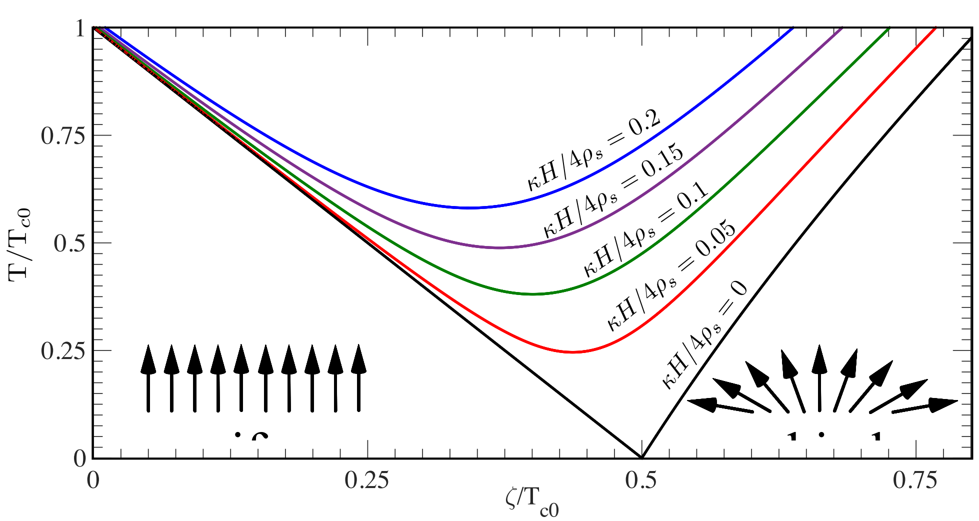
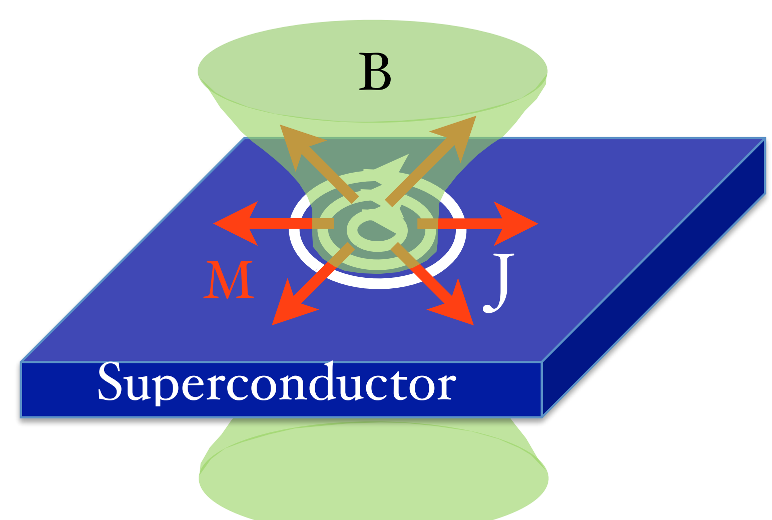
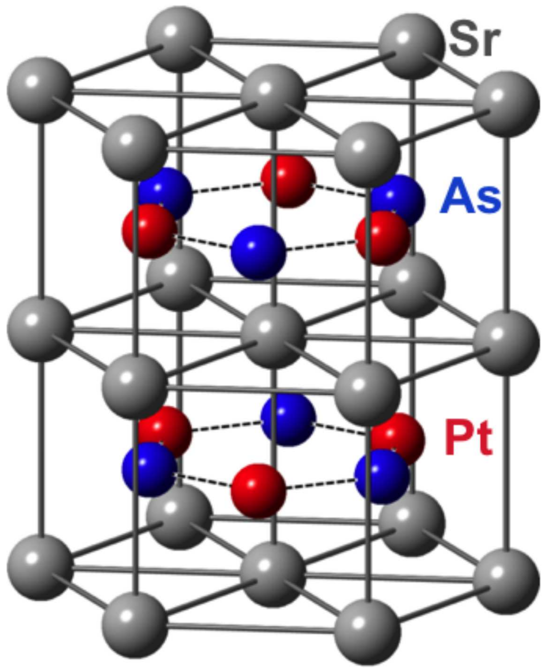
Spontaneous finite momentum pairing in superconductors without inversion symmetry

Karen Michaeli

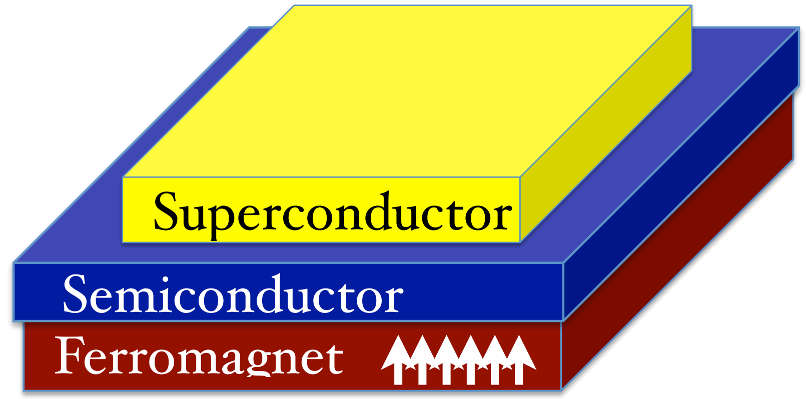




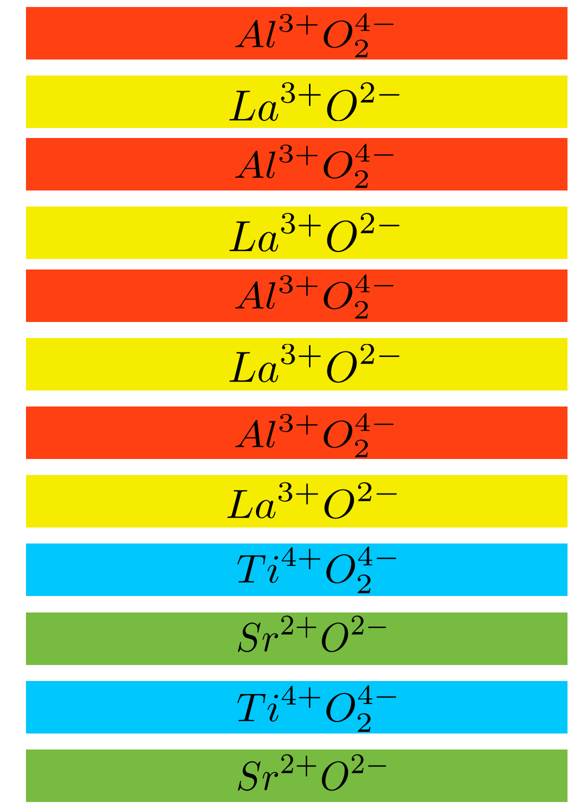
A. Steinbok and KM, 2016



Strongly correlated superconductors



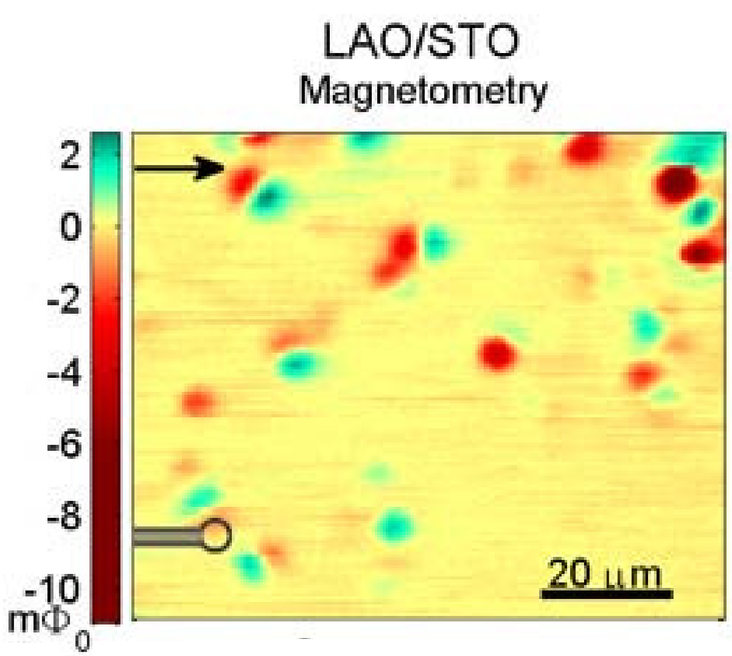
Topological superconductivity



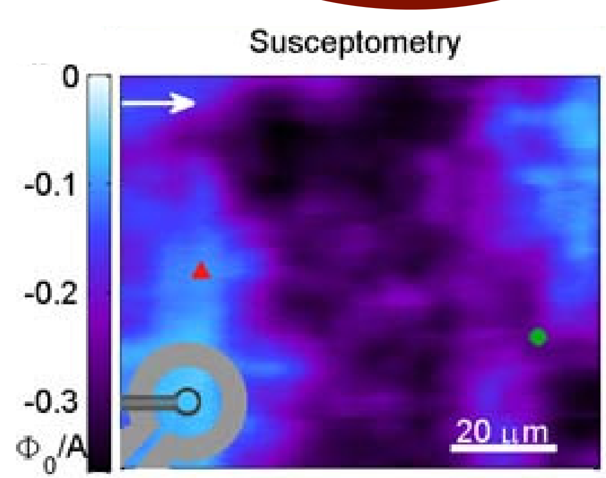
Oxide heterostructures

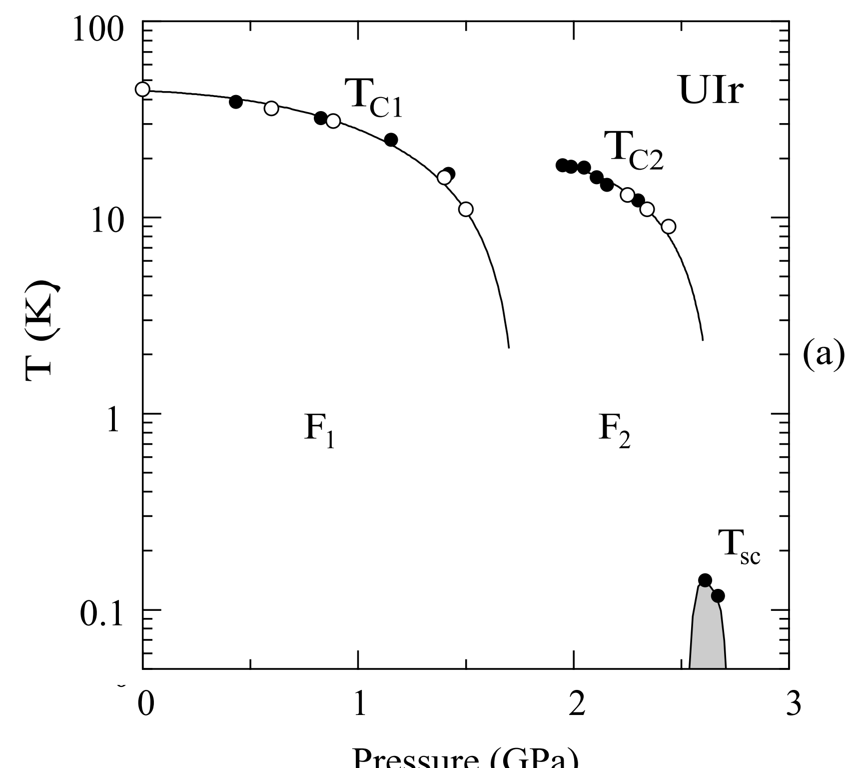
superconductivity

spin - orbit



J. A. Bert, *et al*, 2012



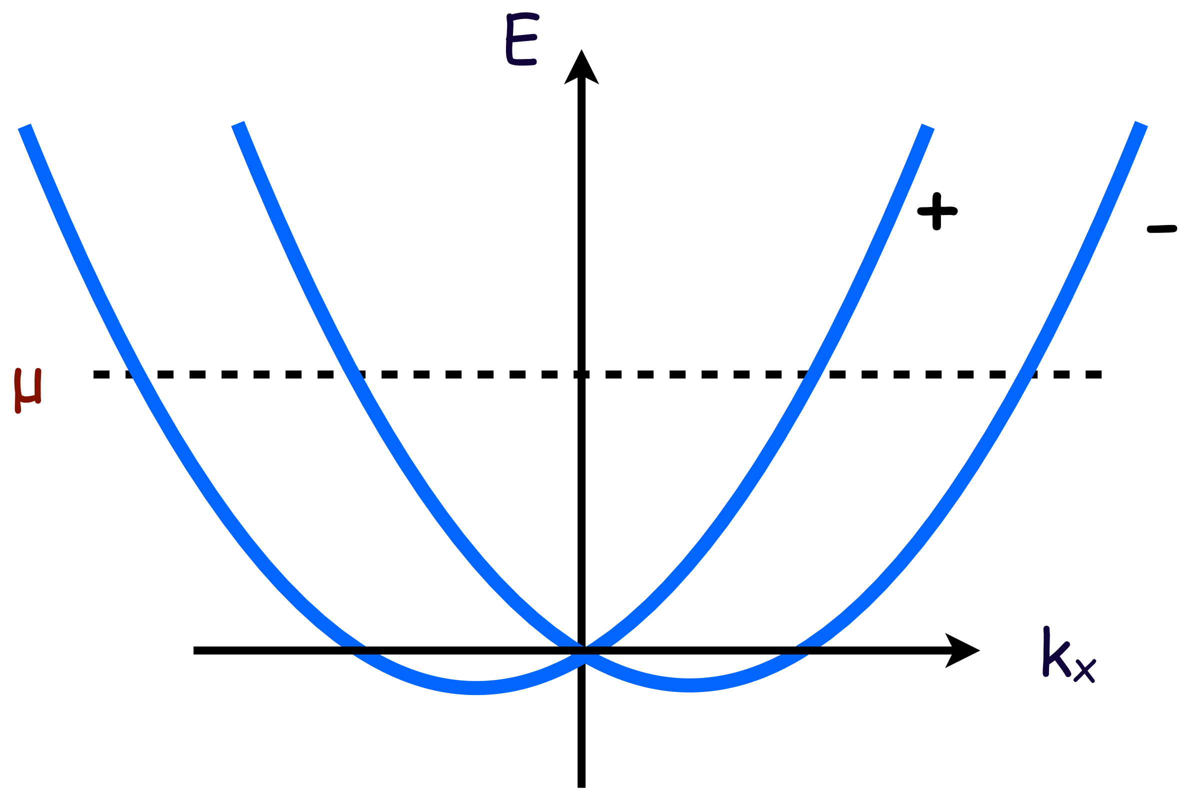


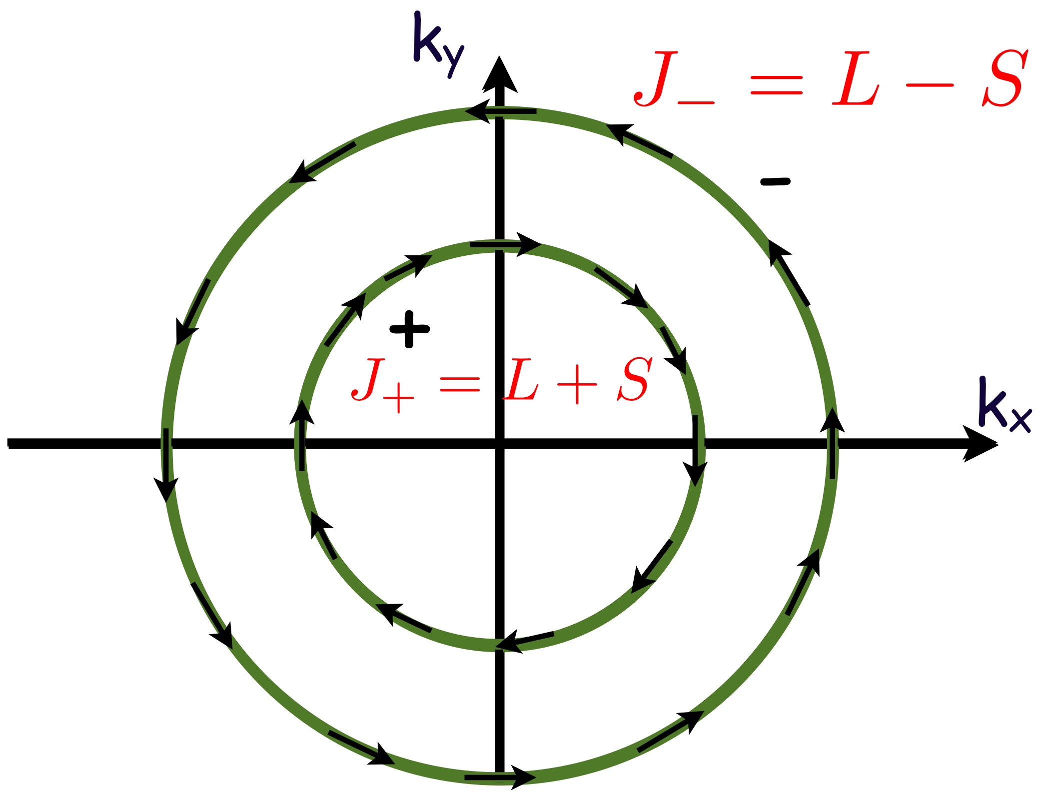
UIr

T Akazawa, *et al*, 2004

Electronic spectrum

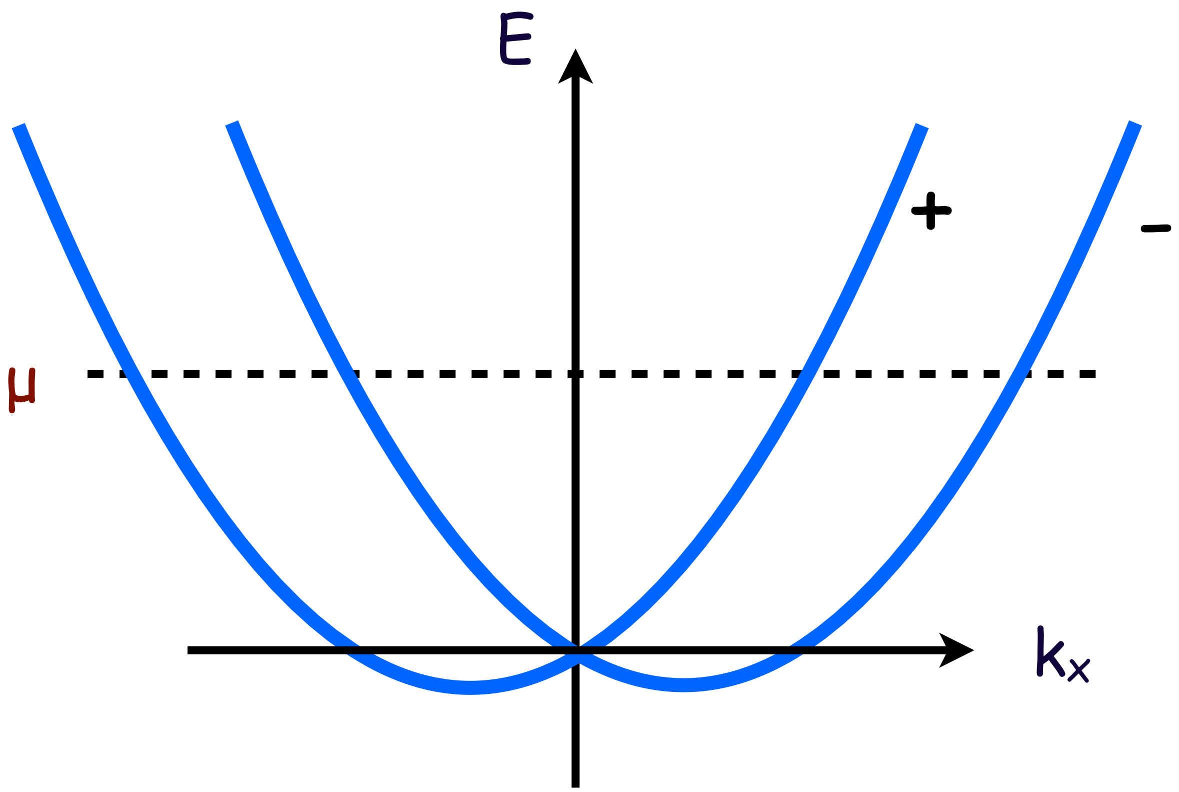
$$\mathcal{H} = \frac{k^2}{2m} + \alpha \hat{z} \cdot (\vec{k} \times \vec{\sigma}) \longrightarrow \varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha |\vec{k}|$$

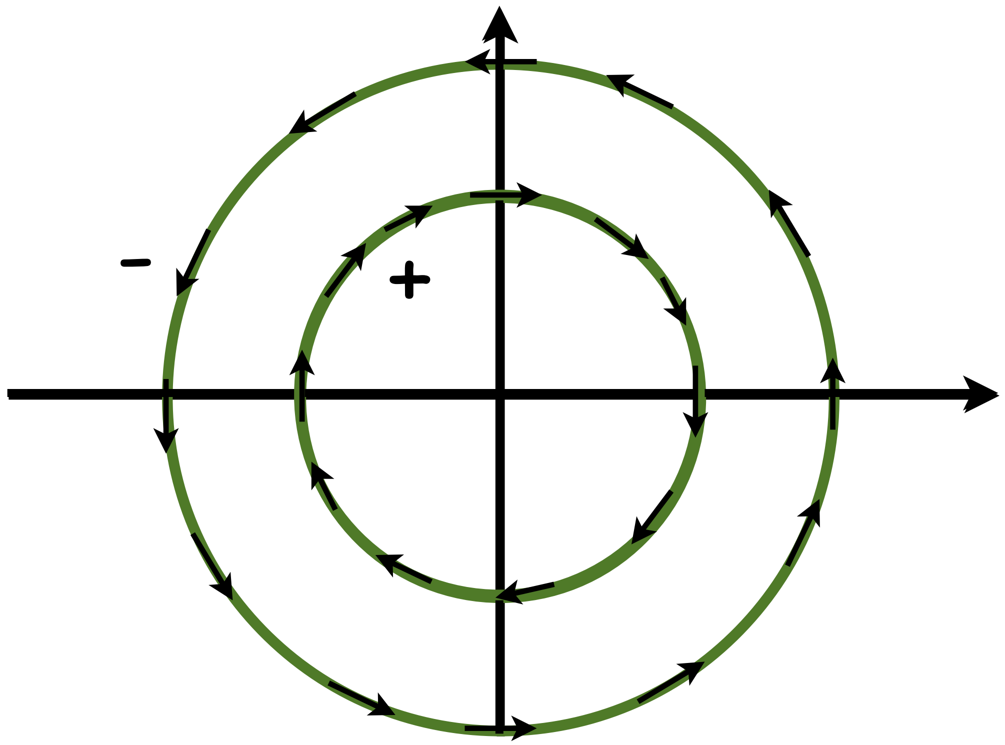




Superconductivity

$$\varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha|\vec{k}|$$

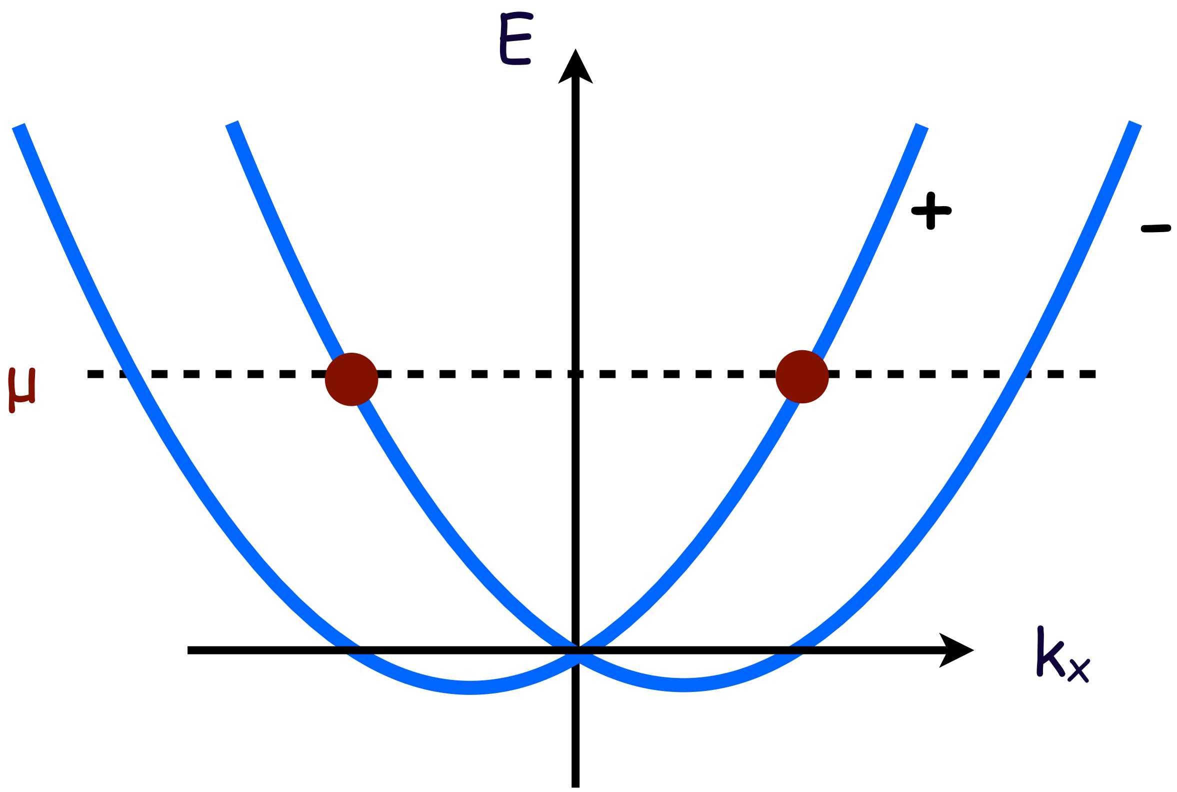


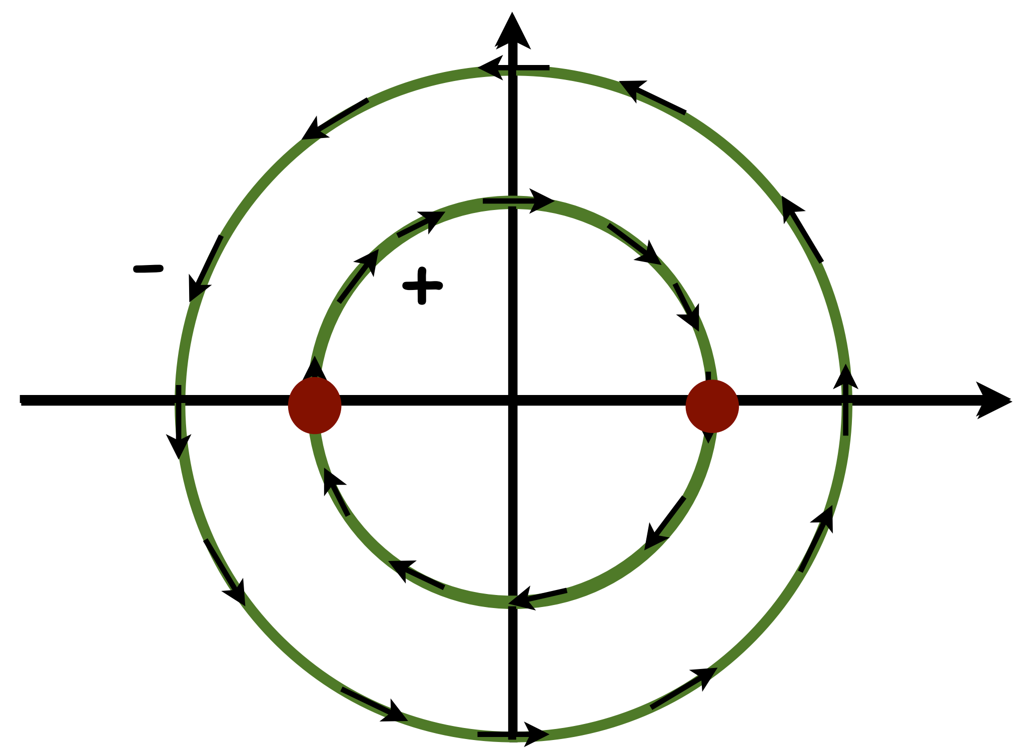


$$\Delta = \sum_k [\psi_{k,\uparrow}\psi_{-k,\downarrow} - \psi_{k,\downarrow}\psi_{-k,\uparrow}]$$

Superconductivity

$$\varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha|\vec{k}|$$





$$\Delta = \sum_k \left[\underbrace{\frac{ik_x + k_y}{k} \psi_{k,+}\psi_{-k,+}}_{\Delta_{p_x - ip_y}} + \underbrace{\frac{ik_x - k_y}{k} \psi_{k,-}\psi_{-k,-}}_{\Delta_{p_x + ip_y}} \right]$$

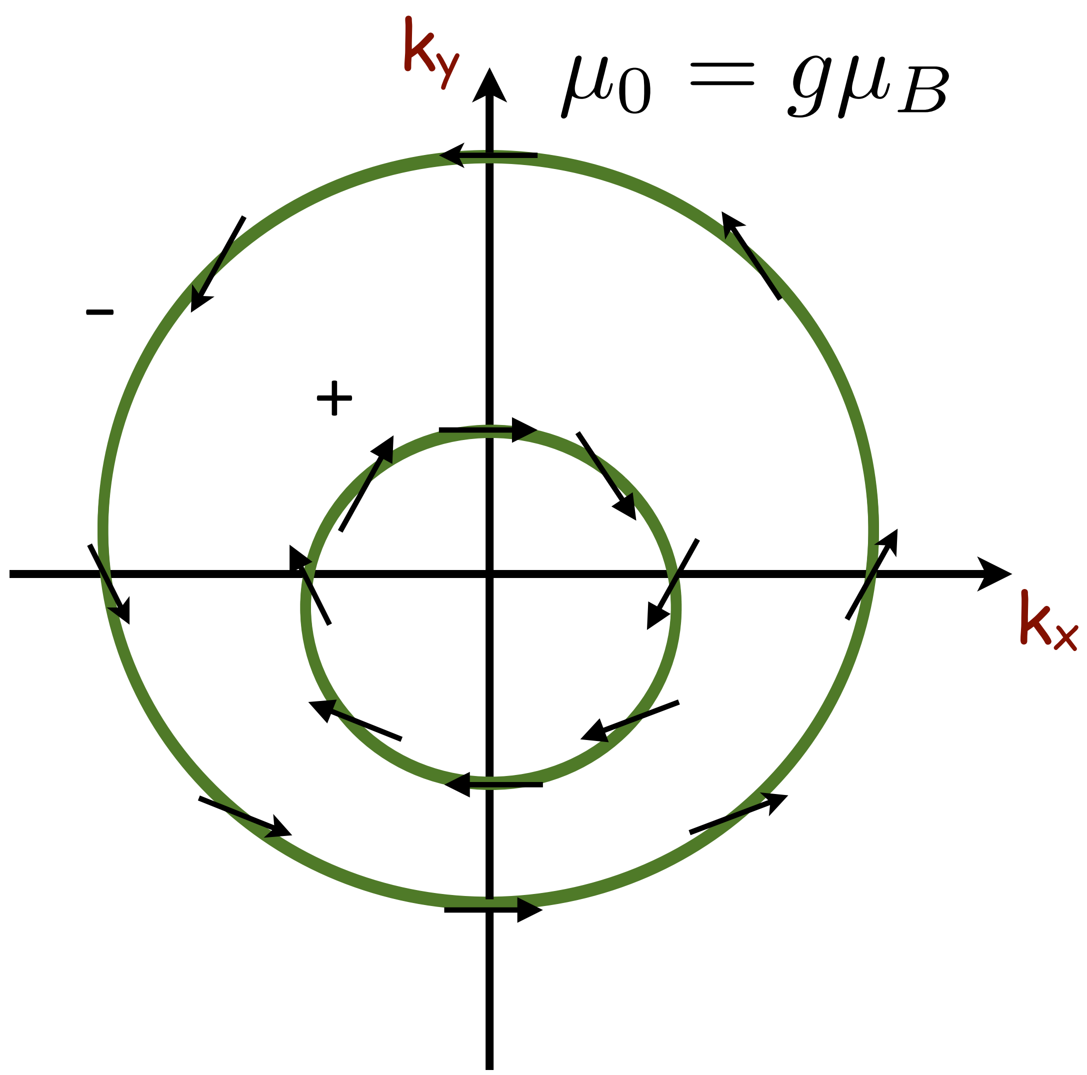
Magnetic field

The two Rashba bands in the presence of a Zeeman field:

$$\vec{B} = B\hat{x}$$

$$\varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha\sqrt{k_x^2 + (k_y + \mu_0 B/\alpha)^2}$$

$$\mu_0 = g\mu_B$$



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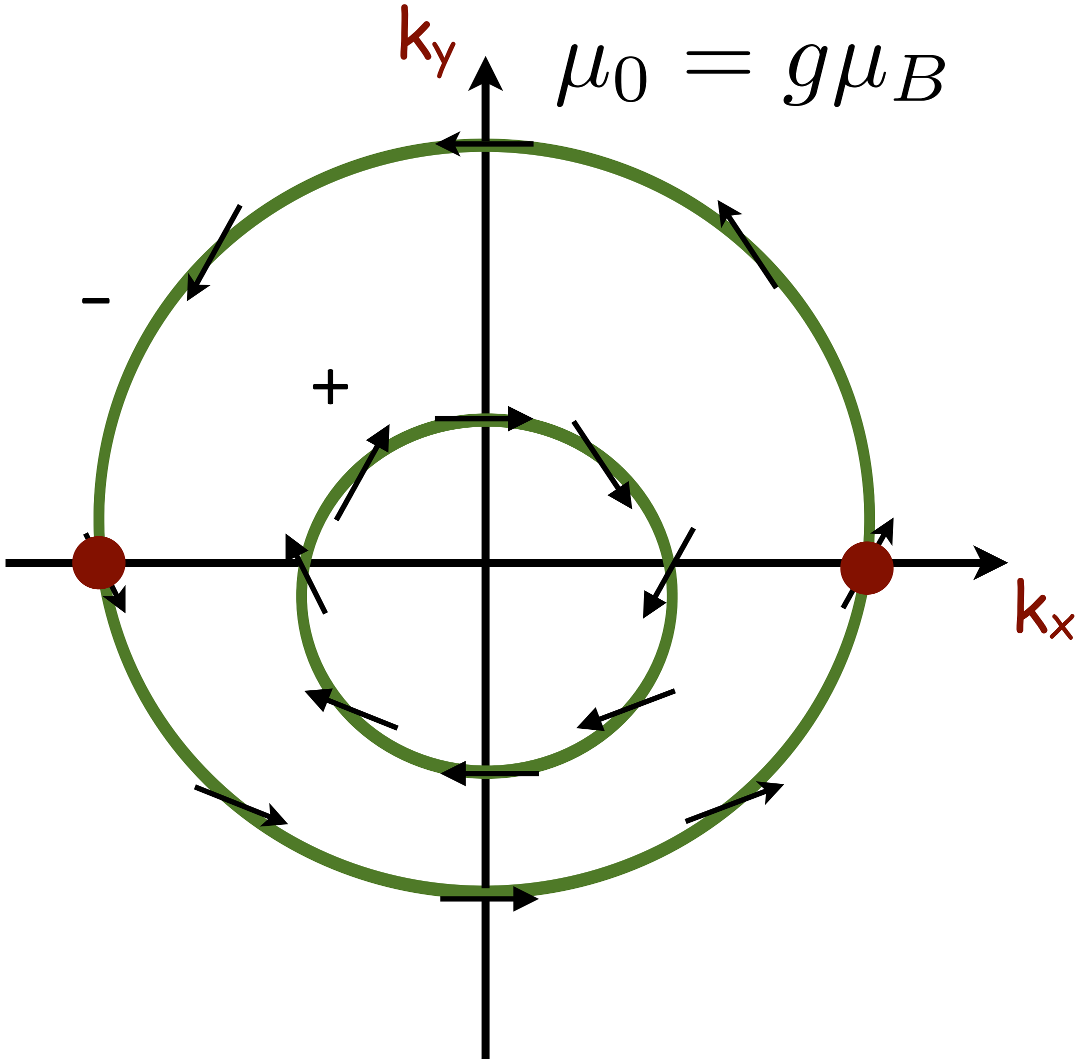

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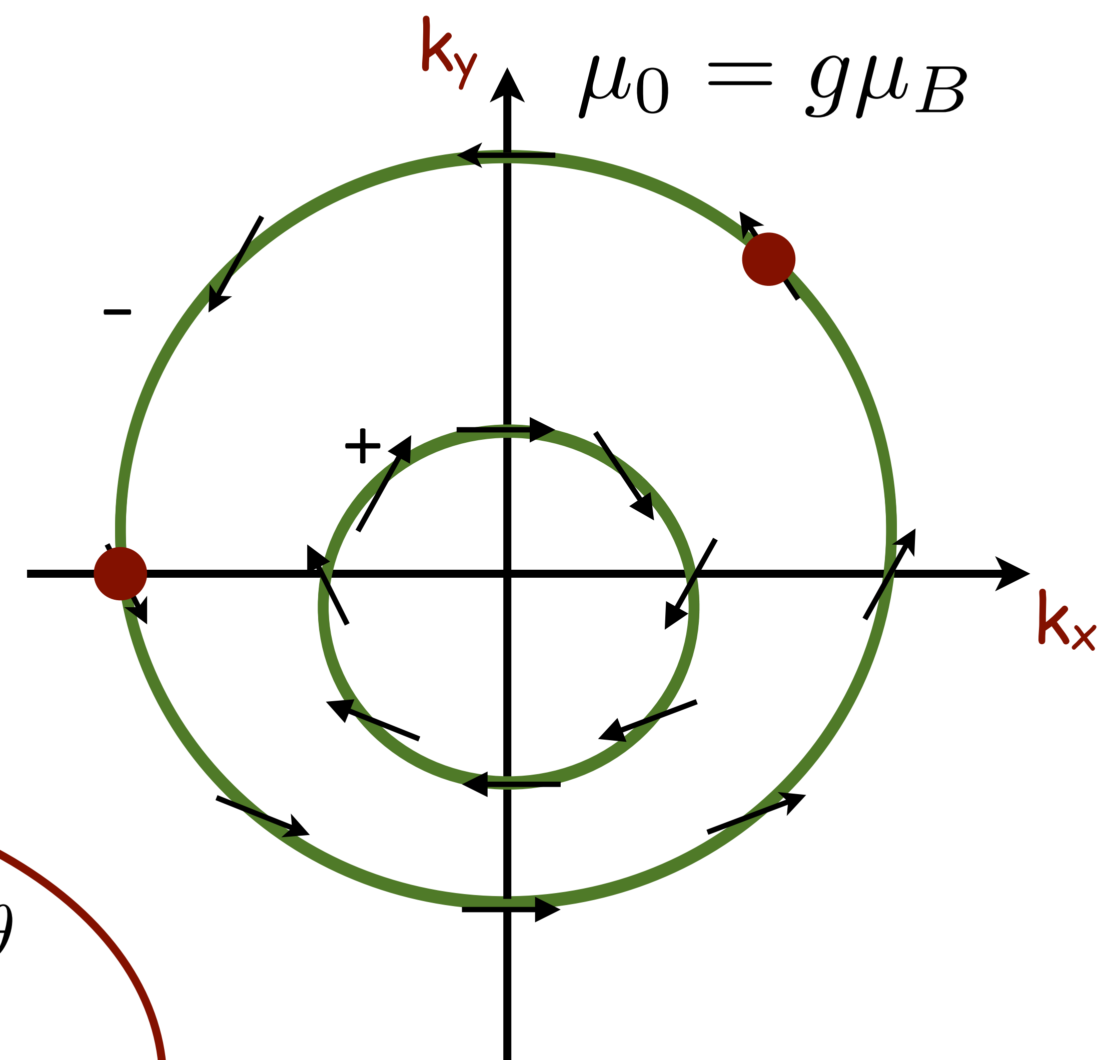


Creating pairs with finite momentum $\vec{q} \perp \vec{B}$:

$$\varepsilon^{\pm}_{k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| + \frac{1}{2}(V_F q \pm 2\mu_0 B)\sin\theta$$

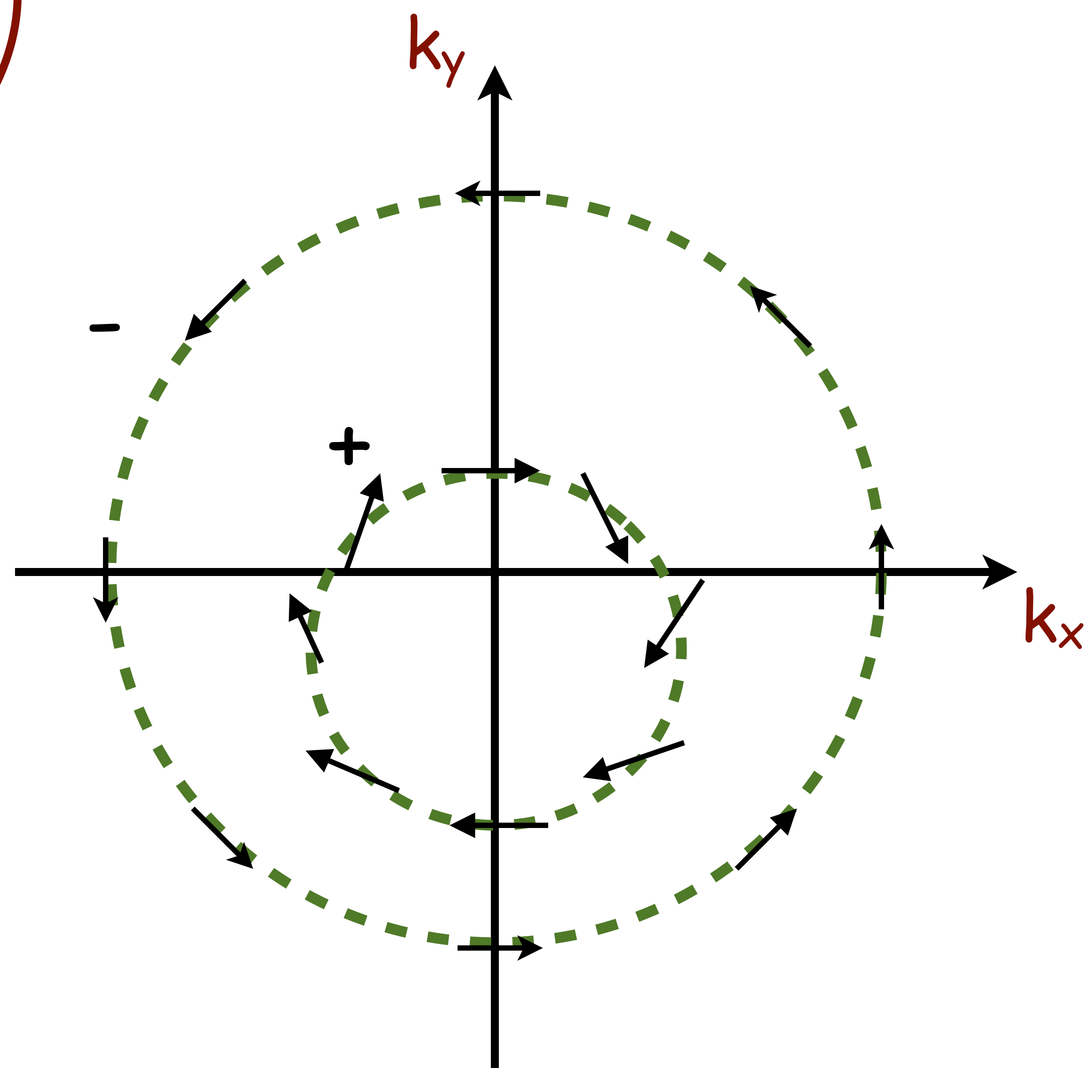
$$\varepsilon^{\pm}_{-k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| - \frac{1}{2}(V_F q \pm 2\mu_0 B)\sin\theta$$

The FFLO state and spin-orbit

$$\varepsilon^{\pm}_{k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| + \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

$$\varepsilon^{\pm}_{-k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| - \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

$$q = \frac{2\mu_0 B}{v_F}$$



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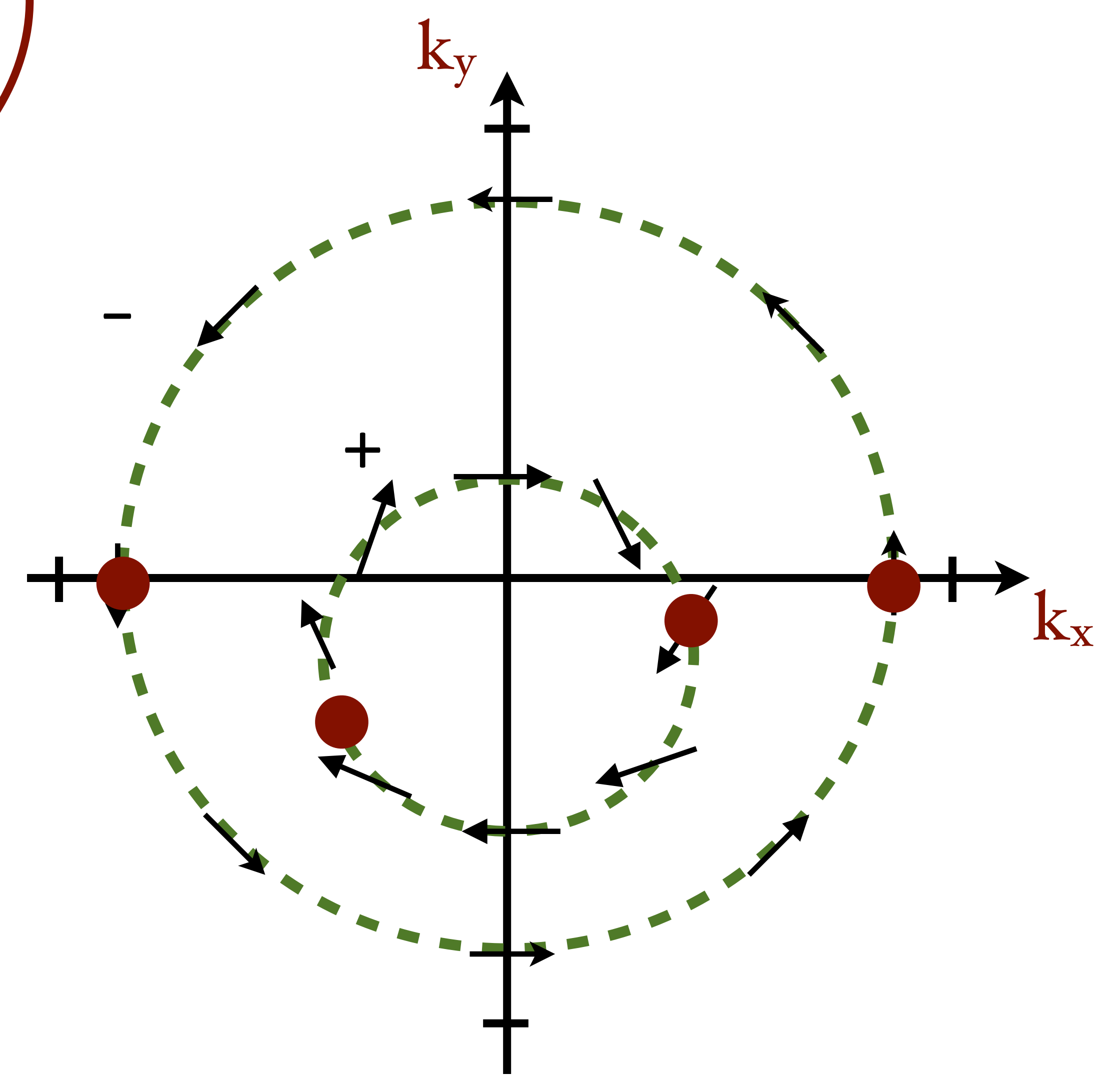


Pairs of electrons in the - band are not affected by the magnetic field

Pairs of electrons in the + band feel the decoherence effect of the magnetic field

The critical field is mainly determined by the + band

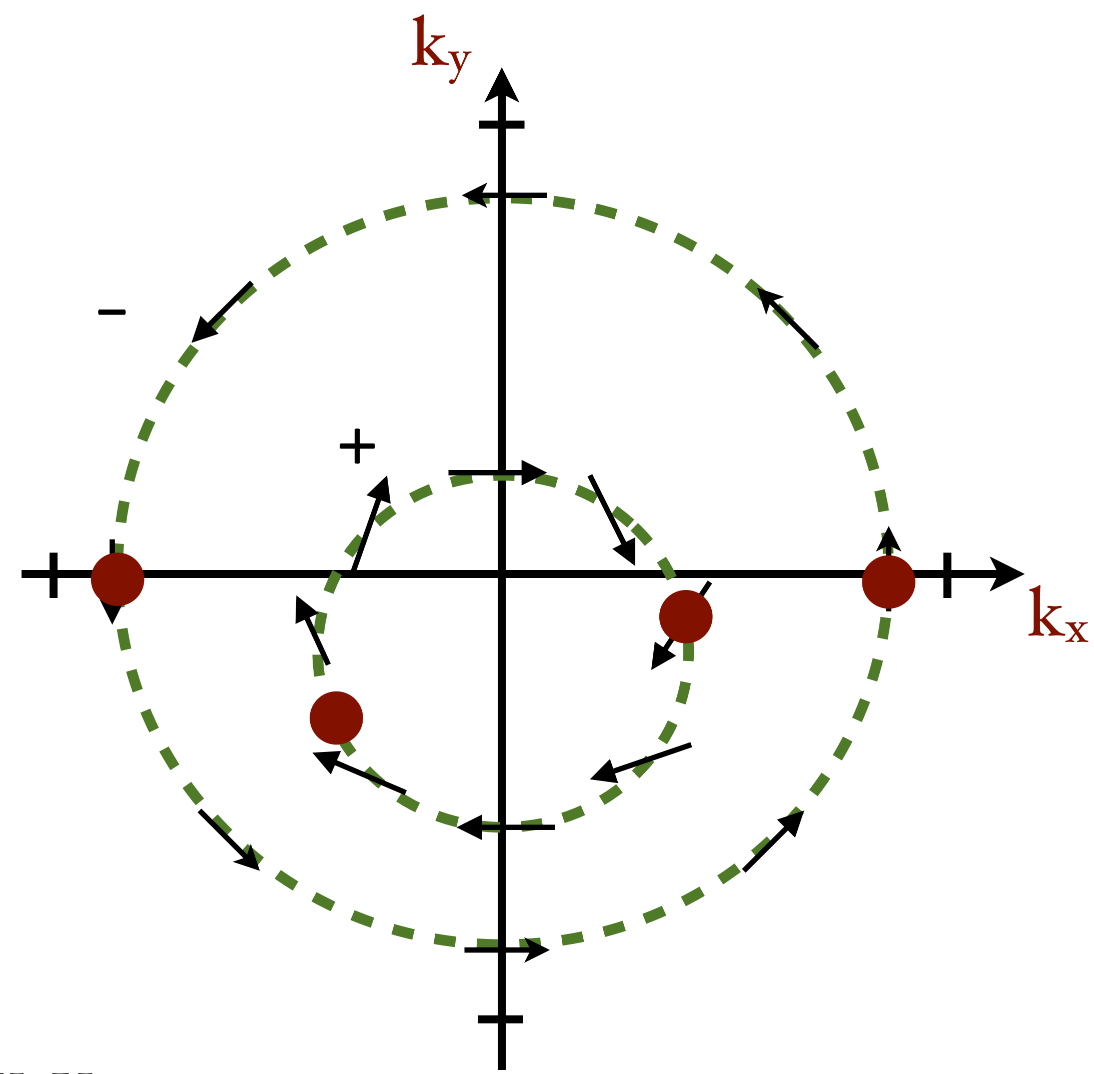
The FFLO state and spin-orbit

V. Barzykin, and L. P. Gorkov, 2002.

$$\mu_0 B_c \sim \Delta_0 \left(\frac{\Delta_{so}}{\Delta_0}\right)^x$$

$$1/2 < x < 2/3$$

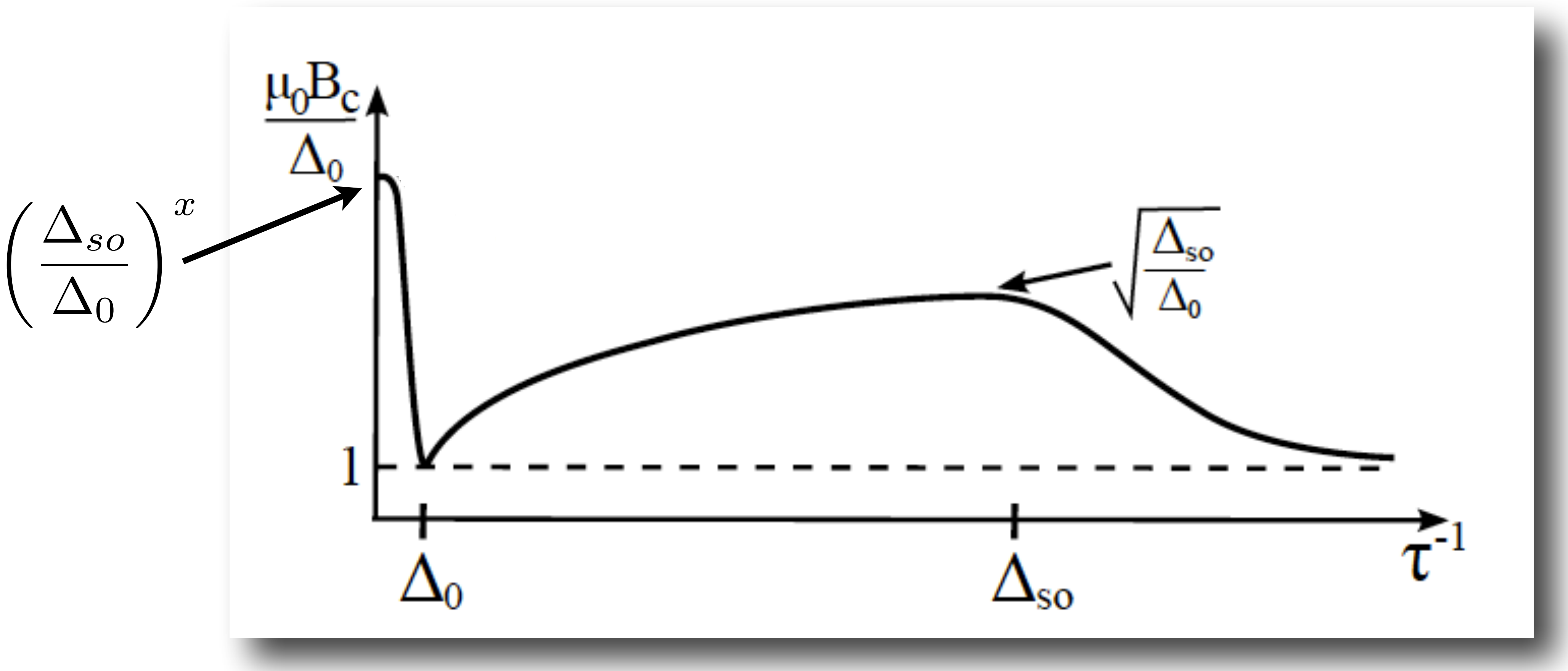
$$\Delta(\vec{r}) = \Delta e^{i\vec{q}\cdot\vec{r}}$$



L. P. Gor'kov, E. I. Rashba, 2001.
A. B. Shick, and W. E. Pickett, 2001.
K. V. Samokhin, 2004.
P. A. Frigeri, D. F. Agterberg, and M. Sigrist, 2004
M.Y. Kharitonov, and M. V. Feigel'man, 2005.

S.-K. Yip, 2005.
H. Q. Yuan, *et. al.*, 2006.
J. Linder, and A. Sudbo, 2007.
T. Neupert, and M. Sigrist, 2011.
F. Loder, A. P. Kampf, and T. Kopp, 2013.

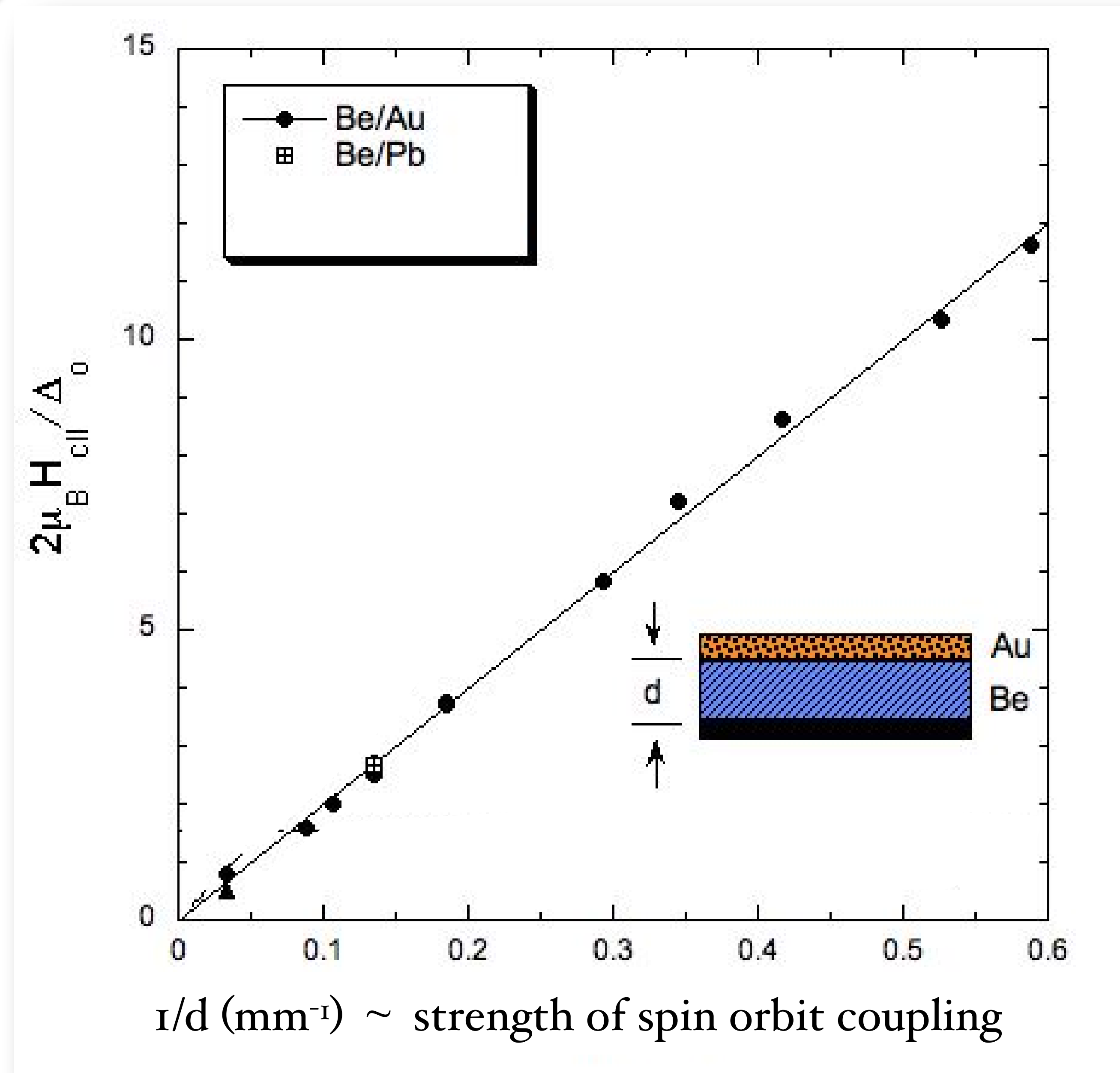
Disorder effects



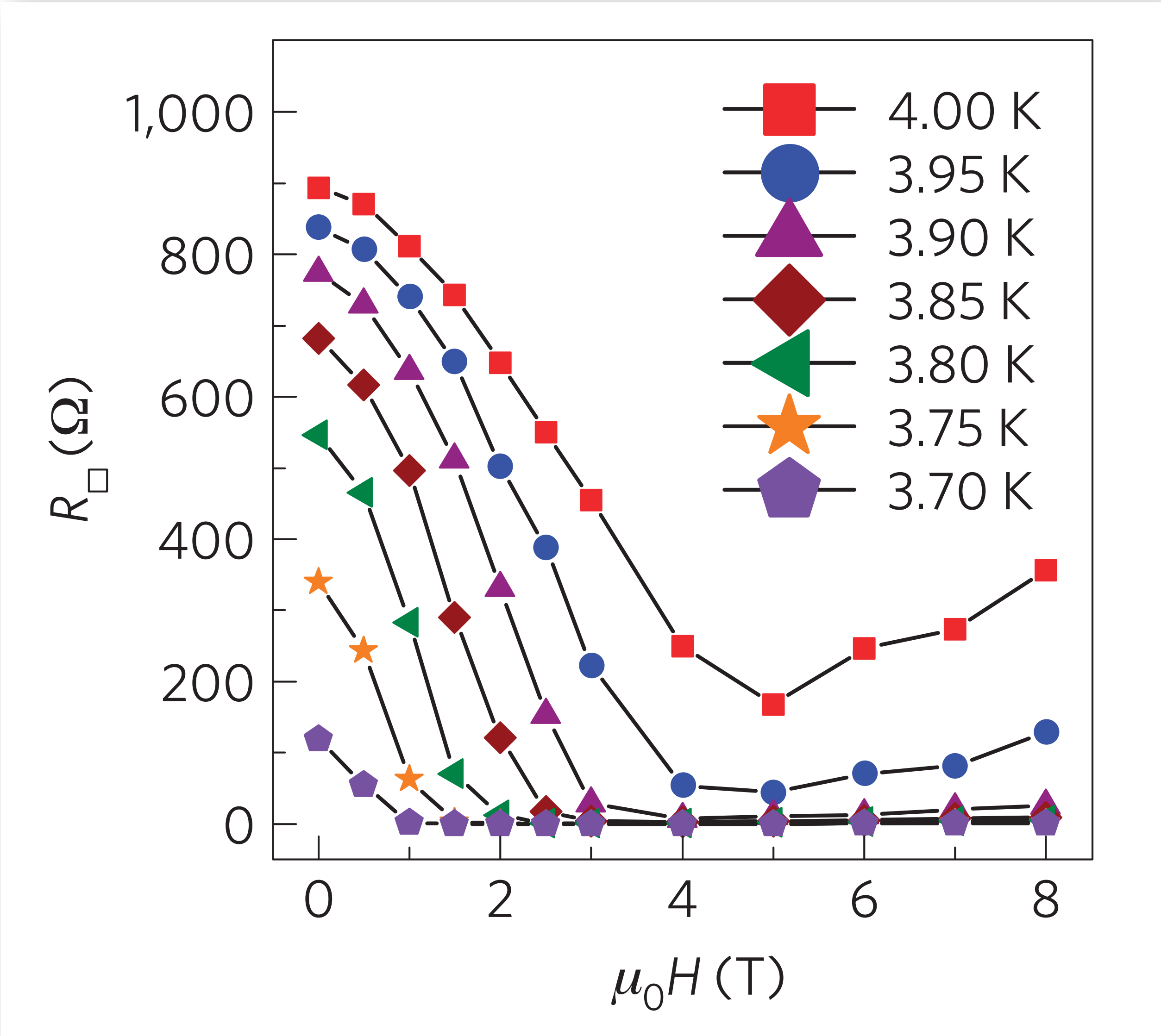
KM, A. C. Potter, and P. A. Lee, PRL 2012

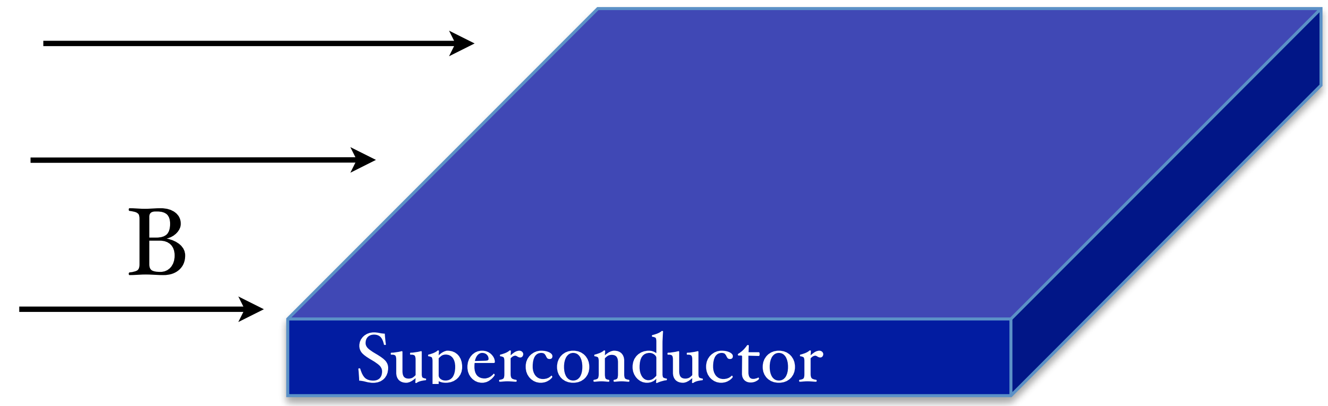
Critical magnetic field

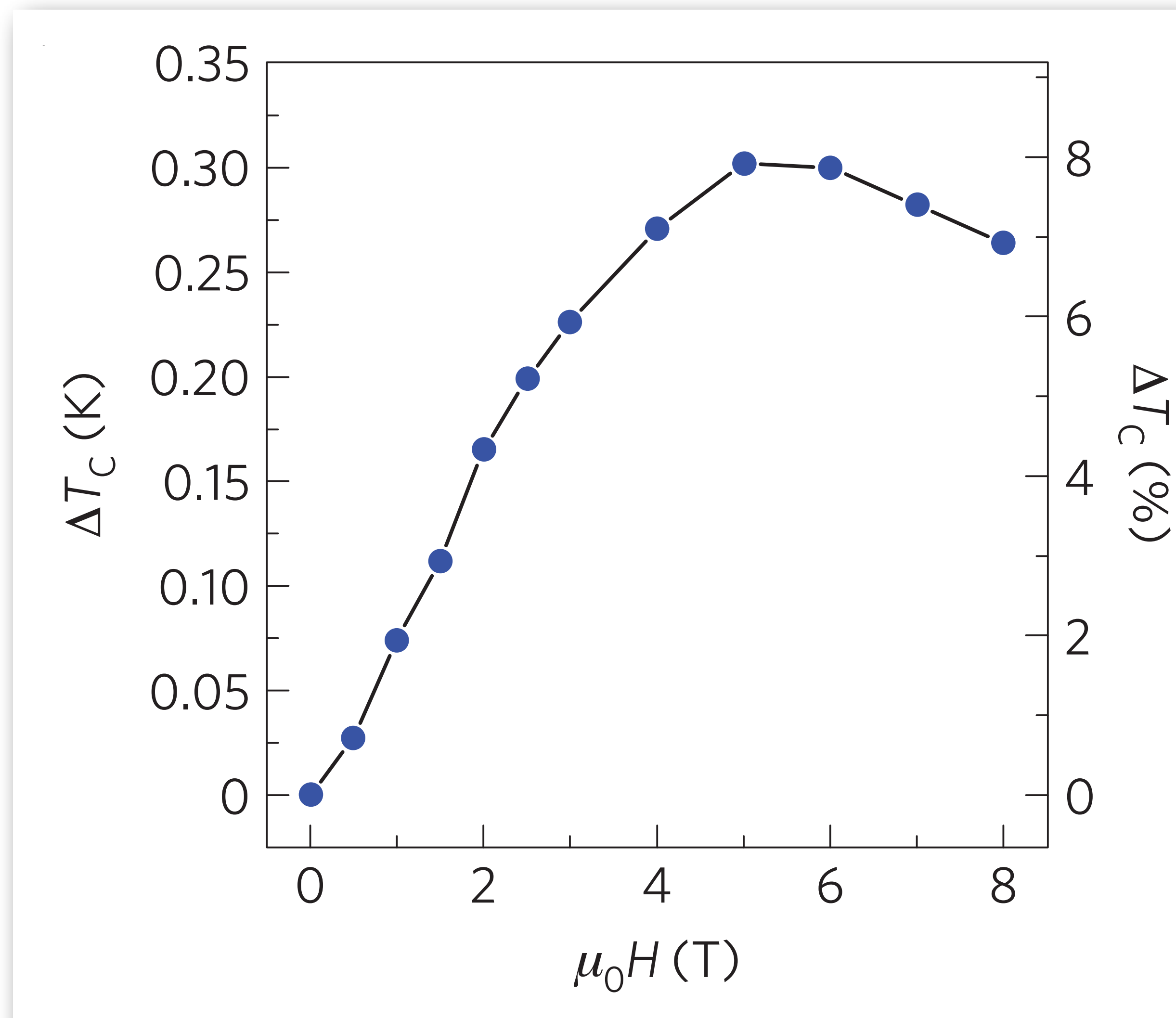
X. S. Wu, *et al*, 2005



Enhancement of T_c





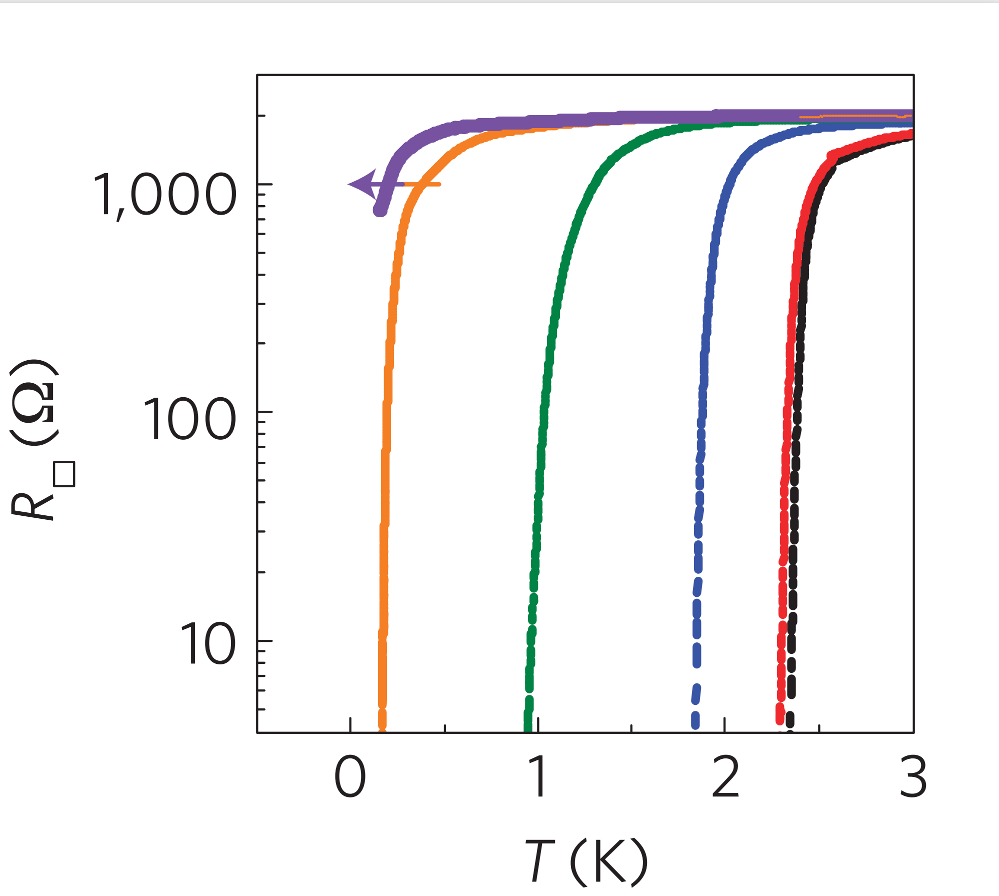


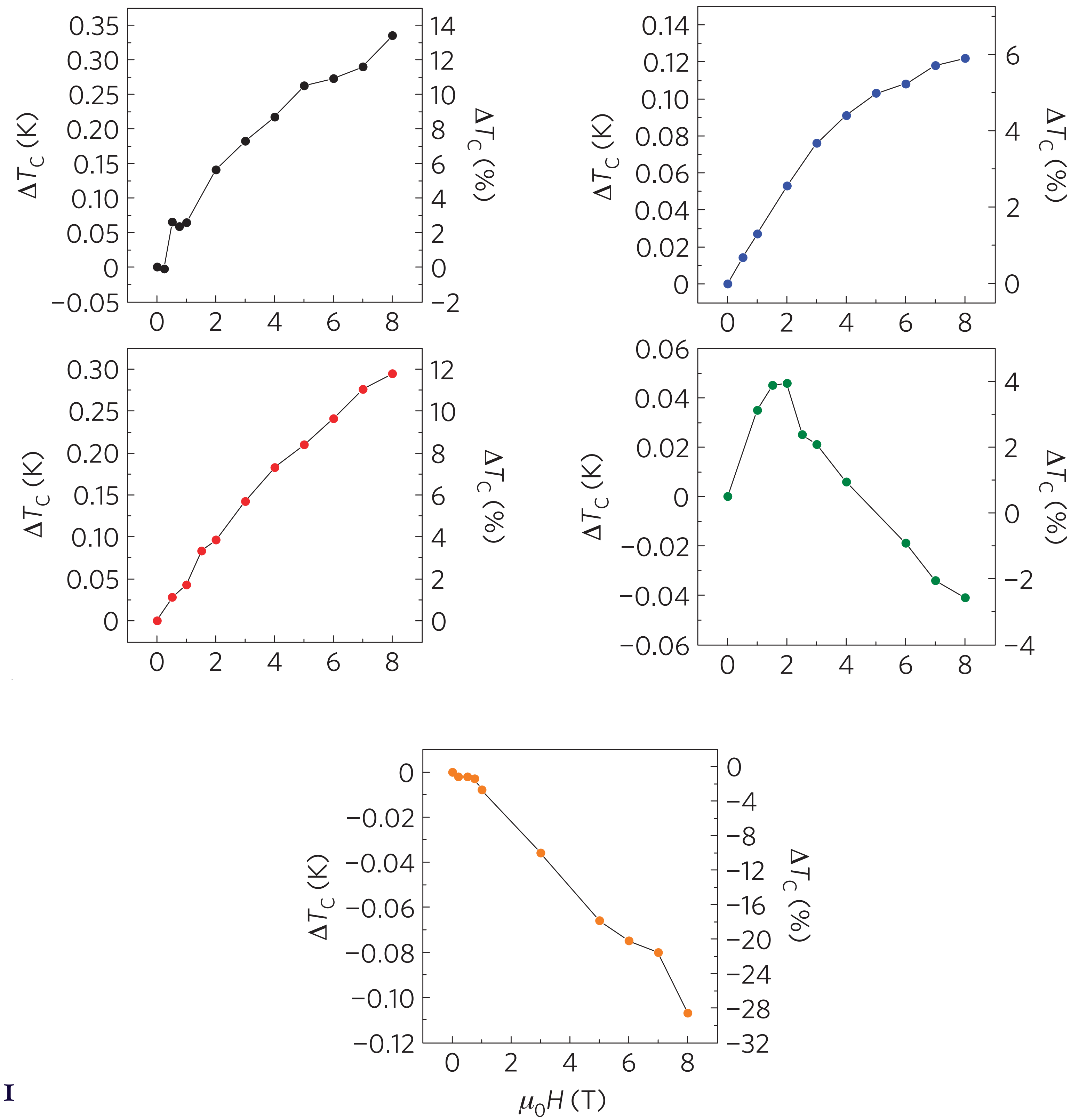
$$Tc(H=0) = 3.612K$$

$$2.1nm$$

H. Gardner, et al, 2011

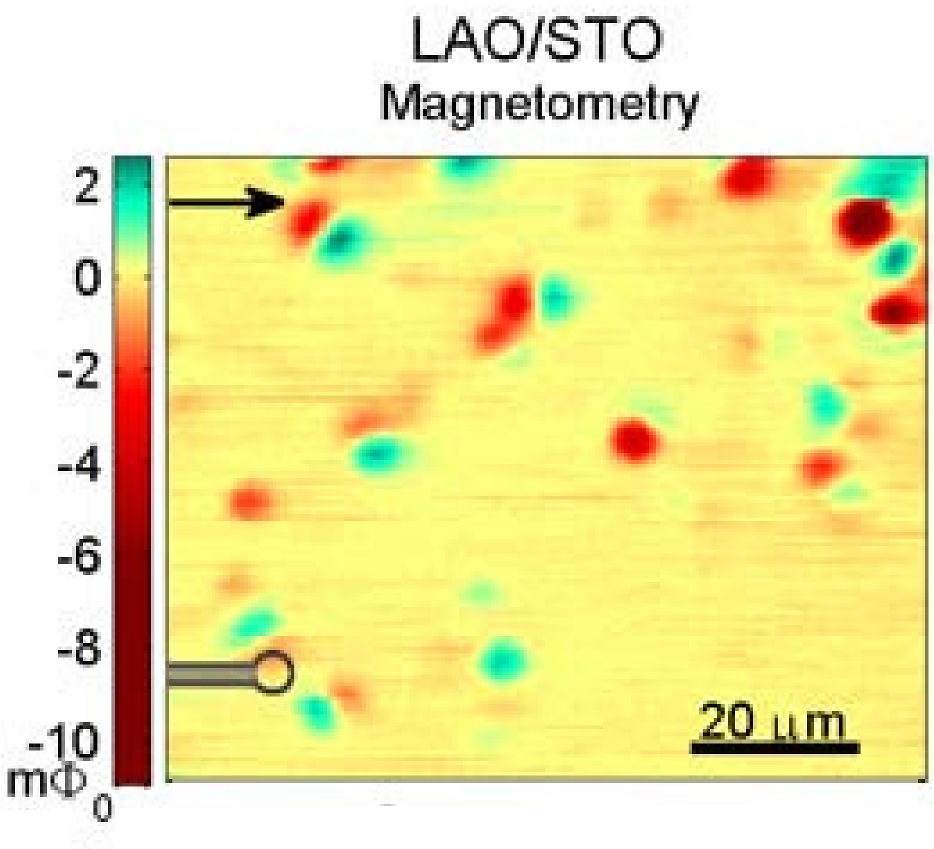
Enhancement of T_c



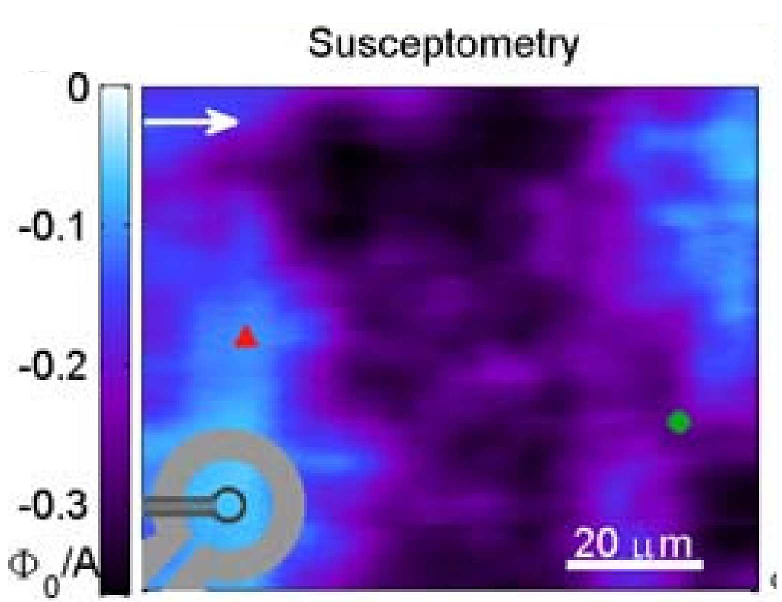


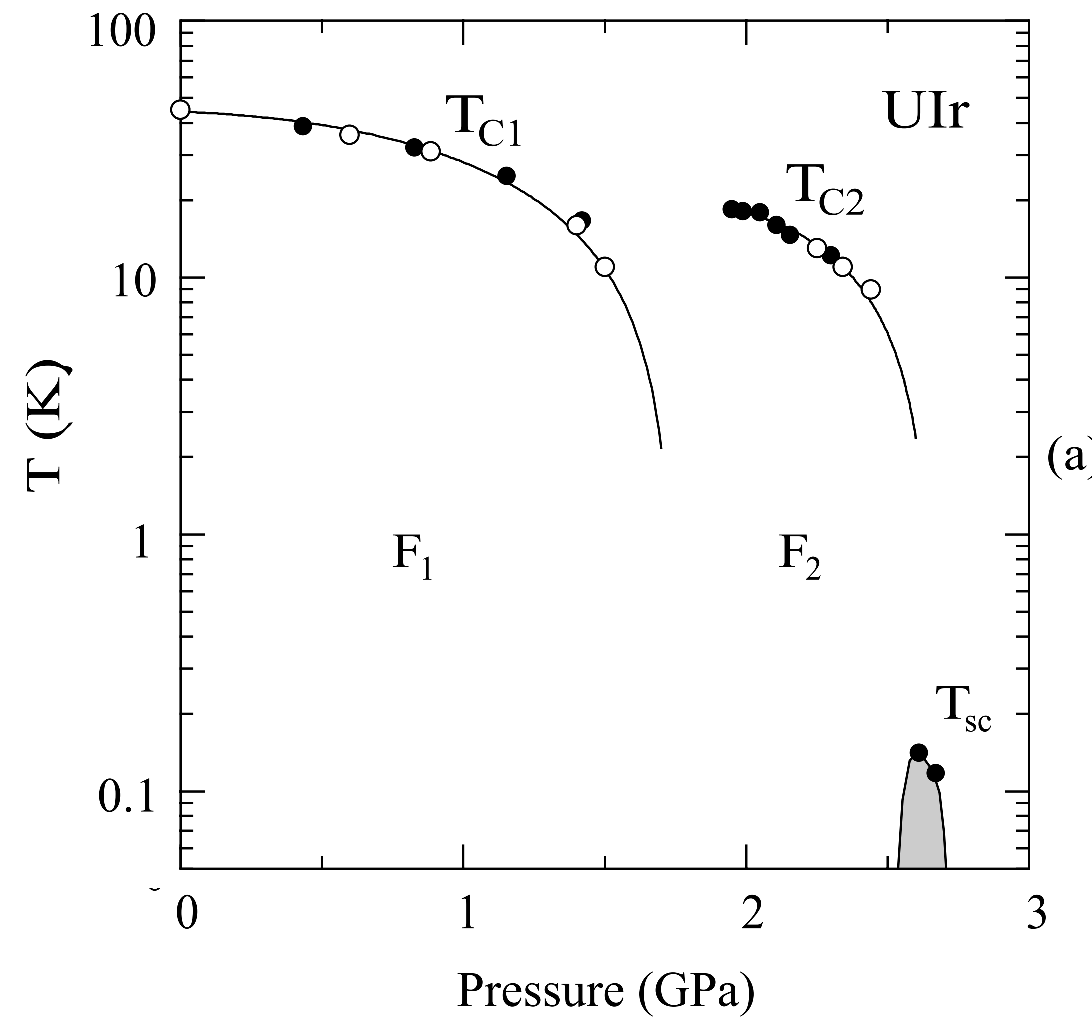
H. Gardner, et al, 2011

Magnetic fluctuations



J. A. Bert, *et al*, 2004





T Akazawa, *et al*, 2004

Free energy

Superconducting order parameter:

$$\Delta(\mathbf{q}) = U \sum_{\mathbf{k}} \left[\Psi_{\mathbf{k},\uparrow}\Psi_{-\mathbf{k}+\mathbf{q},\downarrow} - \Psi_{\mathbf{k},\downarrow}\Psi_{-\mathbf{k}+\mathbf{q},\uparrow}\right] \qquad \Delta = |\Delta| \exp^{i\Phi}$$

Magnetization:

$$\vec{M}(\mathbf{q}) = \mu_B \sum_{\mathbf{k}} \Psi^{\dagger}_{\mathbf{k},\alpha} \vec{\sigma}_{\alpha,\beta} \Psi_{\mathbf{k}+\mathbf{q},\beta}$$

$$F = \sum_{\vec{j},\hat{\nu}} -\rho_s \cos\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right) + \frac{\kappa}{2}(\hat{z} \times \hat{\nu}) \cdot \left(\mathbf{H}_{\mathrm{T}\vec{j}} + \mathbf{H}_{\mathrm{T}\vec{j}+\hat{\nu}}\right) \sin\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right)$$

Free energy

proportional to the spin-orbit coupling

$$\mathbf{H}_{\mathrm{T}} = \mathbf{H} + \frac{2U}{g\mu_B}\mathbf{M}$$

$$F = \sum_{\vec{j},\hat{\nu}} -\rho_s \cos\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right) + \frac{\kappa}{2}(\hat{z}\times\hat{\nu})\cdot\left(\mathbf{H}_{\mathrm{T}\vec{j}} + \mathbf{H}_{\mathrm{T}\vec{j}+\hat{\nu}}\right)\sin\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right)$$

$$+UM_{\vec{j}}^2 - \frac{\chi_s}{2}H^2_{\mathrm{T}\perp,\vec{j}}$$

Free energy

proportional to the spin-orbit coupling

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$$+UM_{\vec{j}}^2 - \frac{\chi_s}{2}H_{\mathrm{T}\perp,\vec{j}}^2$$

$\chi_s \xrightarrow{T\to 0}$ $\frac{1}{2}\chi_n$ x-y plane

χ_n z direction

L. P. Gor'kov and E. I. Rashba, 2001

Current and magnetization

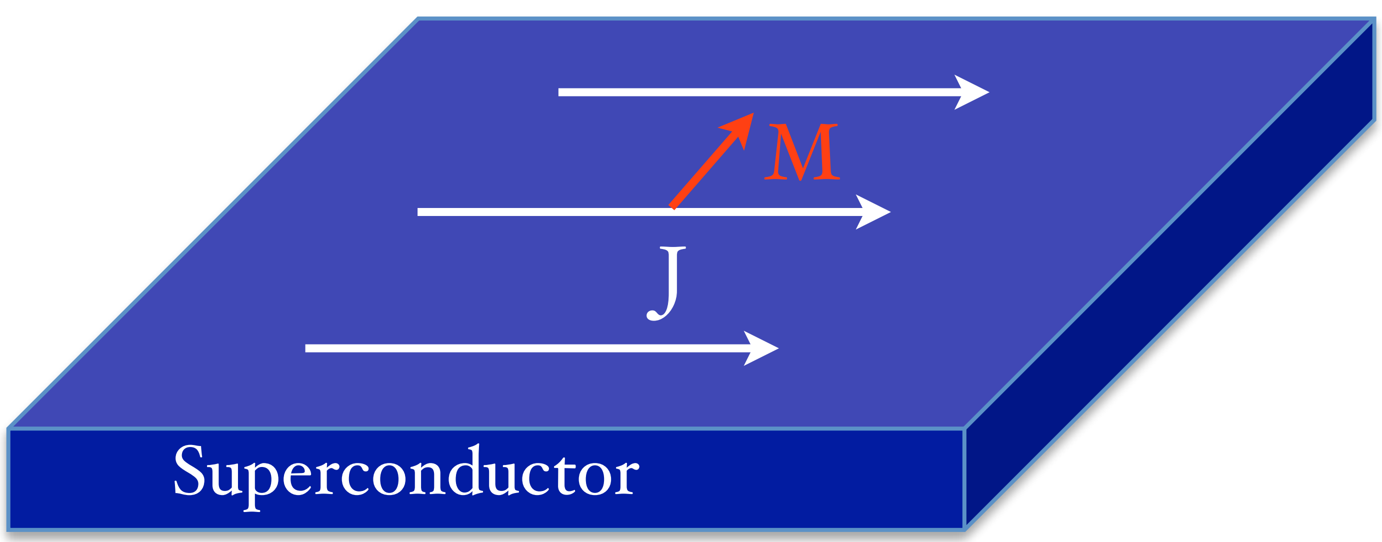
V.M. Edelstein, 1995

$$\vec{J} = -e\rho_s\left[\vec{\nabla}\Phi(\mathbf{r}) - 2e\vec{A}(\mathbf{r})\right] - e\kappa\left[\vec{H}_T \times \hat{z}\right]$$

$$\vec{M} = \frac{\kappa\chi}{\chi_s}\hat{z} \times \left[\vec{\nabla}\Phi(\mathbf{r}) - 2e\vec{A}(\mathbf{r})\right] + \chi\vec{H}_{ext}$$

$$\chi = \frac{\chi_s}{1 - \chi_s U / g^2\mu_B^2}$$

The superconducting current carries magnetization



Current and magnetization

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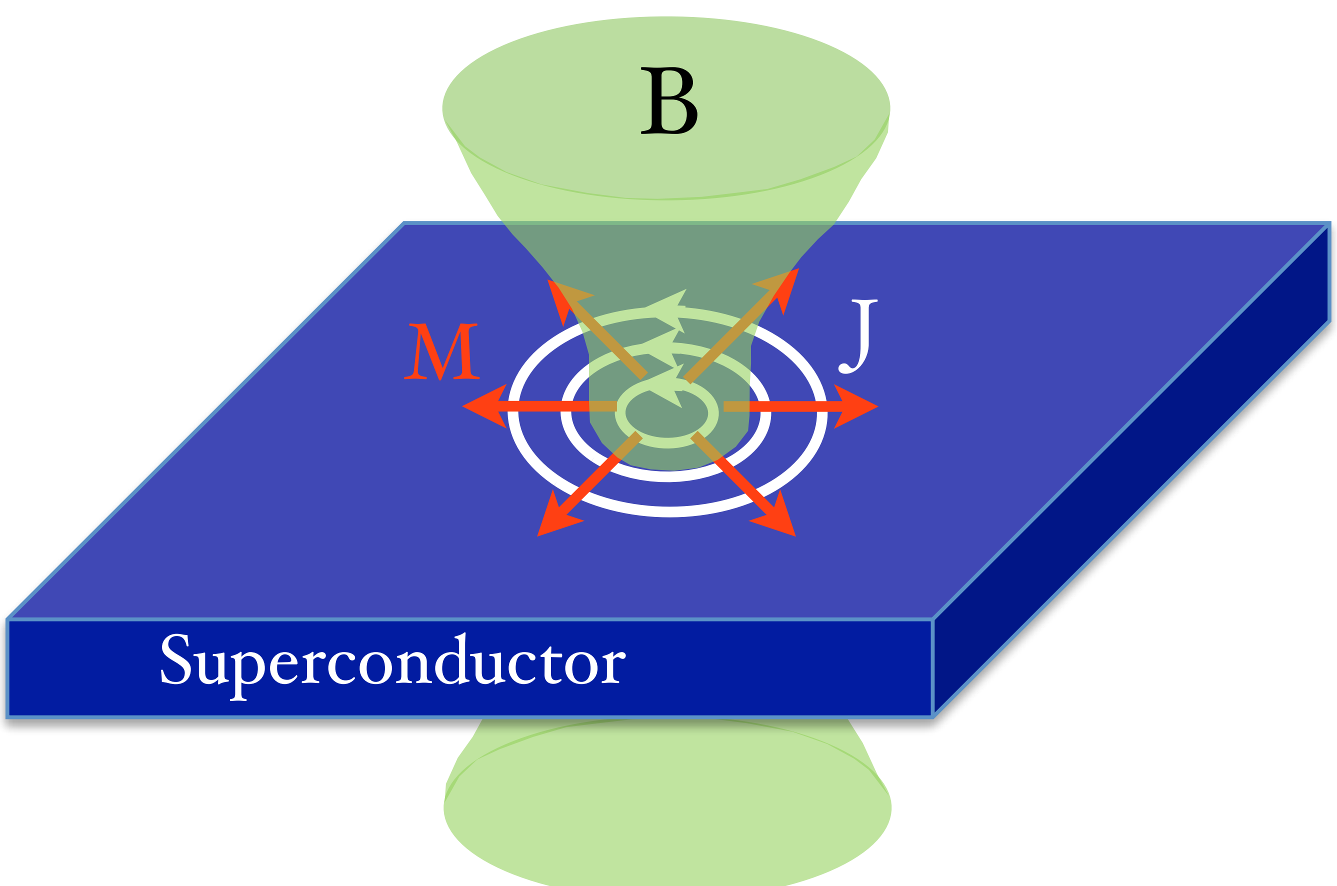

S.-K. Yip, 2005

M. K. Kashyap and D. F. Agterberg, 2013

Free energy

$$F = \sum_{\vec{j},\hat{\nu}} -\rho_s \cos\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right) + \frac{\kappa}{2}(\hat{z} \times \hat{\nu}) \cdot \left(\mathbf{H}_{\mathrm{T}\vec{j}} + \mathbf{H}_{\mathrm{T}\vec{j}+\hat{\nu}}\right) \sin\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right)$$

$$+UM_{\vec{j}}^2 - \frac{\chi_s}{2} H_{\mathrm{T}\perp,\vec{j}}^2$$

A. Steinbok and KM, 2016

Free energy

$$F = -\sum_{\vec{j},\hat{\nu}} \rho_s \cos\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right)$$

$$-\frac{\zeta}{4}\sum_{\vec{j},\hat{\nu}}\left[\sin\left(\Phi_{\vec{j}+\hat{\nu}} - \Phi_{\vec{j}}\right) + \sin\left(\Phi_{\vec{j}} - \Phi_{\vec{j}-\hat{\nu}}\right)\right]^2$$

$$\zeta = \frac{U\kappa^2/(g\mu_B)^2}{1 - 2\chi_\perp U/g^2\mu_B^2}$$

A. Steinbok and KM, 2016

Free energy

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$$\zeta = \frac{U\kappa^2/(g\mu_B)^2}{1 - 2\chi_\perp U/g^2\mu_B^2}$$

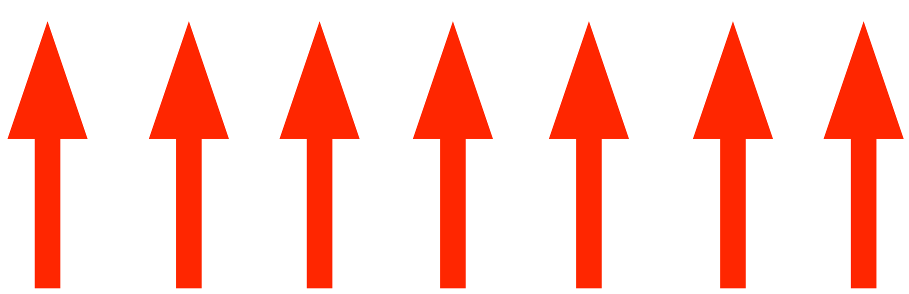
$$\vec{S}_{\vec{i}} = \begin{pmatrix} \cos\Phi_{\vec{i}} \\ \sin\Phi_{\vec{i}} \end{pmatrix}$$

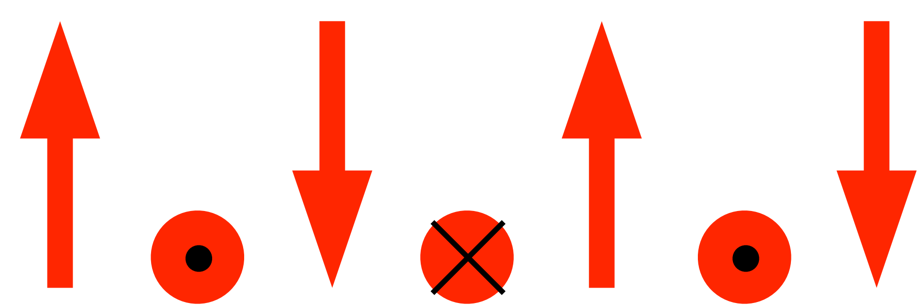
A. Steinbok and KM, 2016

Free energy

$$F = -\rho_s \sum_{\vec{i},\hat{\mu}} \left\{ \vec{S}_i \cdot \vec{S}_{i+\hat{\mu}} + \frac{\zeta}{\rho_s} \left[\vec{S}_{\vec{i}+\hat{\mu}} \times \vec{S}_{\vec{i}} + \vec{S}_{\vec{i}} \times \vec{S}_{\vec{i}-\hat{\mu}} \right]^2 \right\}$$

$$\vec{S}_{\vec{i}} = \begin{pmatrix} \cos \Phi_{\vec{i}} \\ \sin \Phi_{\vec{i}} \end{pmatrix}$$

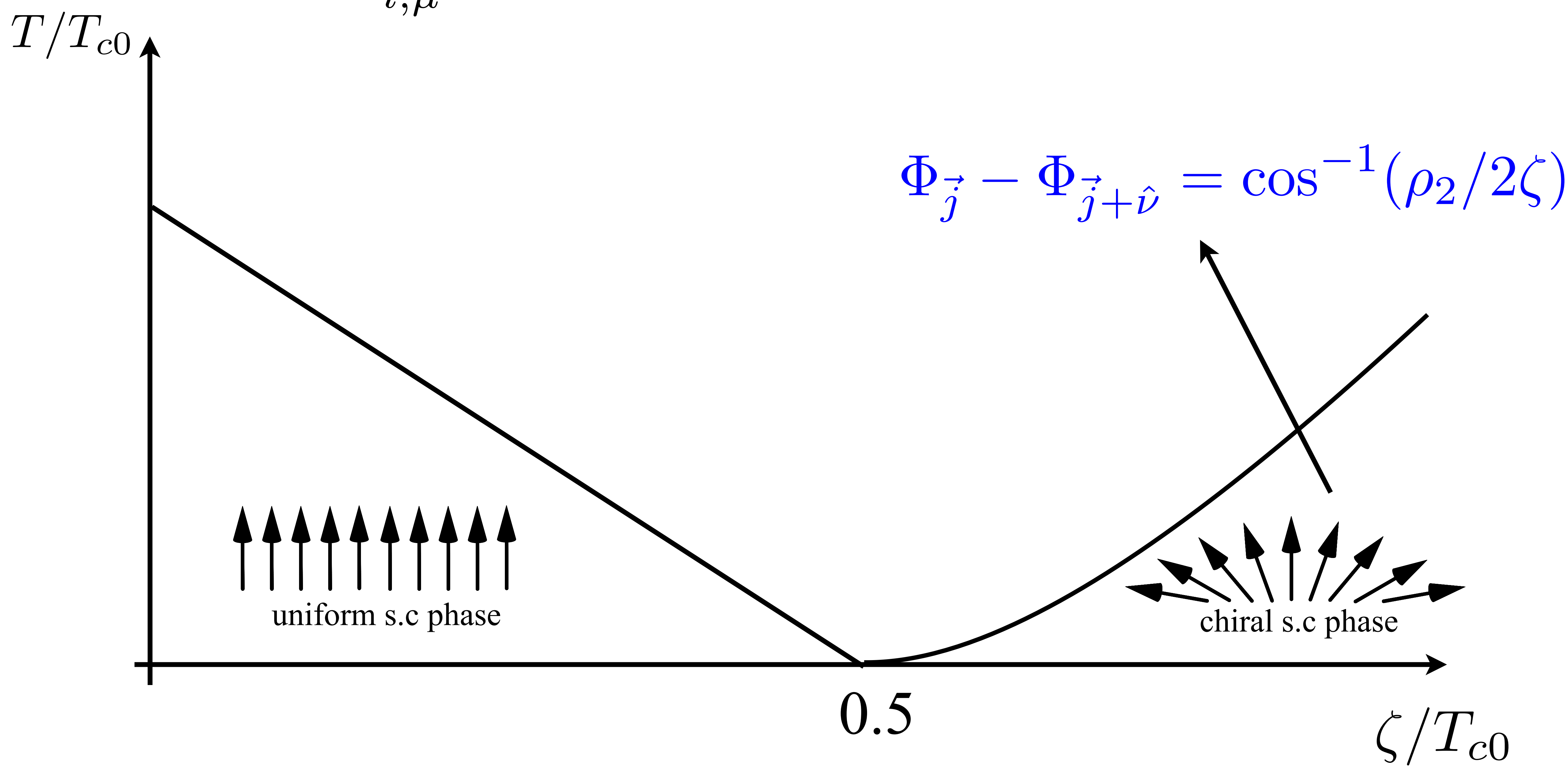




A. Steinbok and KM, 2016

Phase diagram

$$F = -\rho_s \sum_{\vec{i},\hat{\mu}} \left\{ \vec{S}_i \cdot \vec{S}_{i+\hat{\mu}} + \frac{\zeta}{\rho_s} \left[\vec{S}_{\vec{i}+\hat{\mu}} \times \vec{S}_{\vec{i}} + \vec{S}_{\vec{i}} \times \vec{S}_{\vec{i}-\hat{\mu}} \right]^2 \right\}$$



Phase diagram

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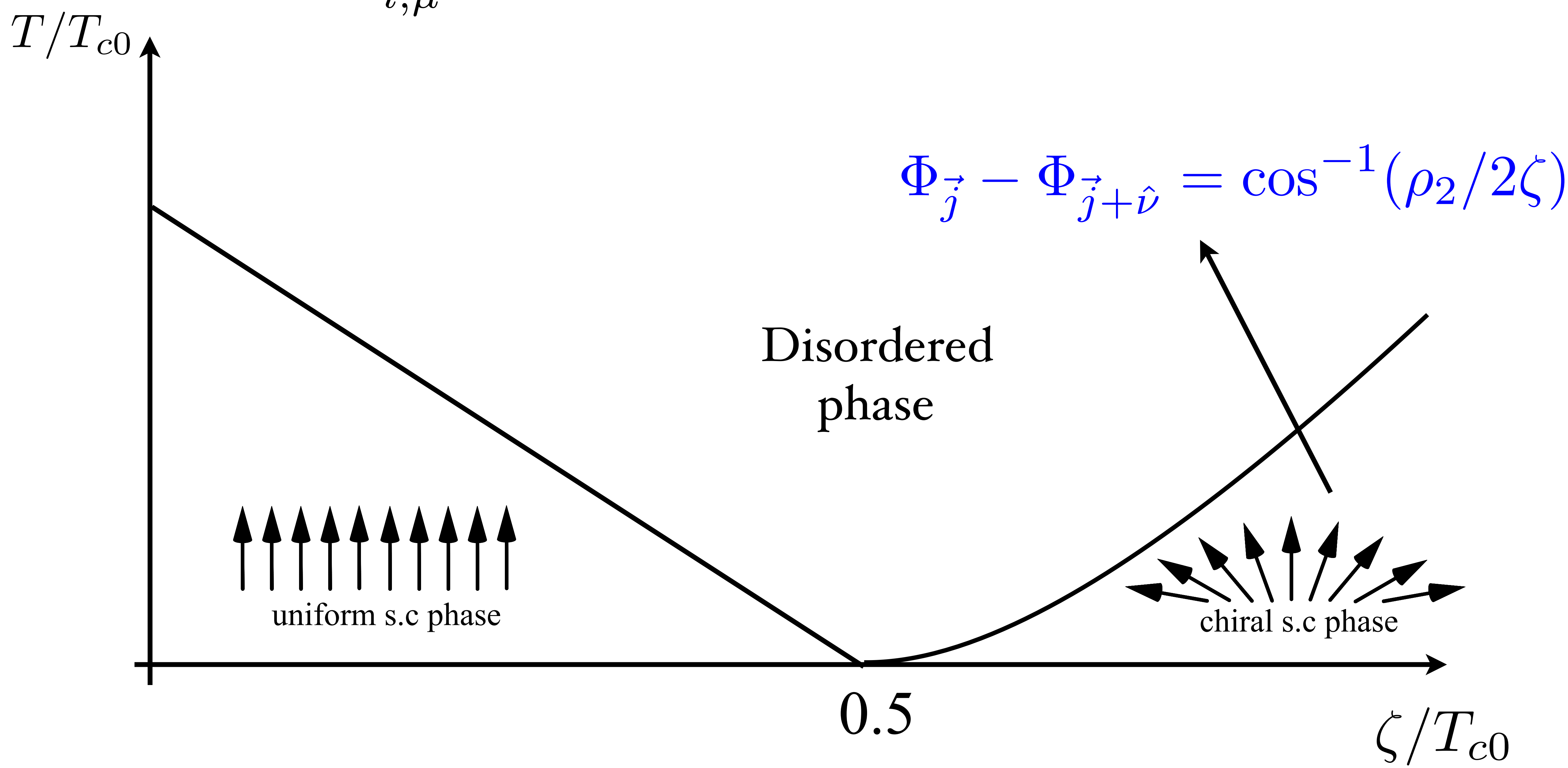
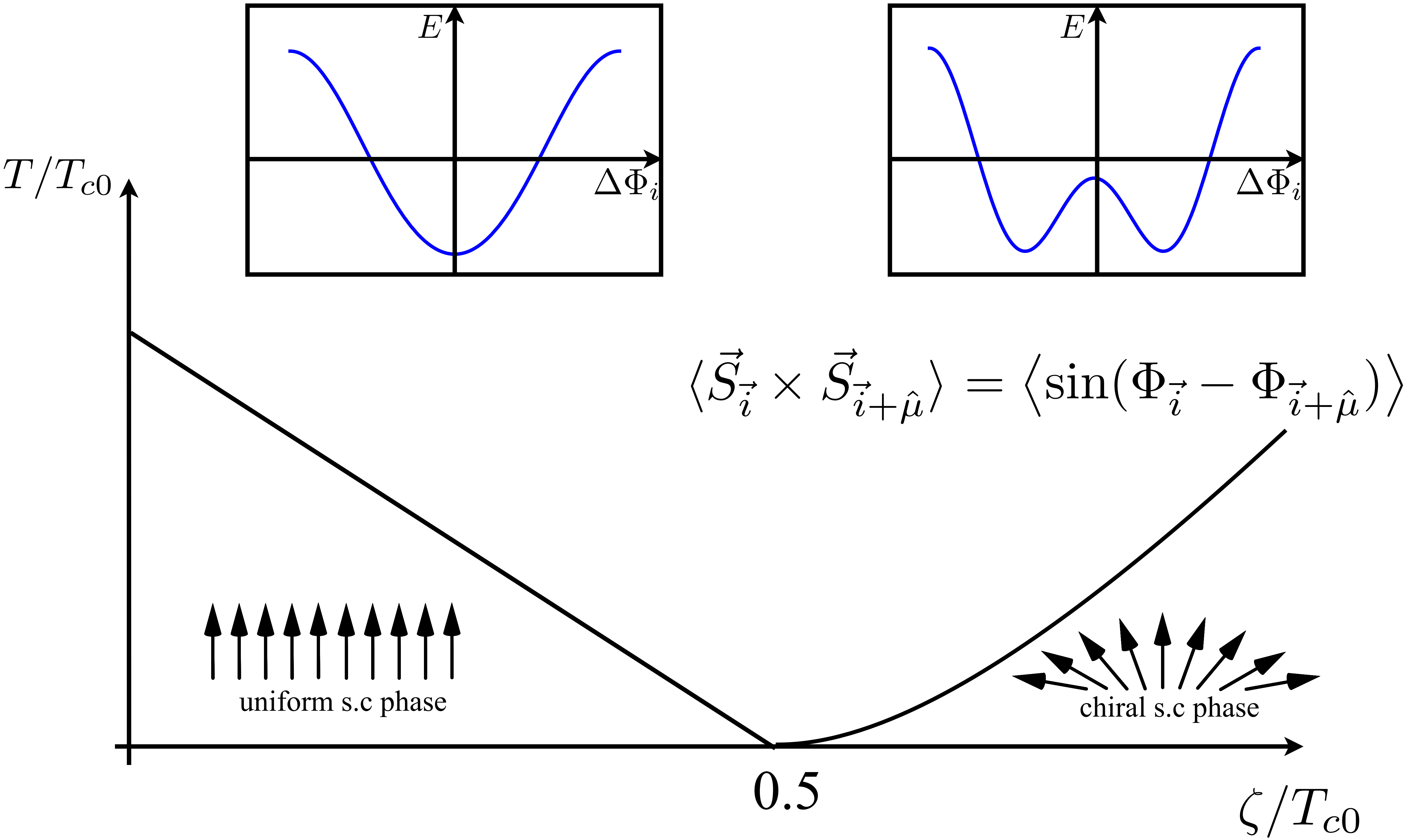


Phase diagram



Magnetic field

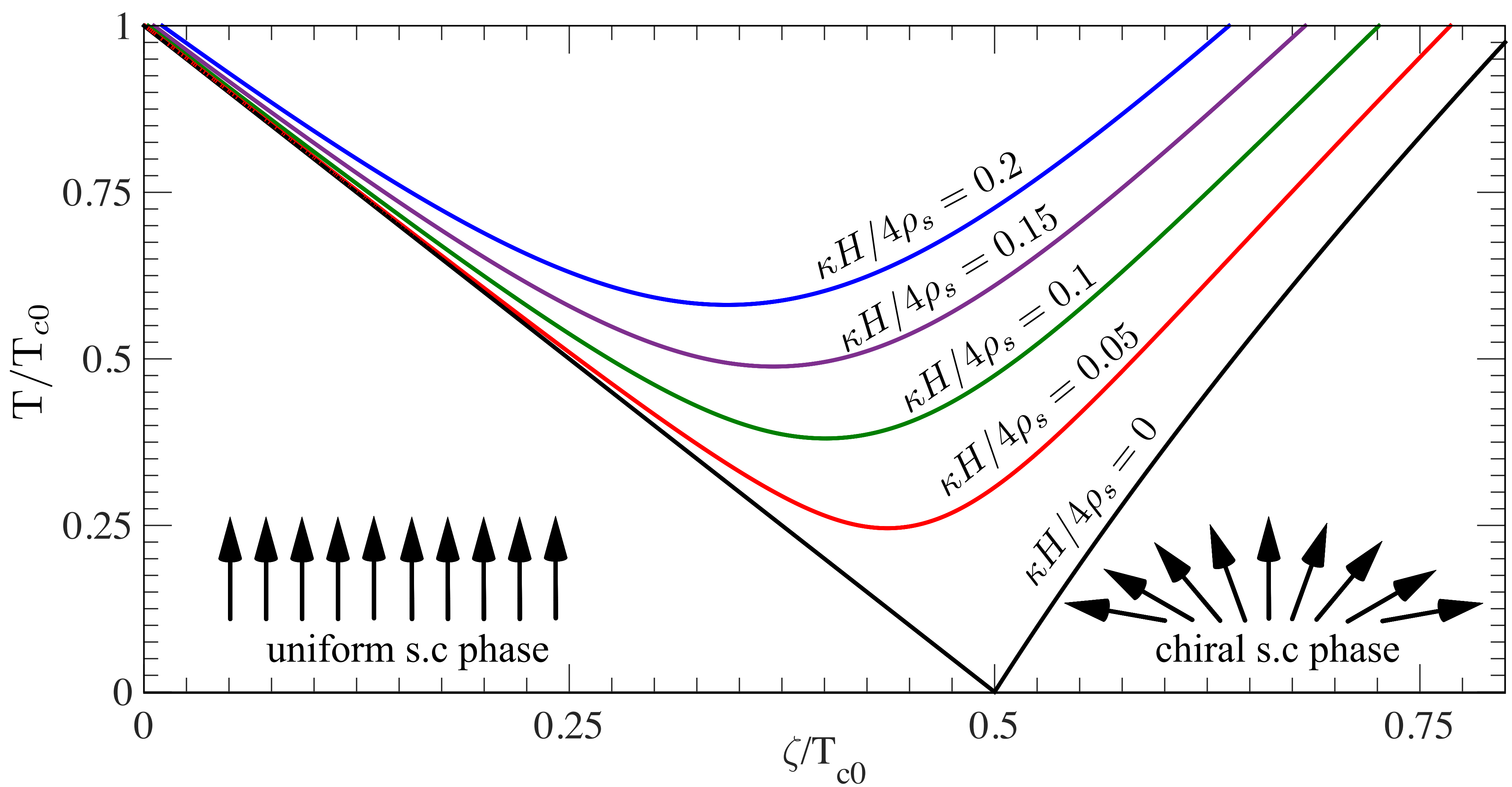
$$F = -\rho_s \sum_{\vec{i},\hat{\mu}} \left\{ \vec{S}_i \cdot \vec{S}_{i+\hat{\mu}} + \frac{\zeta}{\rho_s} \left[\vec{S}_{\vec{i}+\hat{\mu}} \times \vec{S}_{\vec{i}} + \vec{S}_{\vec{i}} \times \vec{S}_{\vec{i}-\hat{\mu}} \right]^2 \right\}$$

$$+ \frac{\kappa}{4} \sum_{\vec{i},\hat{\mu}} \hat{z} \cdot \left(\hat{\mu} \times \vec{H}_{ext} \right) \vec{S}_{\vec{i}+\hat{\mu}} \times \vec{S}_{\vec{i}}$$

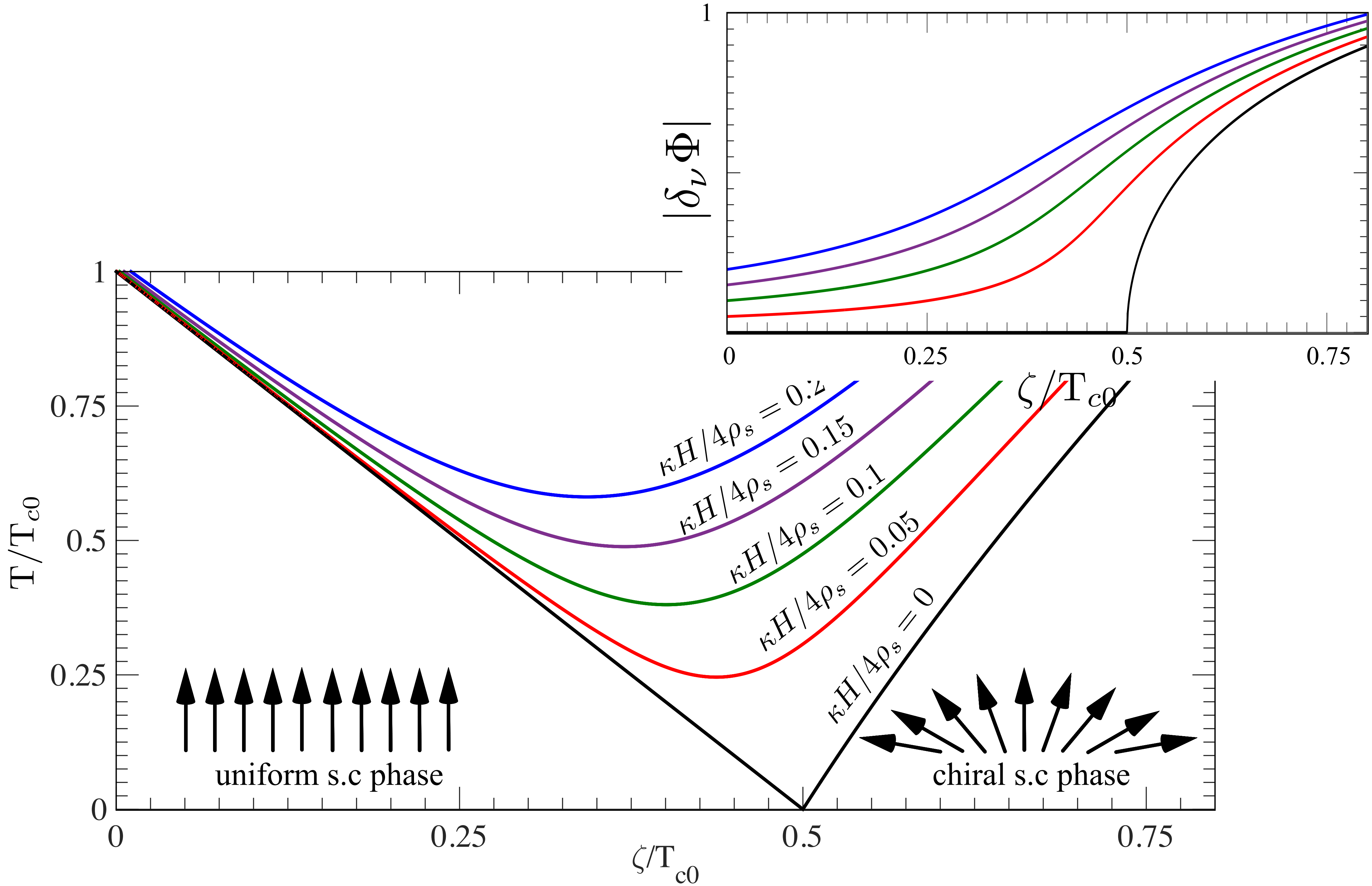
$$\rho_s \to \sqrt{\rho_s^2 + (\kappa H)^2/16}$$

Helical phase for all values of ζ

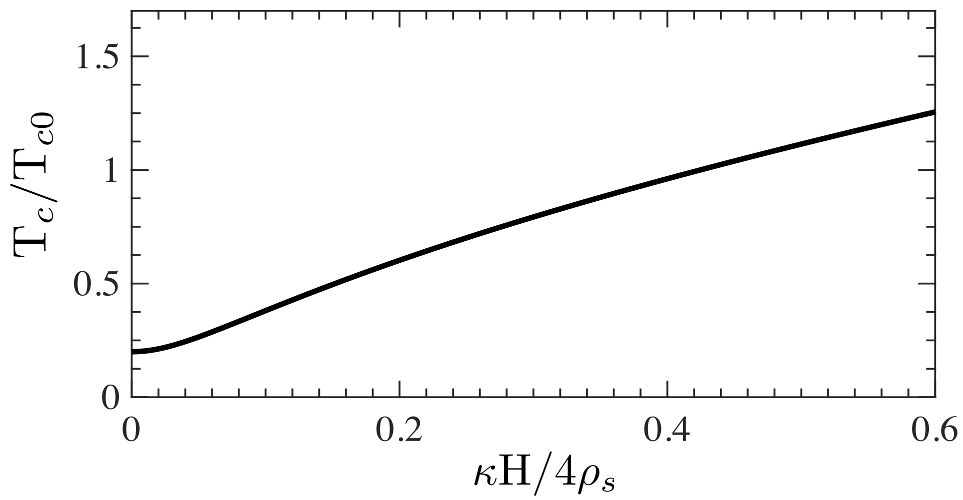
Magnetic field

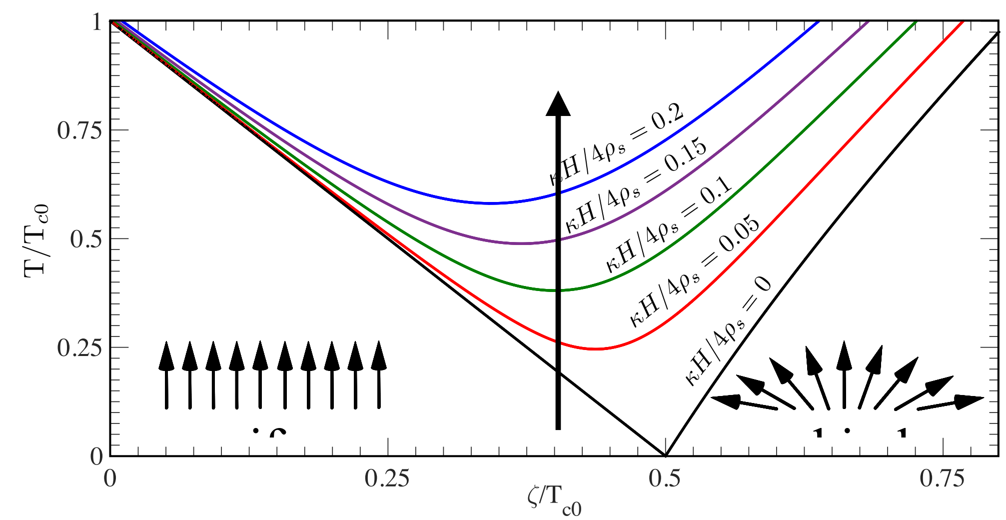


Magnetic field

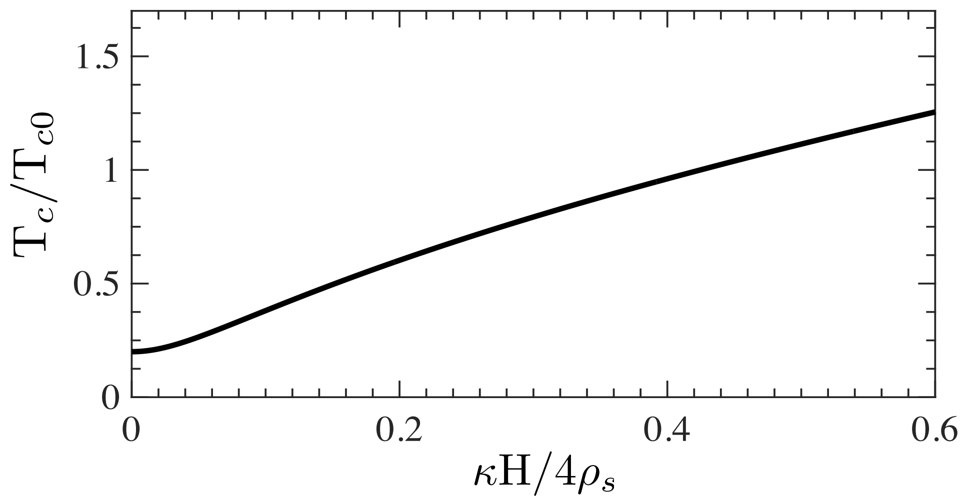


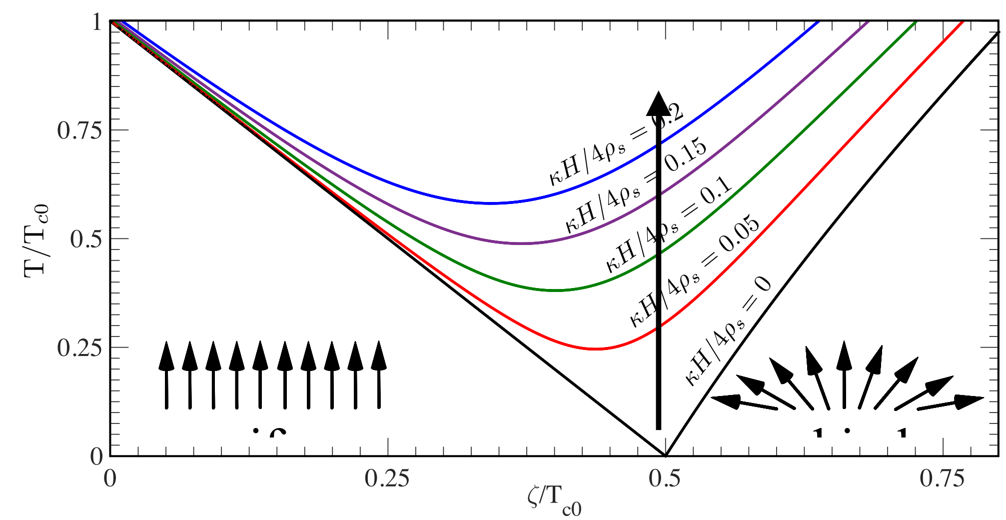
Magnetic field

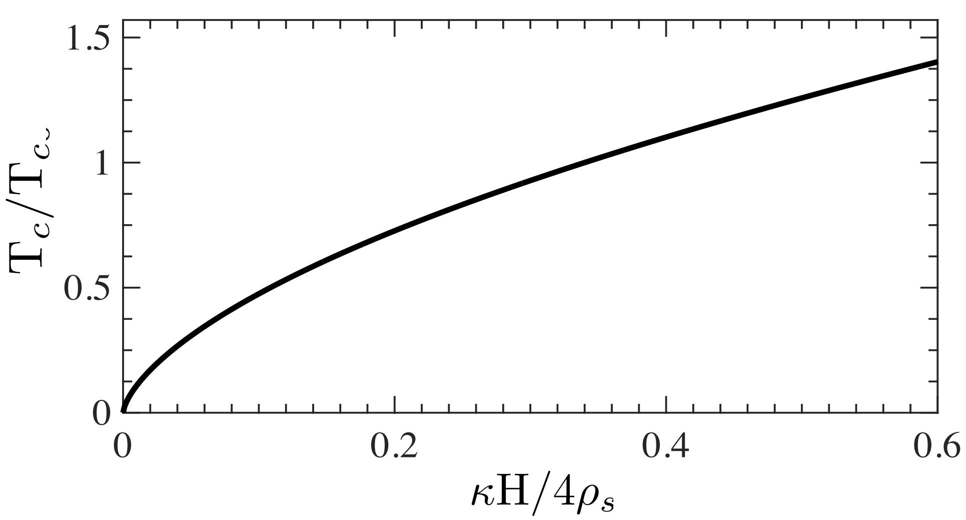




Magnetic field







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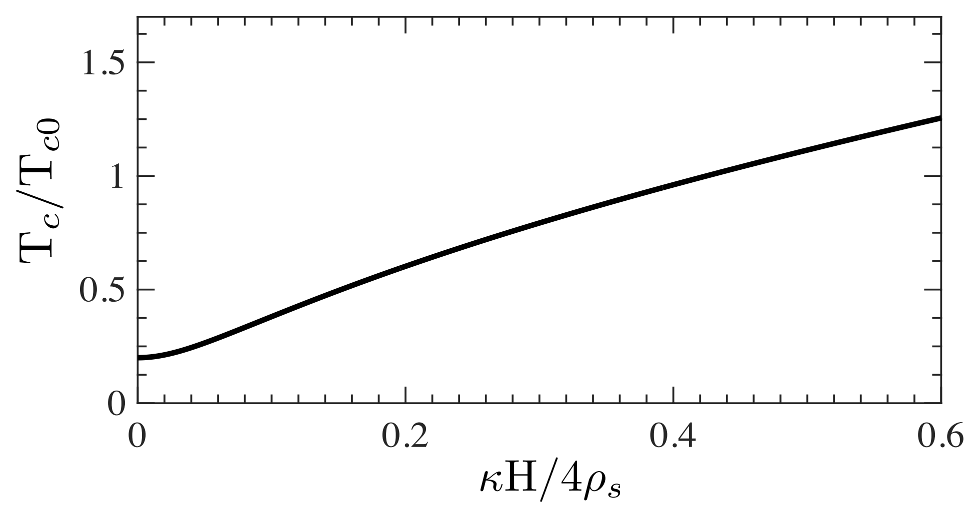
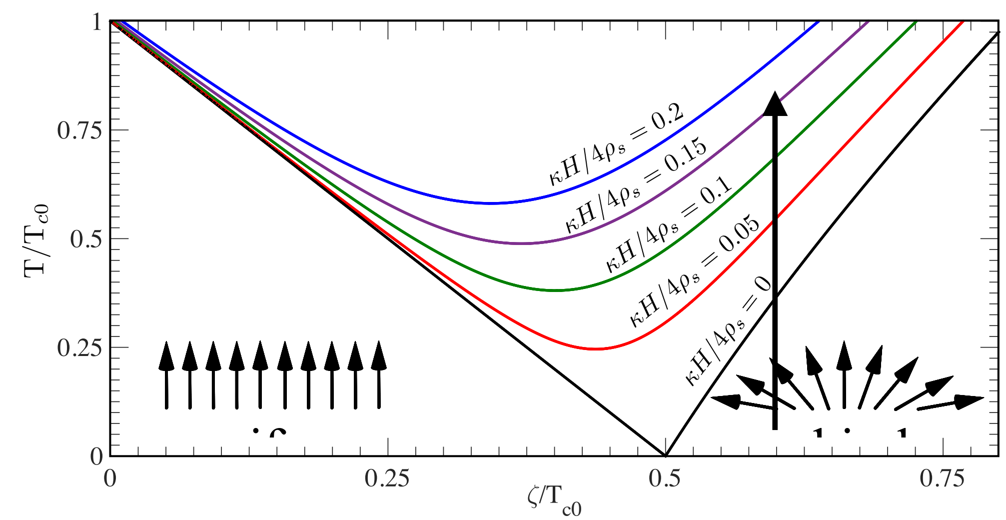
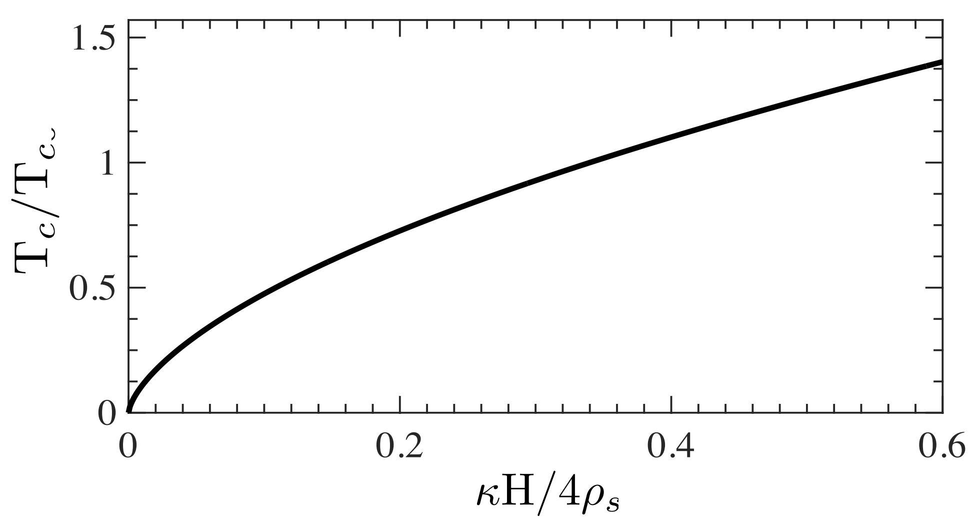
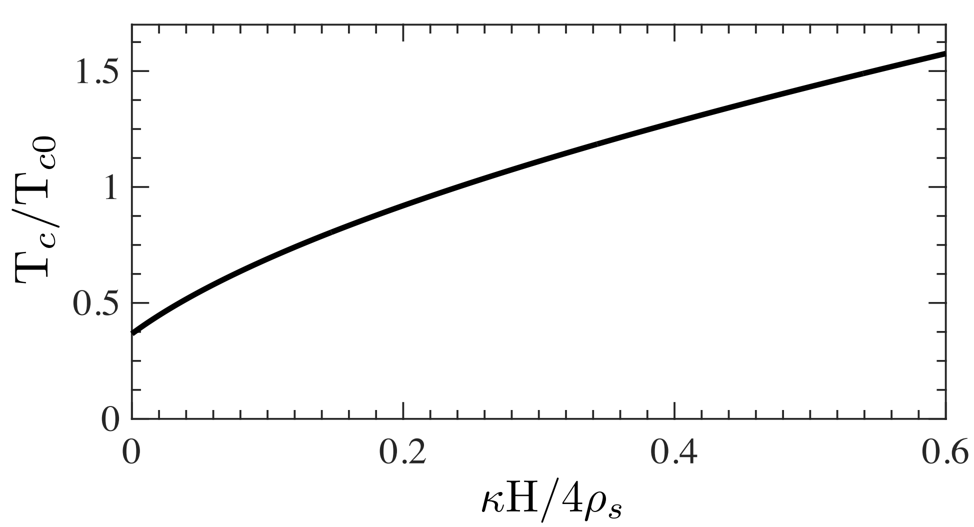
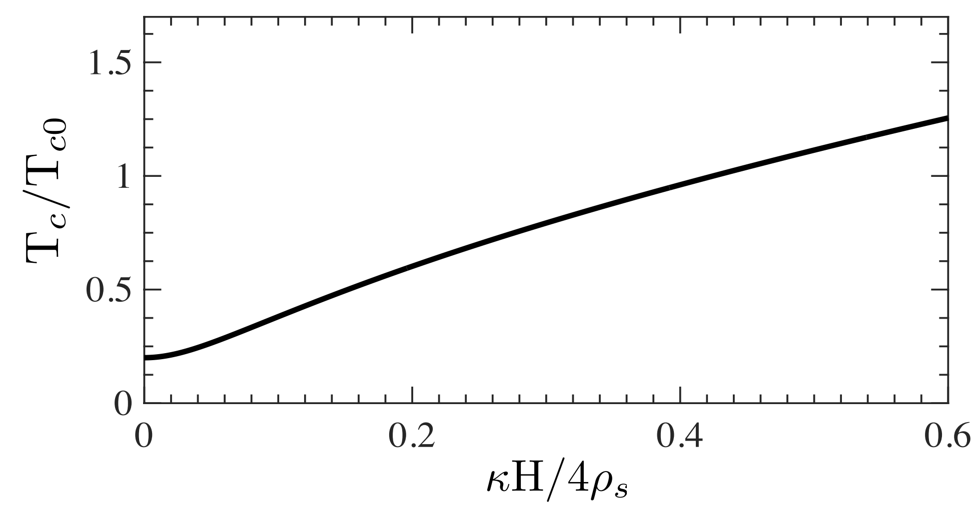


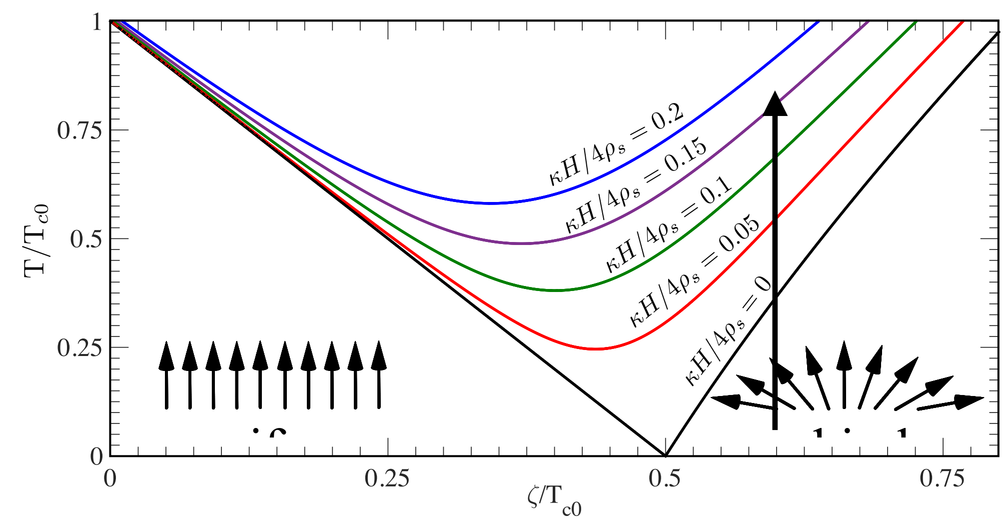


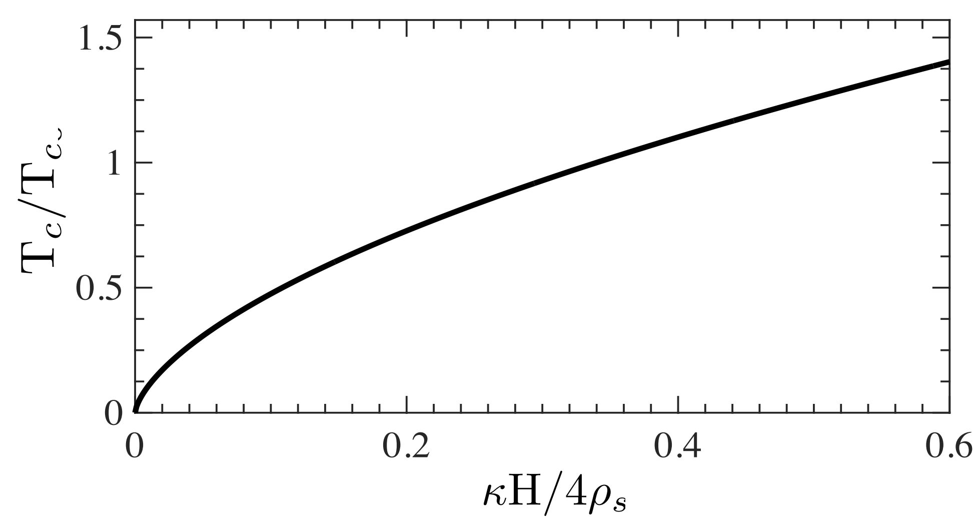


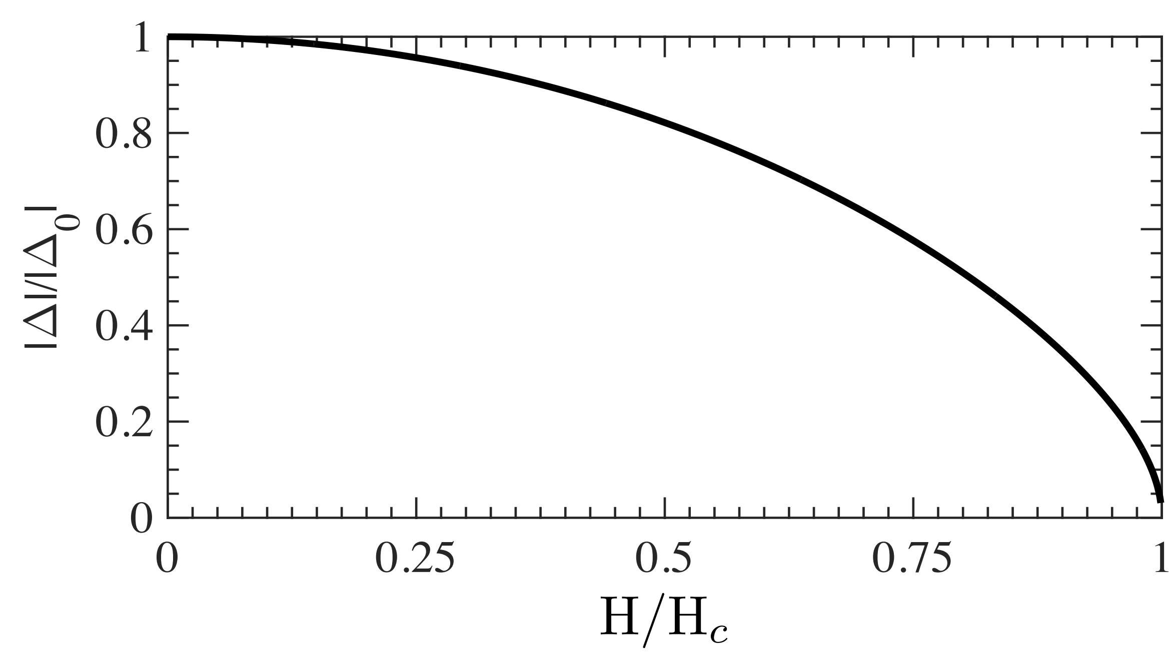


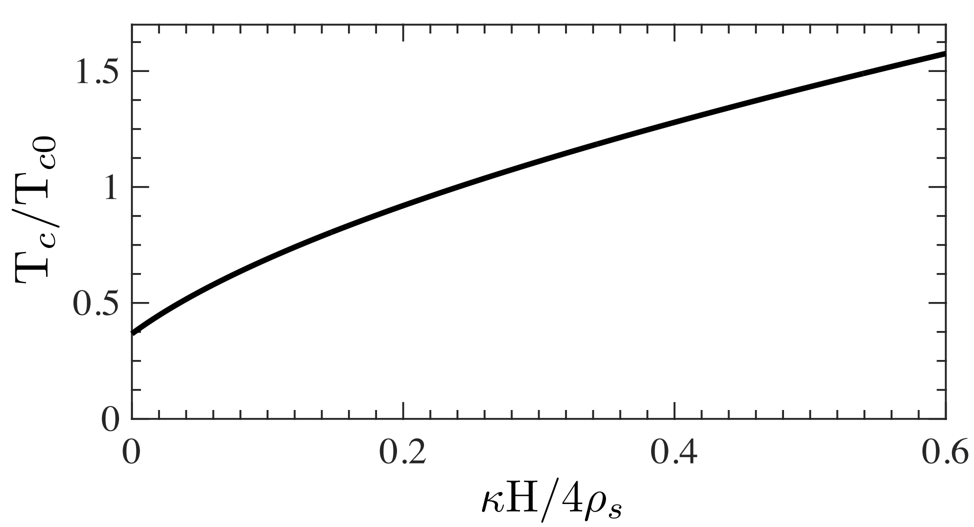
Magnetic field











Ring geometry

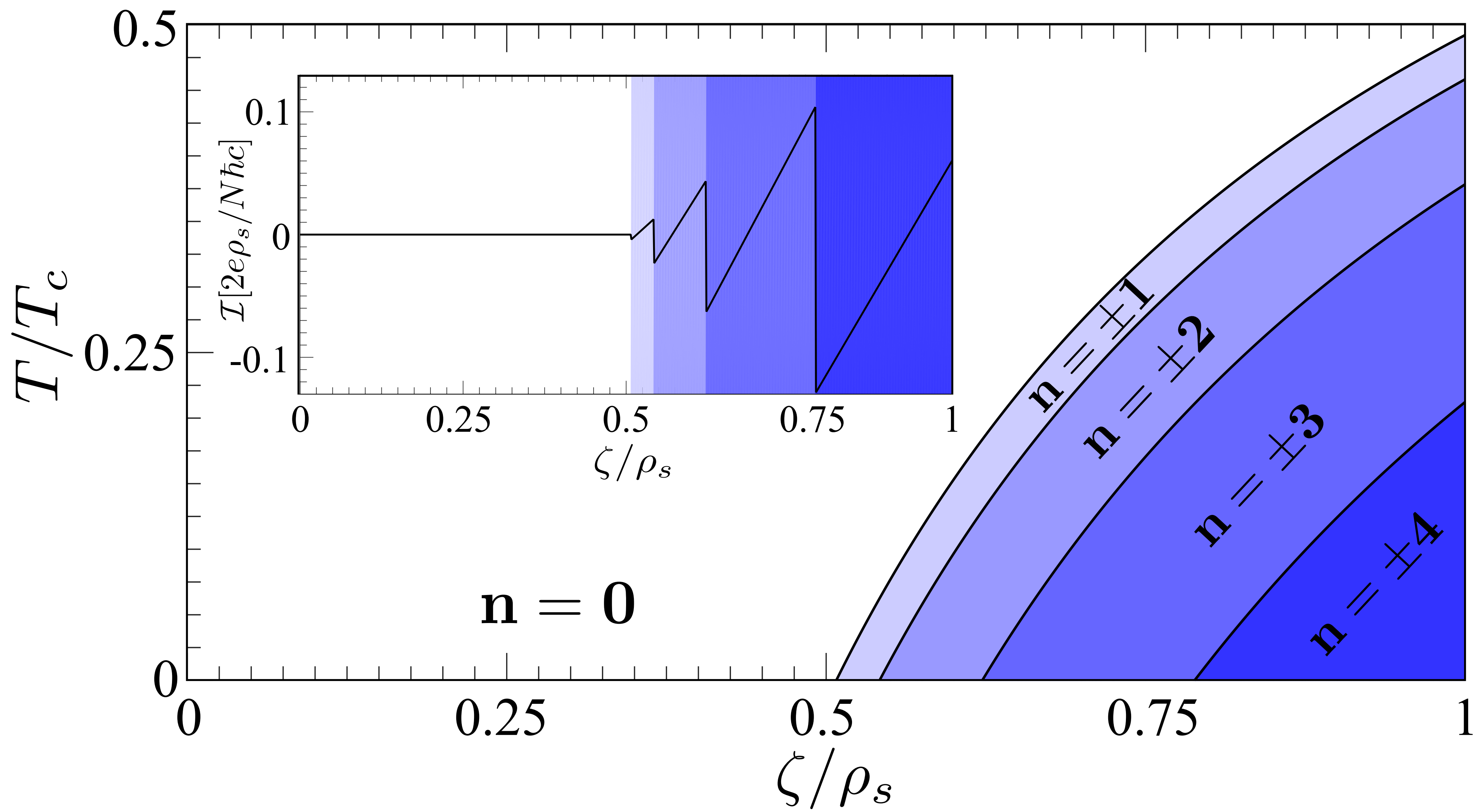
$$\Phi_{\vec{j}} \;=\; \Phi_{\vec{j}+N\hat{x}} + 2\pi n$$

$$\Phi_{\vec{j}+\hat{x}} - \Phi_{\vec{j}} = 2\pi n/N$$

$$F_{\rm ring} = -\rho_s \cos\left(\frac{2\pi n}{N}\right) - \zeta \sin^2\left(\frac{2\pi n}{N}\right)$$

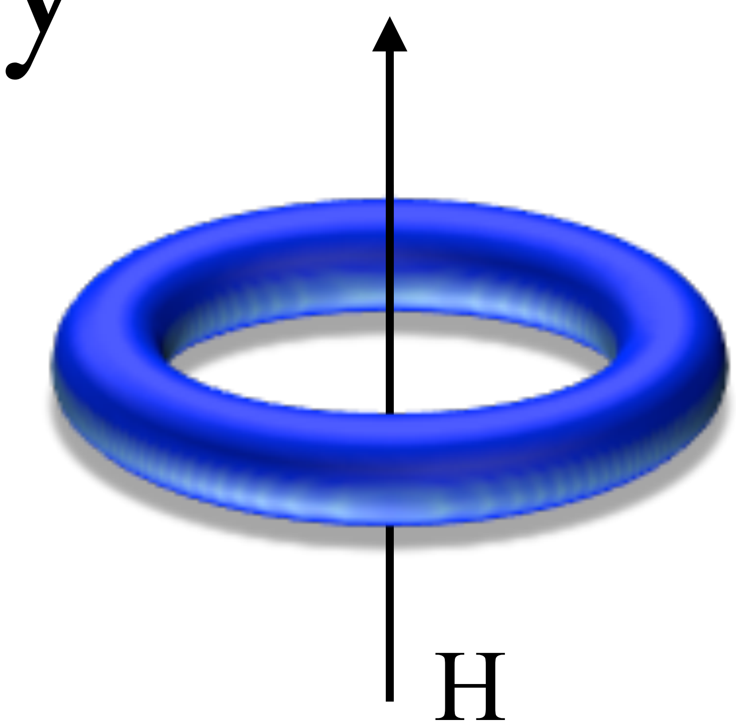
Ring geometry

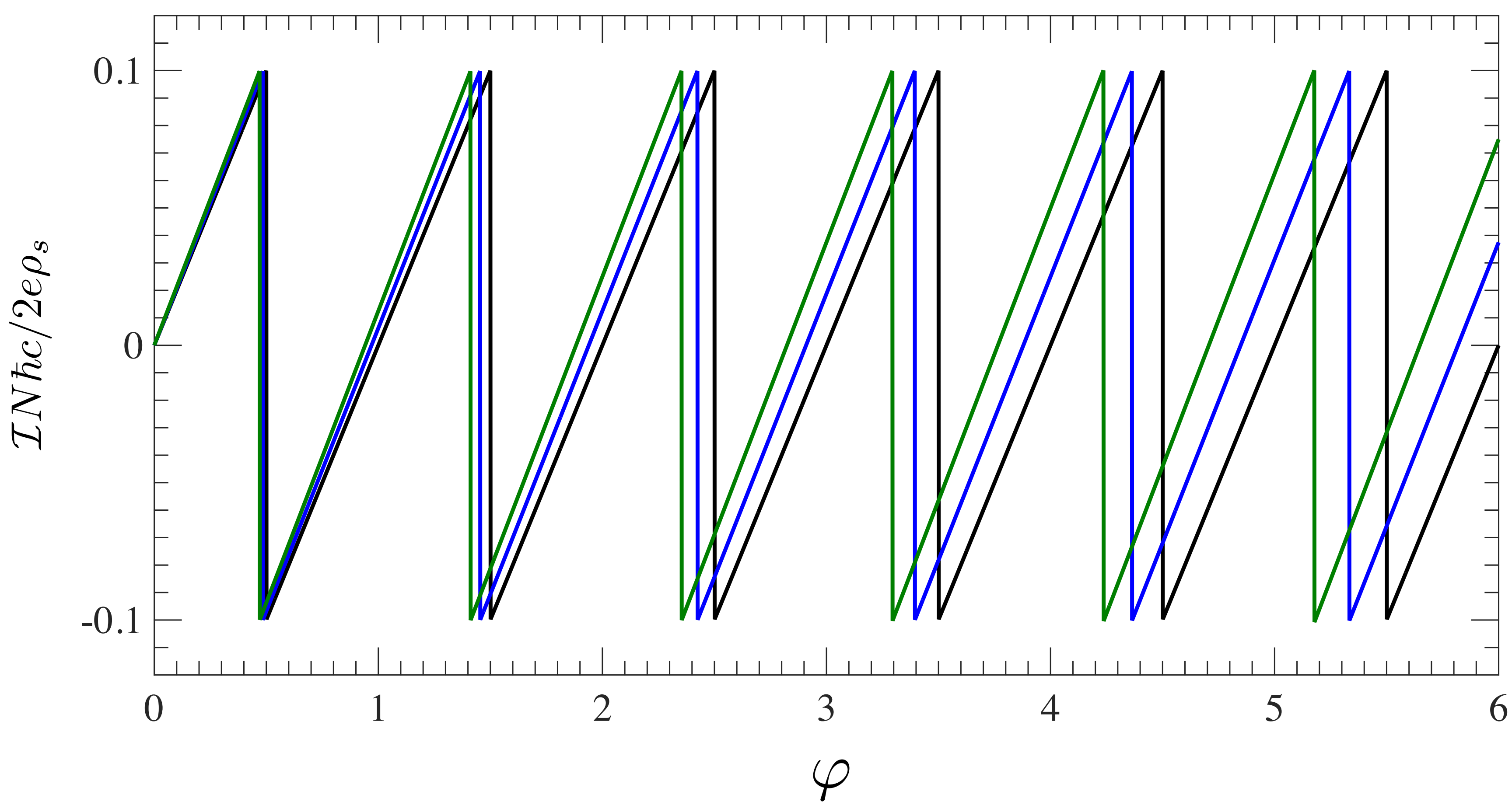
$$\Phi_{\vec{j}} = \Phi_{\vec{j}+N\hat{x}} + 2\pi n$$



Ring geometry

$$\Phi_{\vec{j}} \;=\; \Phi_{\vec{j}+N\hat{x}} + 2\pi n$$





Ring geometry

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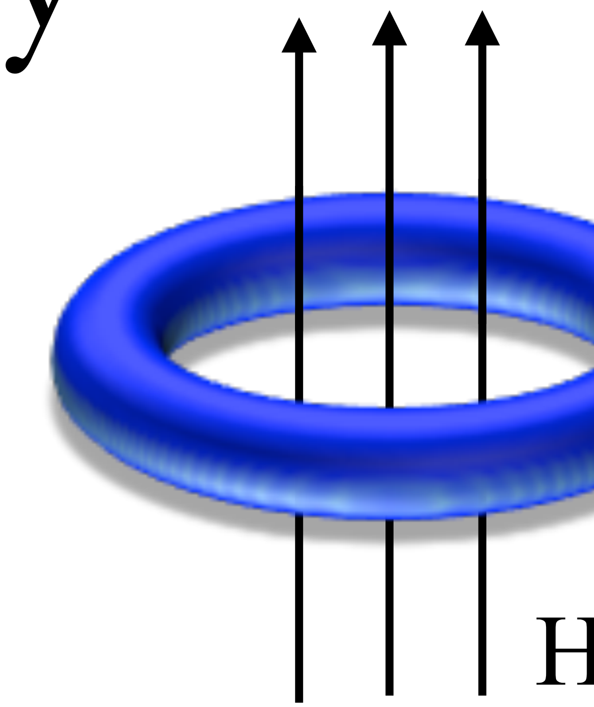
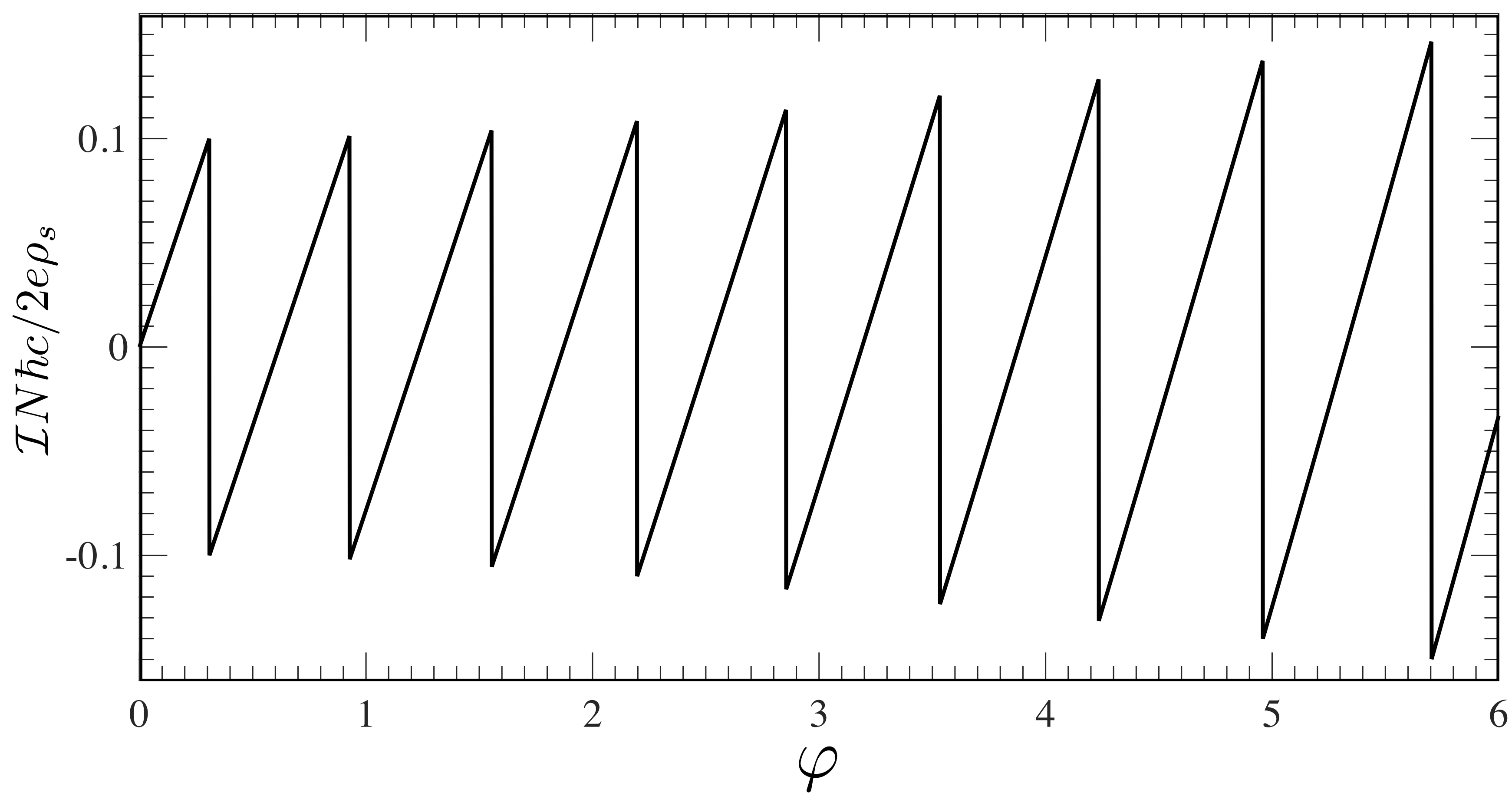
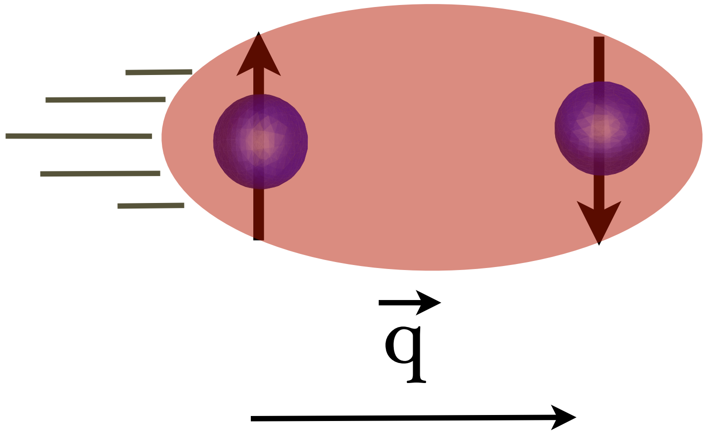
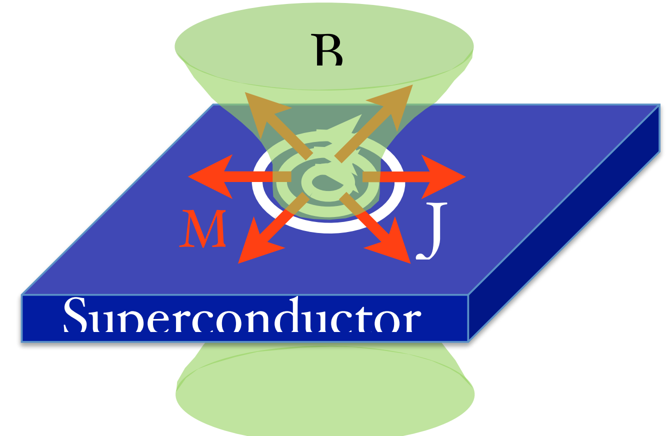






Stable finite momentum pairing

Peculiar s.c phase-magnetization relation



superconductivity

spin - orbit