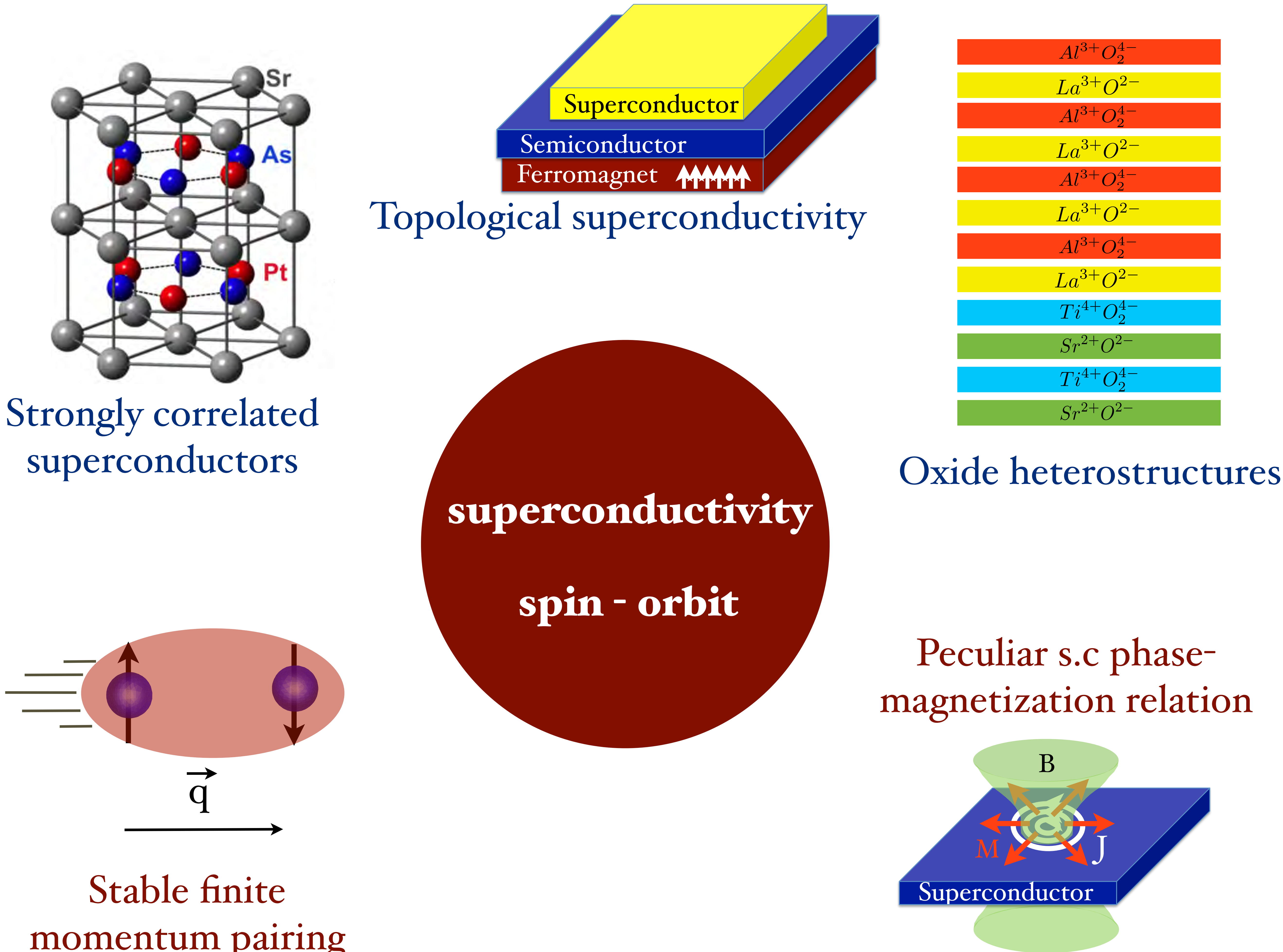
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Superconductivity in the presence of spin-orbit coupling - old dog, new tricks

Karen Michaeli



Sr
As
Pt
Strongly correlated superconductors
Superconductor
Semiconductor
Ferromagnet
Topological superconductivity
$Al^{3+}O_2^{4-}$
$La^{3+}O^{2-}$
$Al^{3+}O_2^{4-}$
$La^{3+}O^{2-}$
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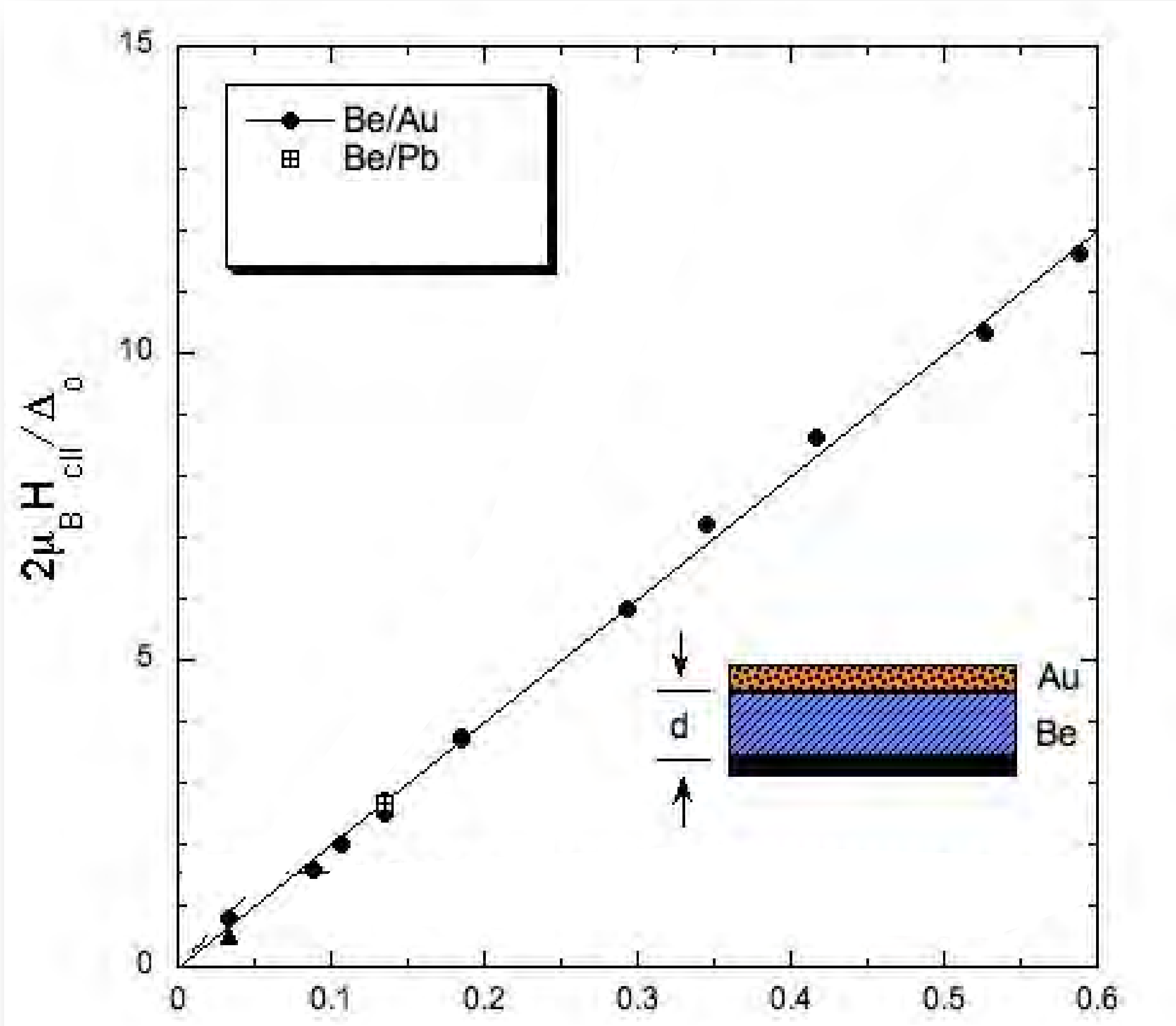
$Ti^{4+}O_2^{4-}$
$Sr^{2+}O^{2-}$
$Ti^{4+}O_2^{4-}$
$Sr^{2+}O^{2-}$
Oxide heterostructures
superconductivity
spin - orbit
$\vec{q}$
Stable finite momentum pairing
Peculiar s.c phase-magnetization relation
B
M
J
Superconductor

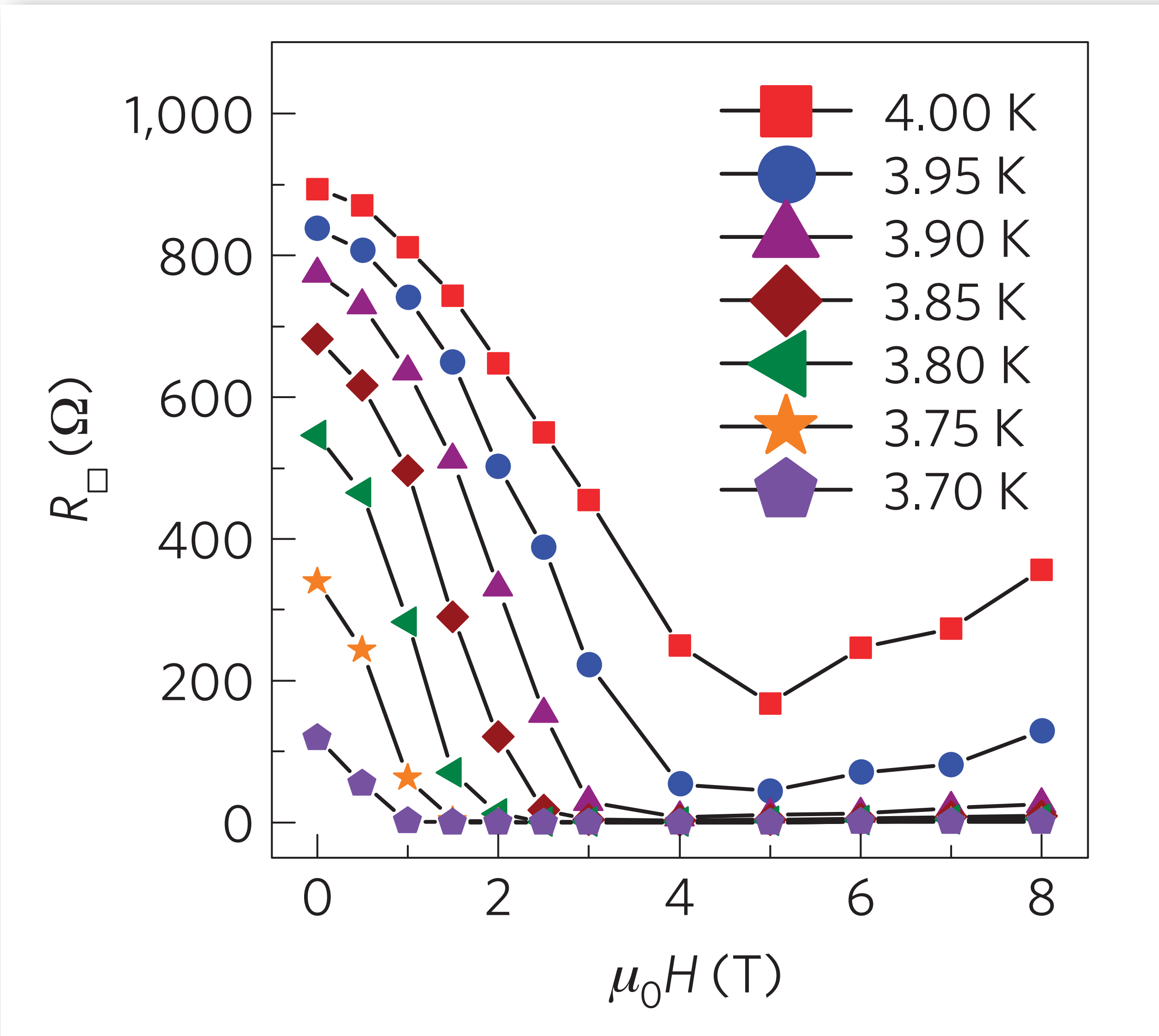
Critical magnetic field

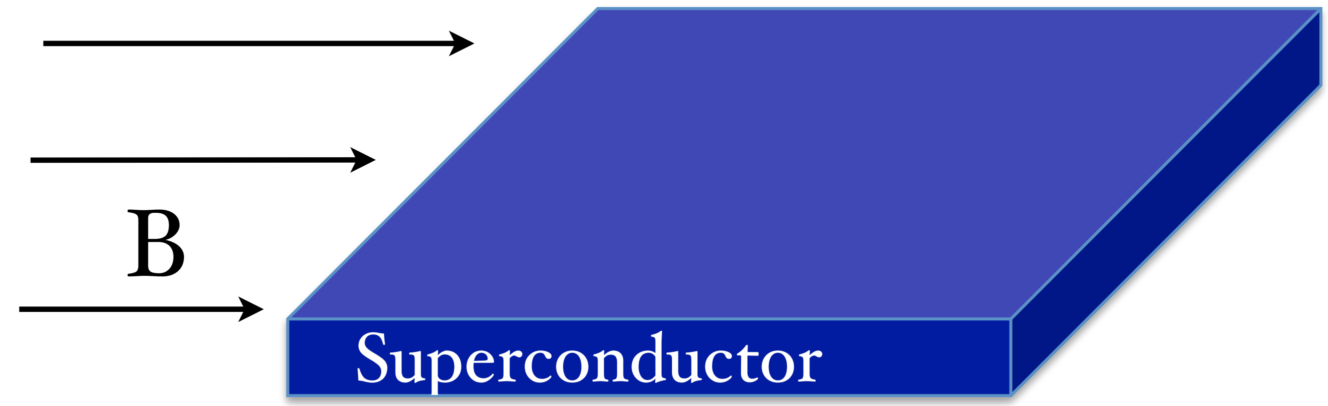
X. S. Wu, *et al*, 2005

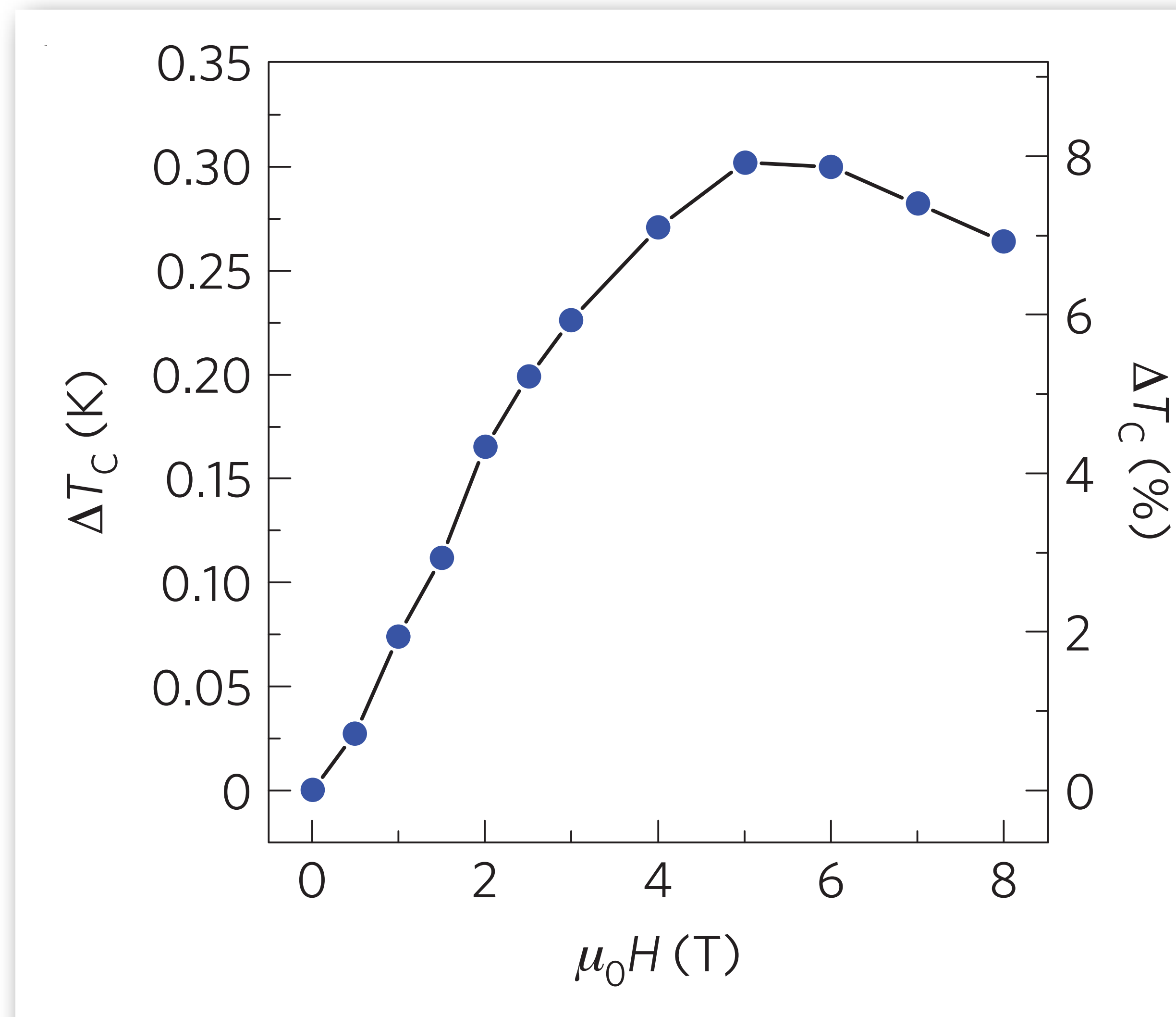


1/d (mm^{-1}) ~ strength of spin orbit coupling

Enhancement of T_c





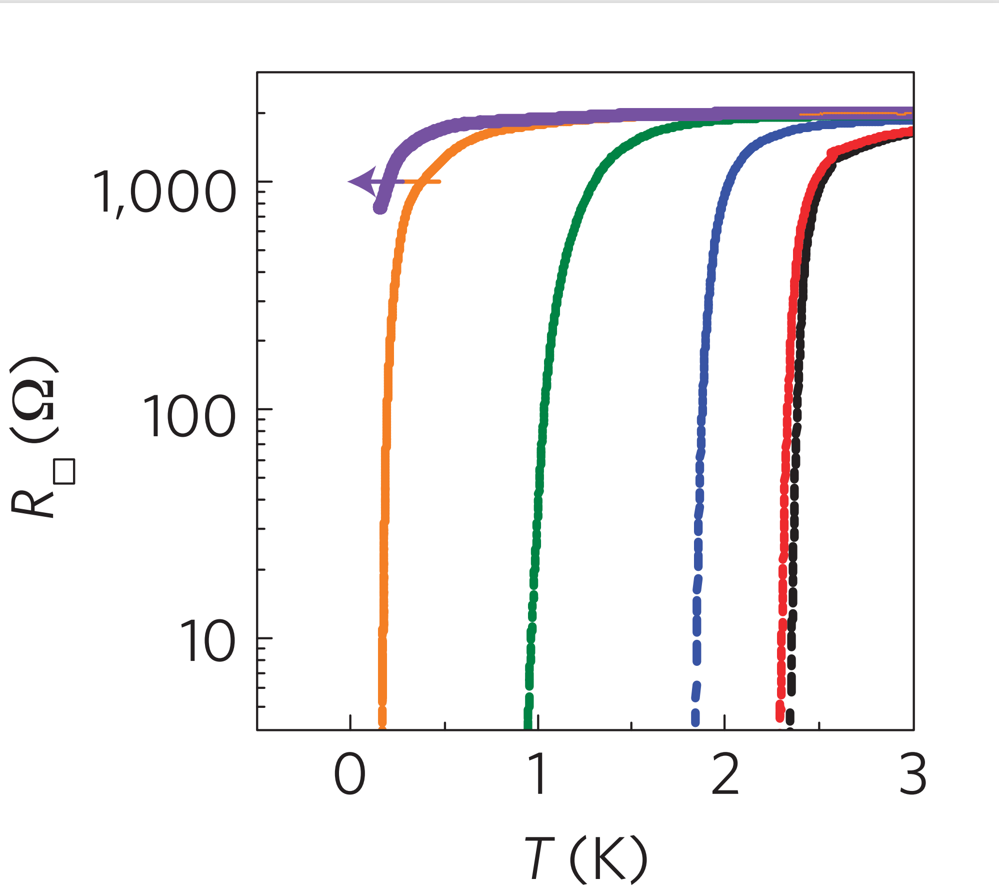


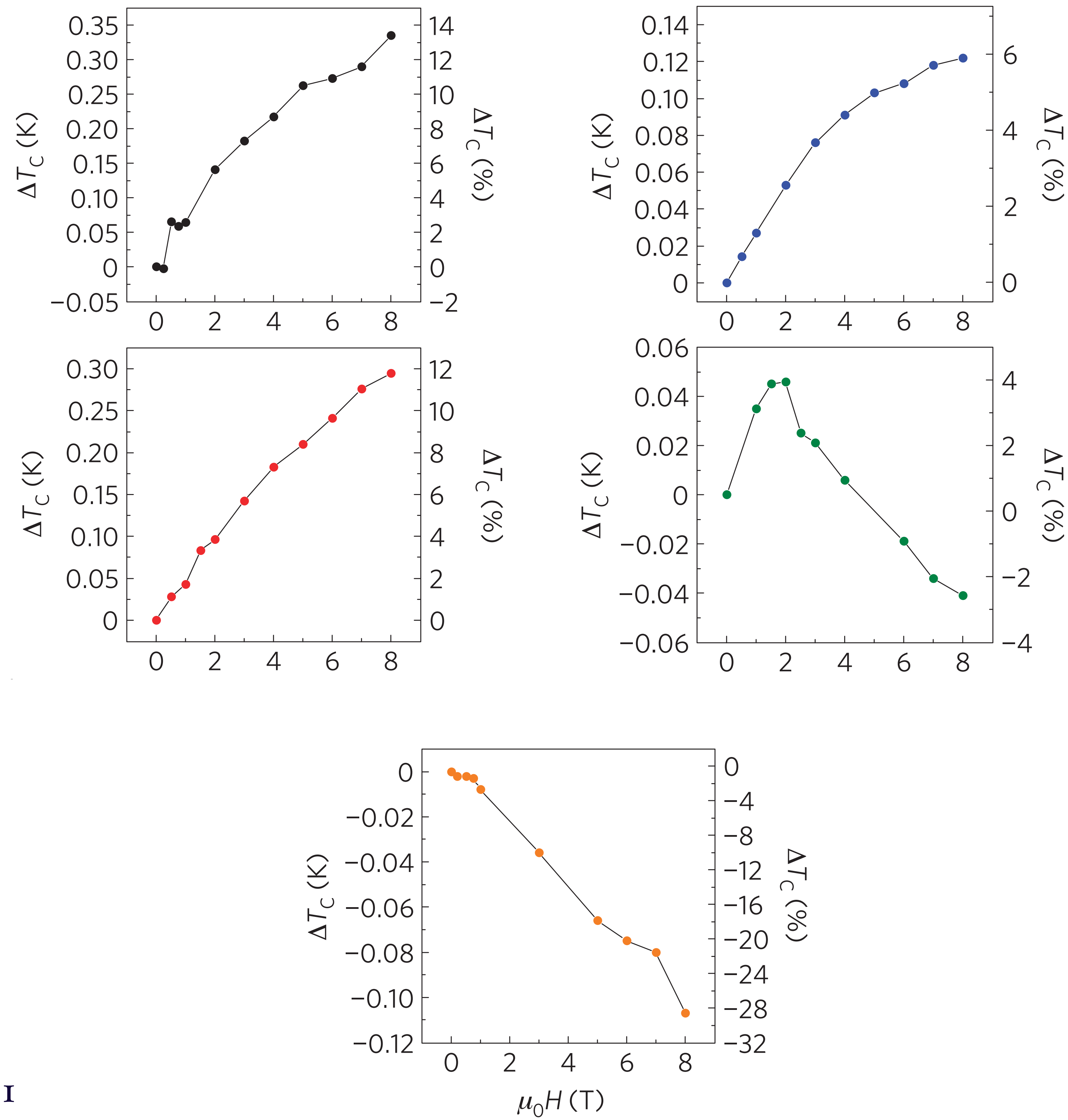
$$Tc(H=0) = 3.612K$$

$$2.1nm$$

H. Gardner, et al, 2011

Enhancement of T_c

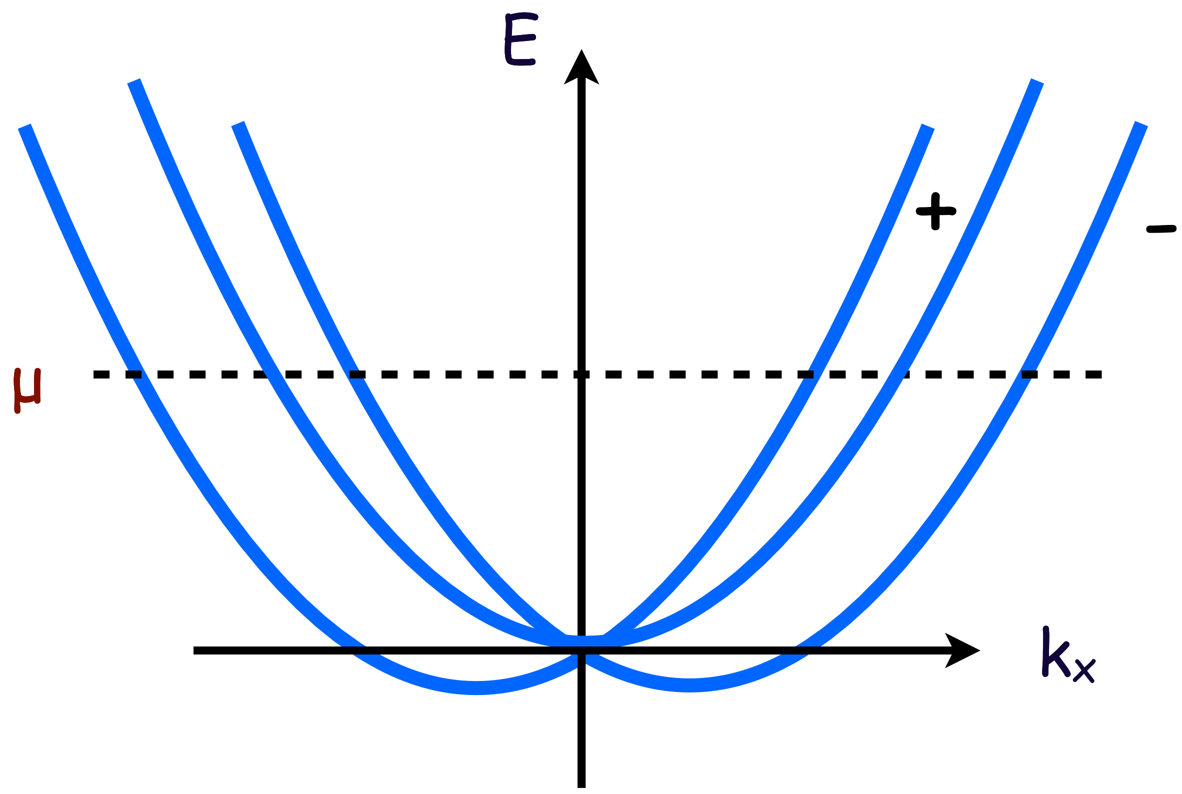


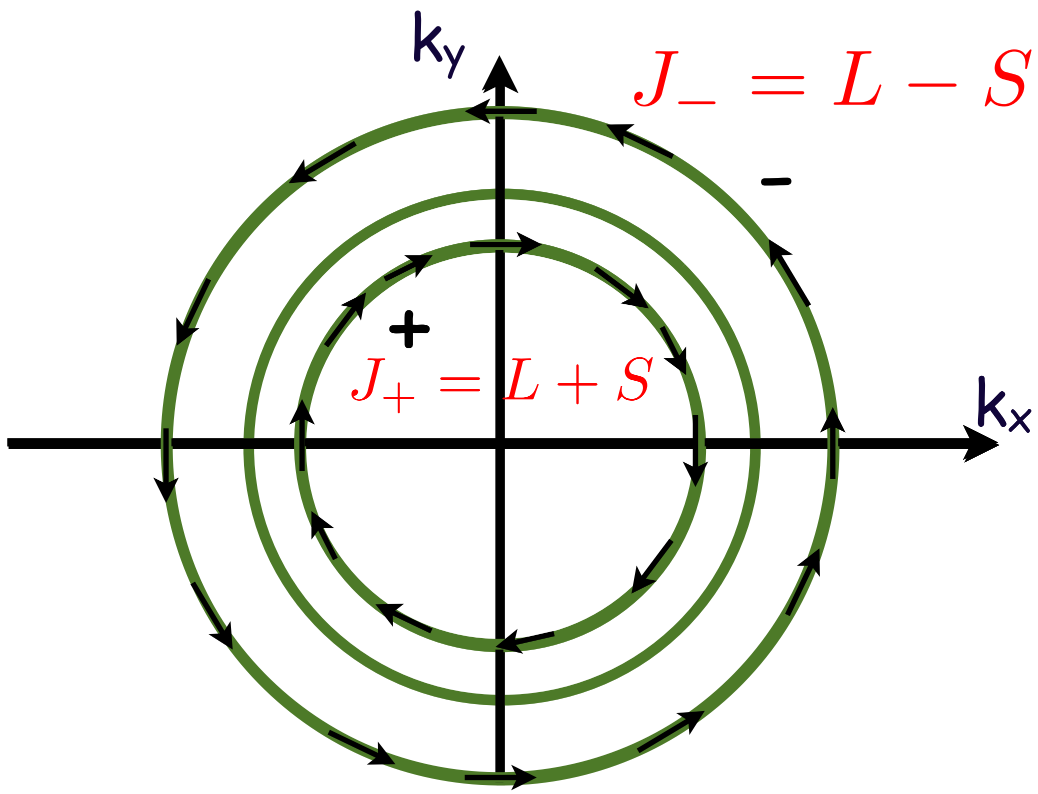


H. Gardner, et al, 2011

Electronic spectrum

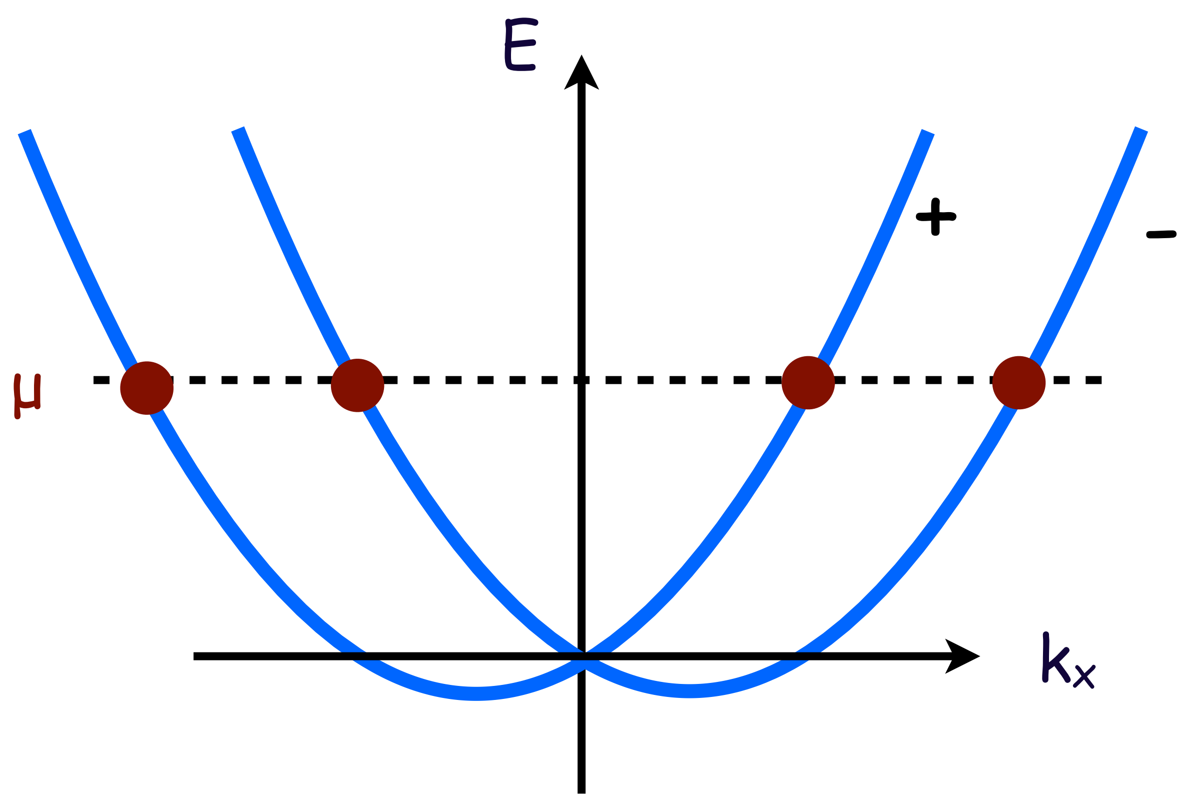
$$\mathcal{H} = \frac{k^2}{2m} + \alpha \hat{z} \cdot (\vec{k} \times \vec{\sigma}) \longrightarrow \varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha |\vec{k}|$$

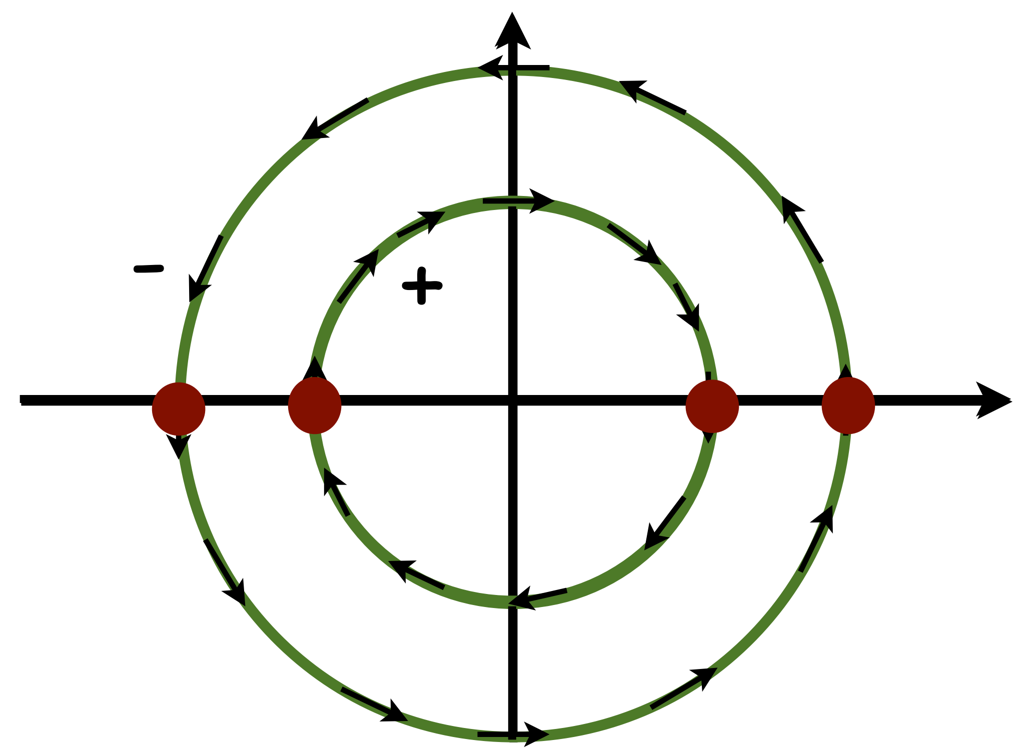




Superconducitvity

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





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

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

Magnetic field

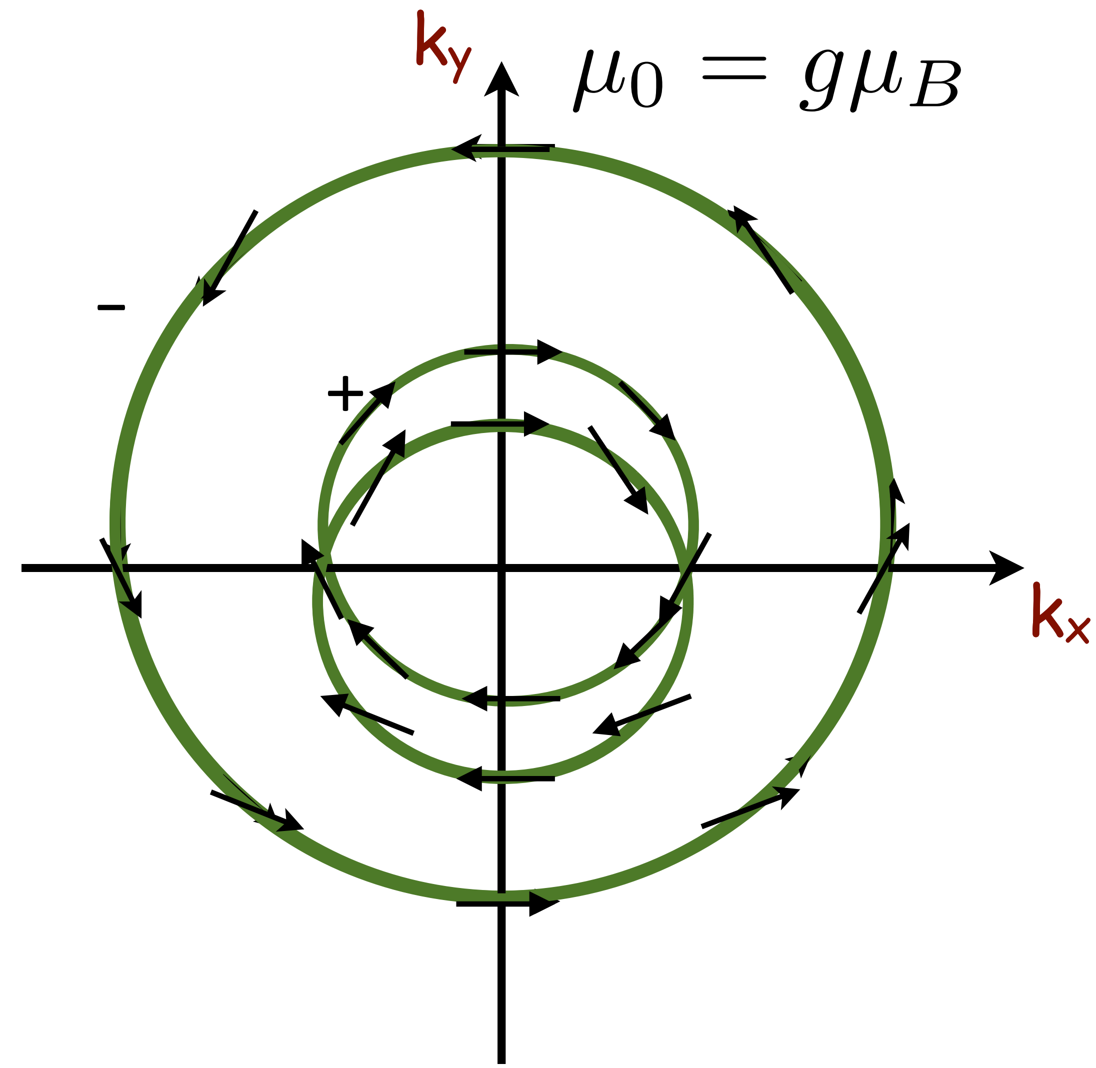
The two Rashba bands in the presence of a Zeeman field:

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

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

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

$$\mu_0 = g\mu_B$$



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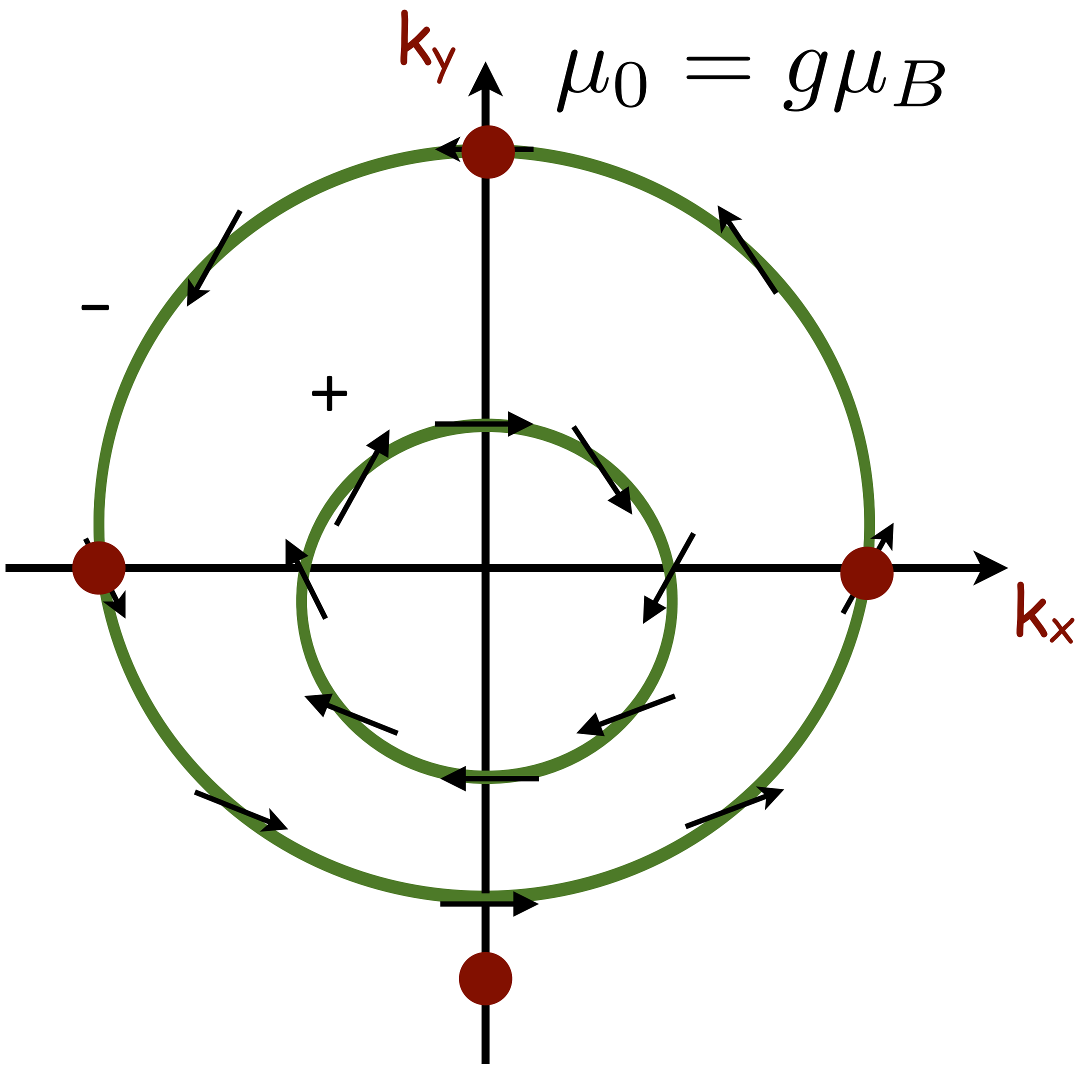

Magnetic field

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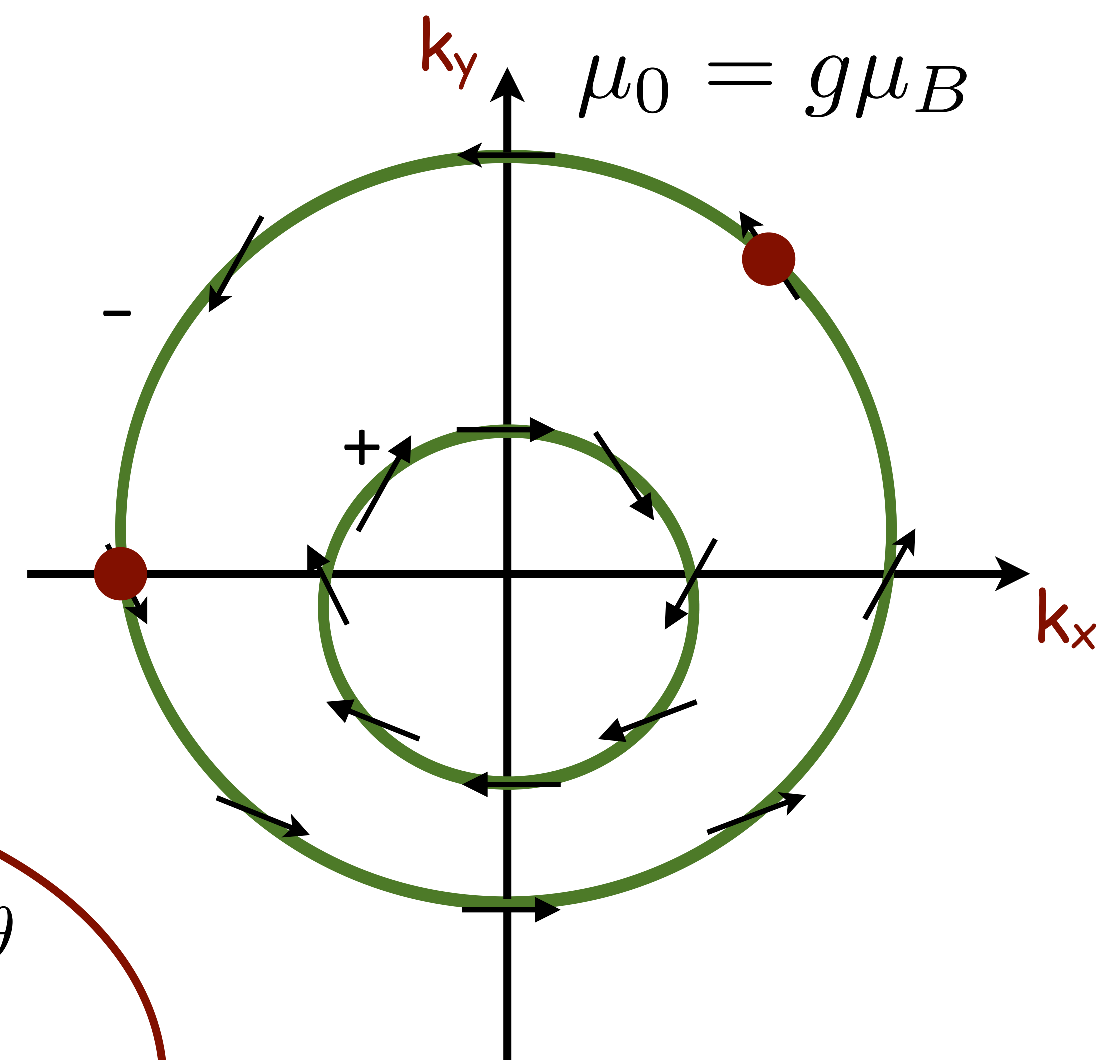


Creating pairs with finite momentum $\vec{q} \perp \vec{B}$:

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

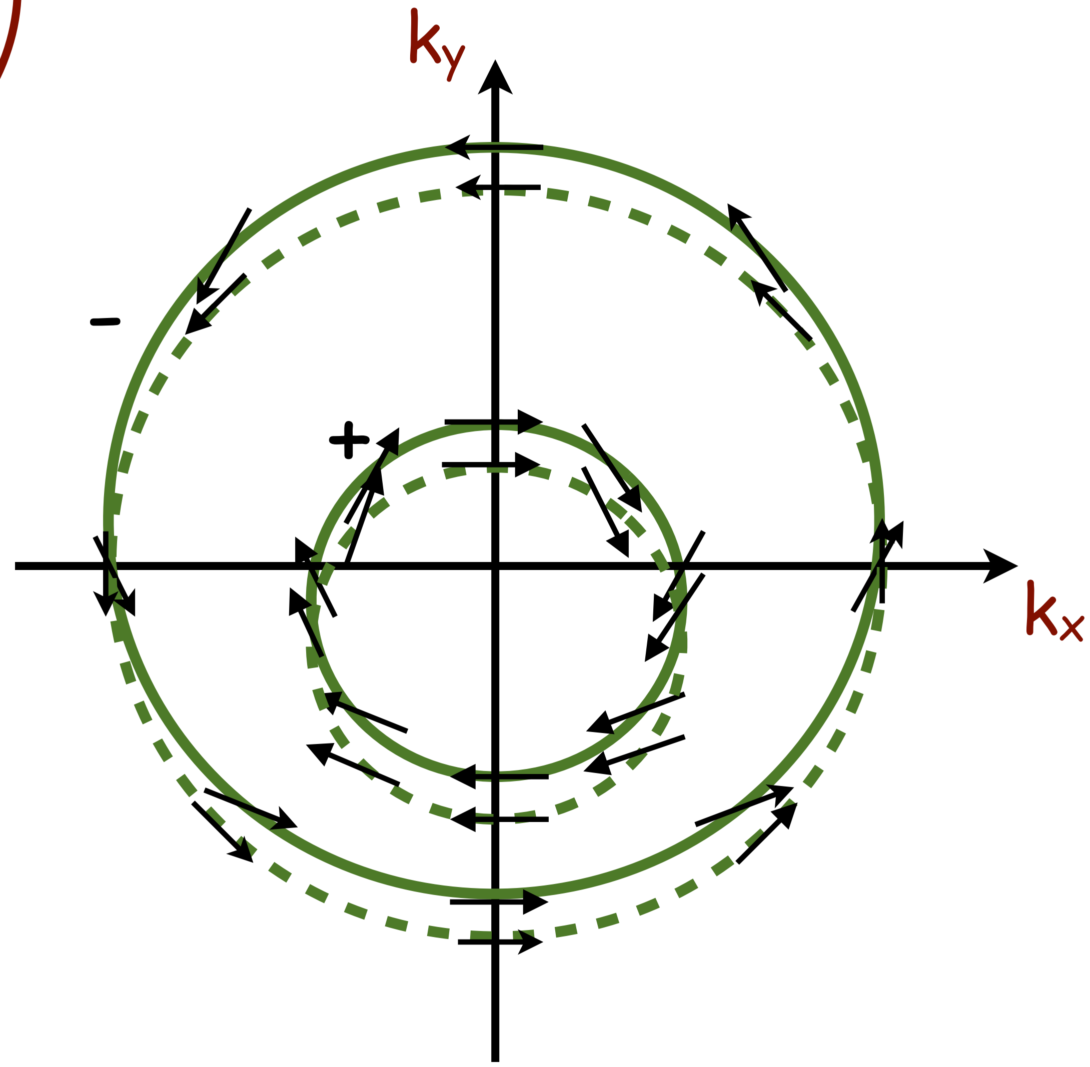
$$\varepsilon^{\pm}_{-k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| - \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

The FFLO state and spin-orbit

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

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

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



The FFLO state and spin-orbit

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

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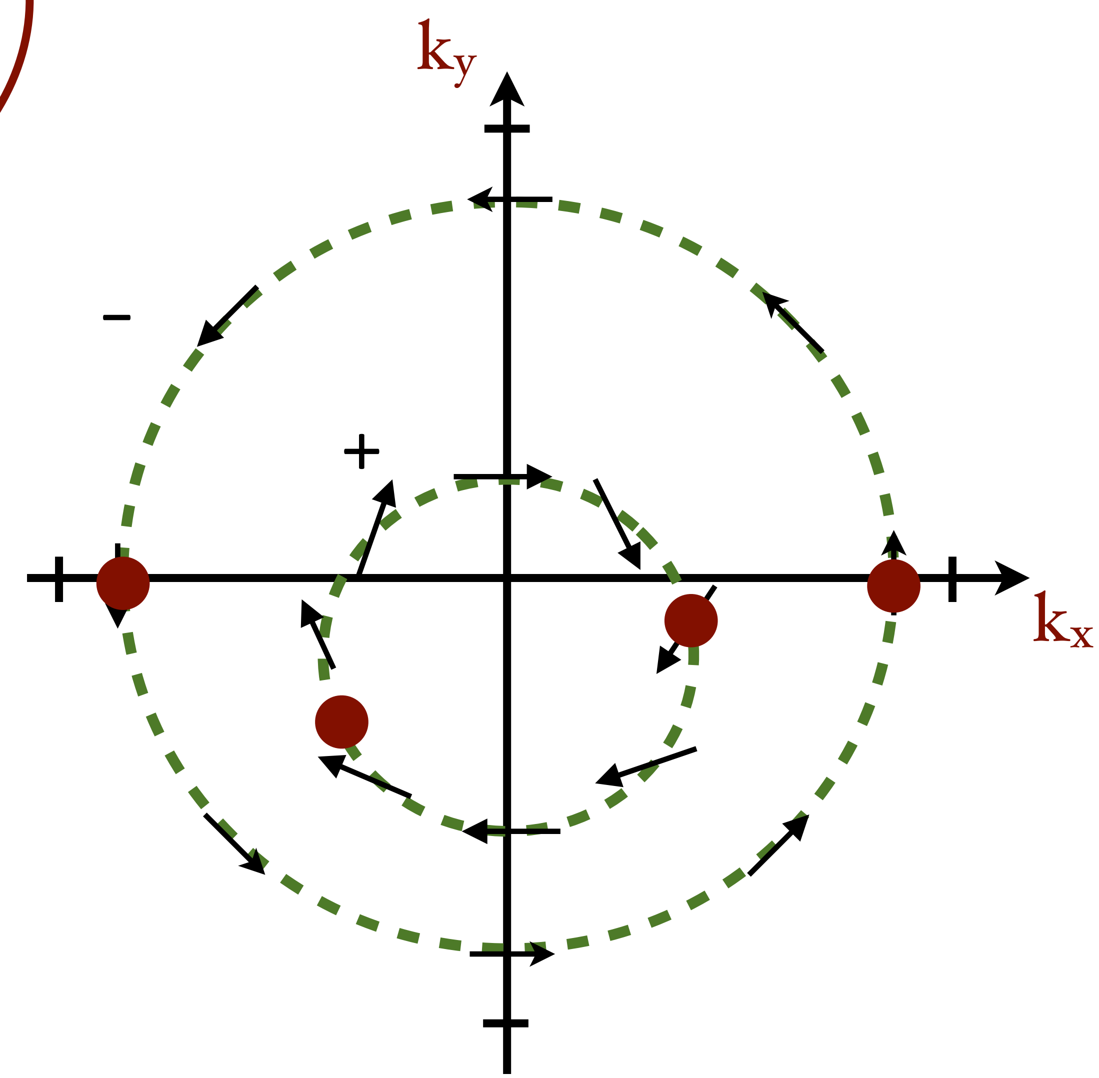
$$q = \frac{2\mu_0 B}{v_F}$$



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

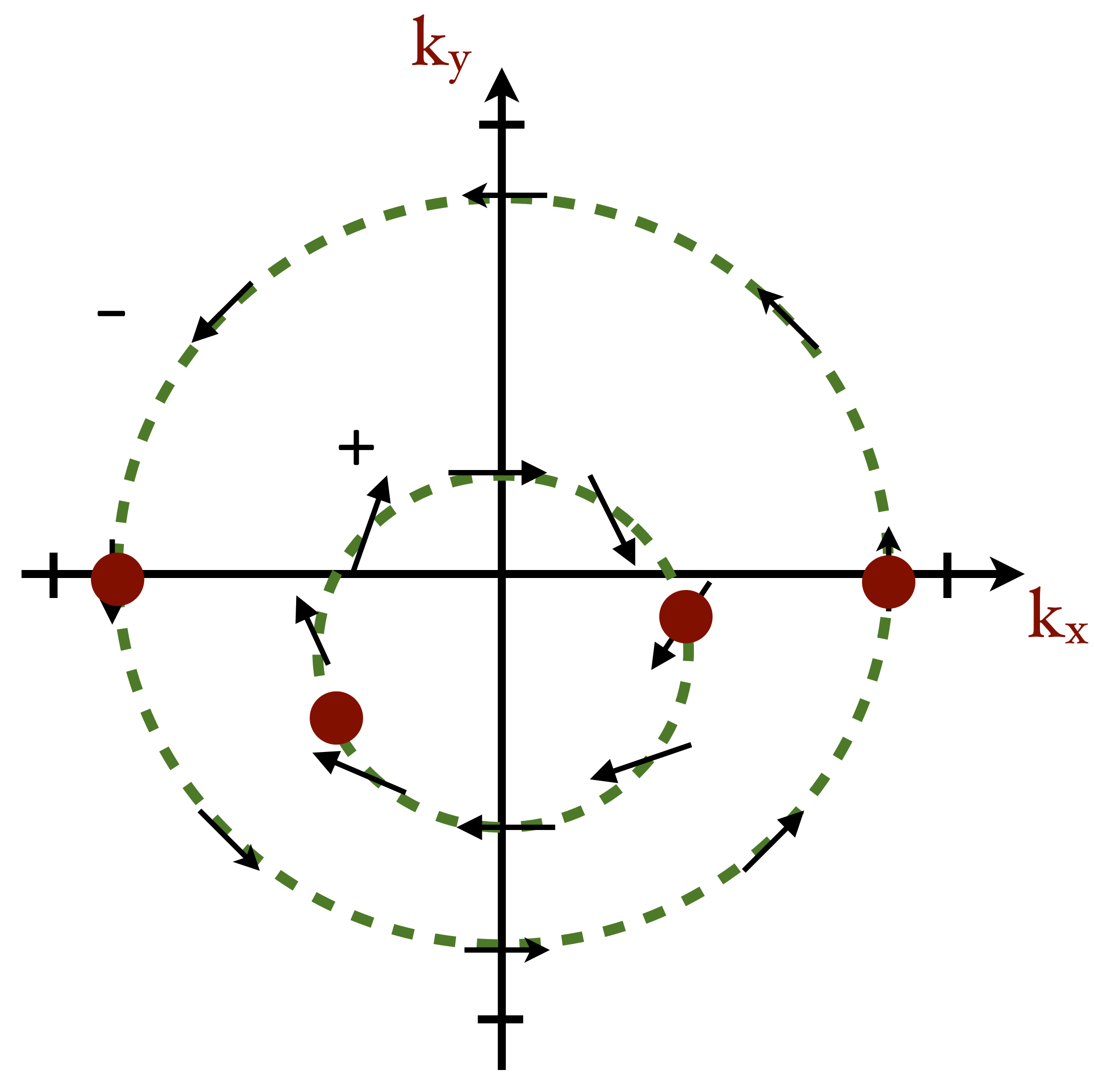
The critical field is mainly determined by the + band

The FFLO state and spin-orbit

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

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

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

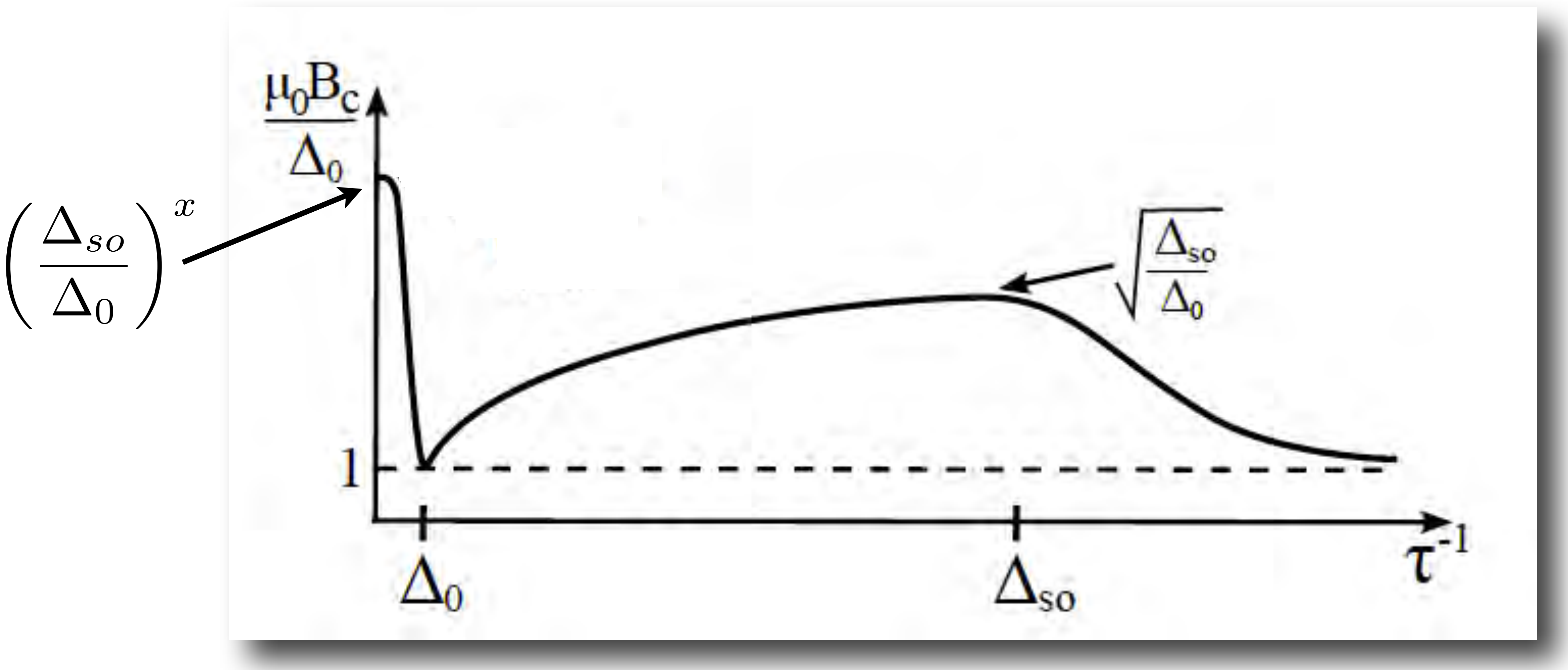


The FFLO state

P. Fulde and R. A. Ferrell, 1964
A. I. Larkin and Yu. N. Ovchinnikov, 1964

Effect of disorder

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



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:

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

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

Free energy

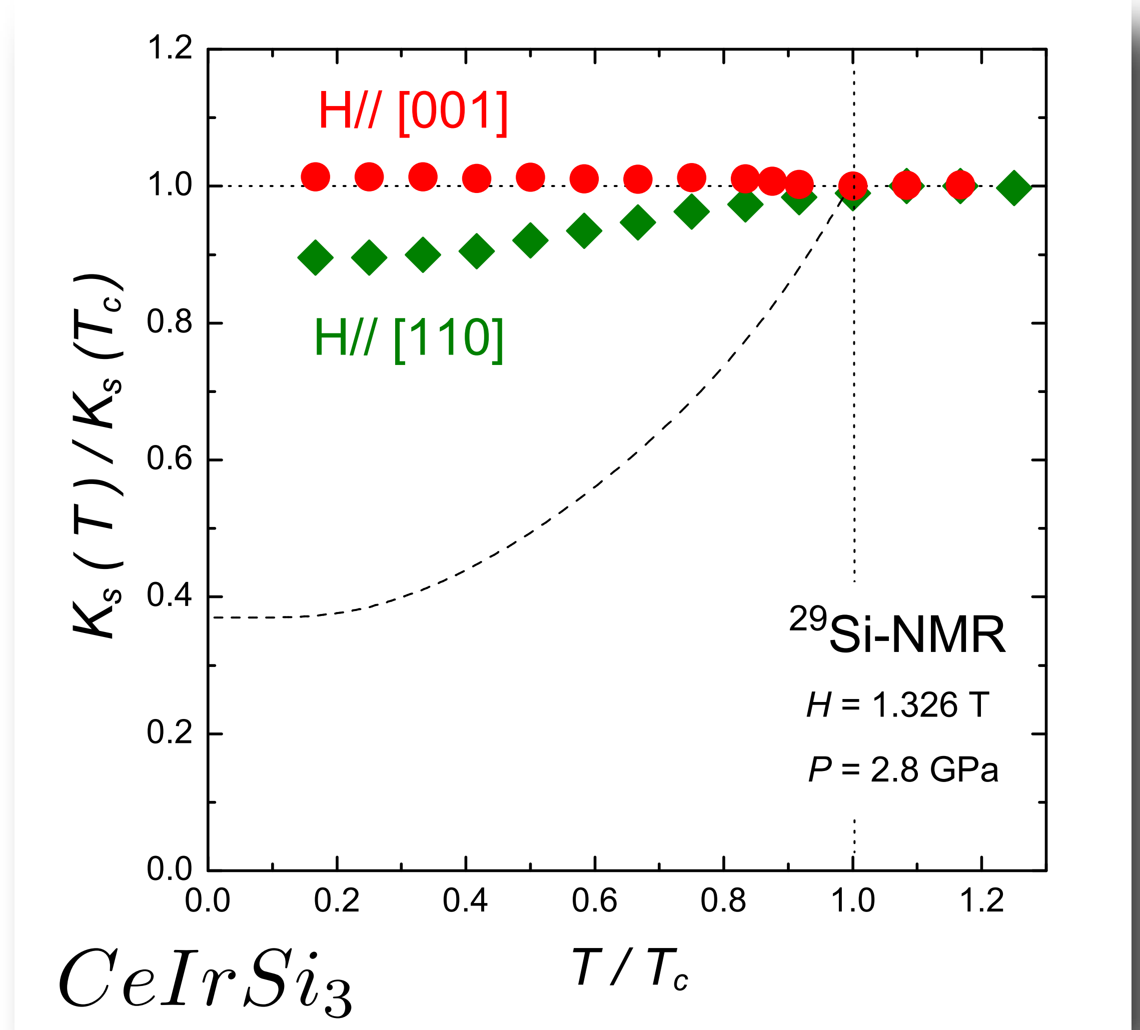
proportional to the spin-orbit coupling

$$\vec{H}_T = \vec{H}_{ext} + \frac{U}{\mu_B^2}\vec{M}$$

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

Free energy

H. Mukuda, et al, 2009



$$\chi_s \xrightarrow{T\to 0} \begin{cases} \frac{1}{2}\chi_n & \text{x-y plane} \\ \chi_n & \text{z direction} \end{cases}$$

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

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

$$-\frac{\chi_s}{2}H_T^2 + \frac{U}{2\mu_B^2}M^2$$

Current and magnetization

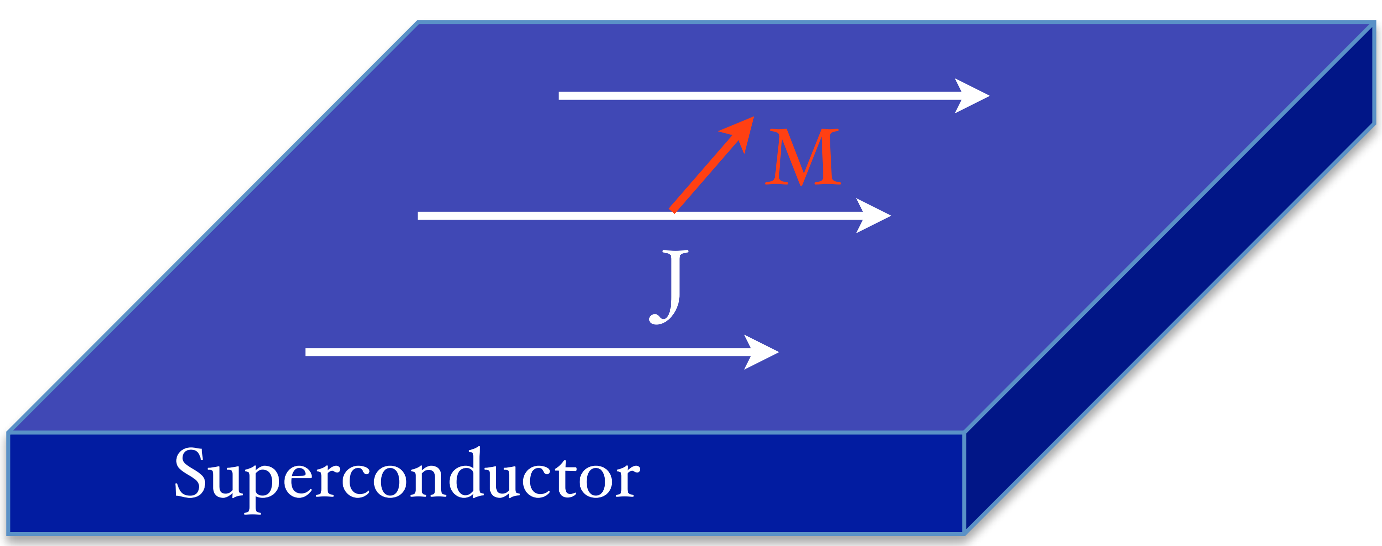
V.M. Edelstein, 1995

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

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

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

The superconducting current carries magnetization



Current and magnetization

V.M. Edelstein, 1995

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

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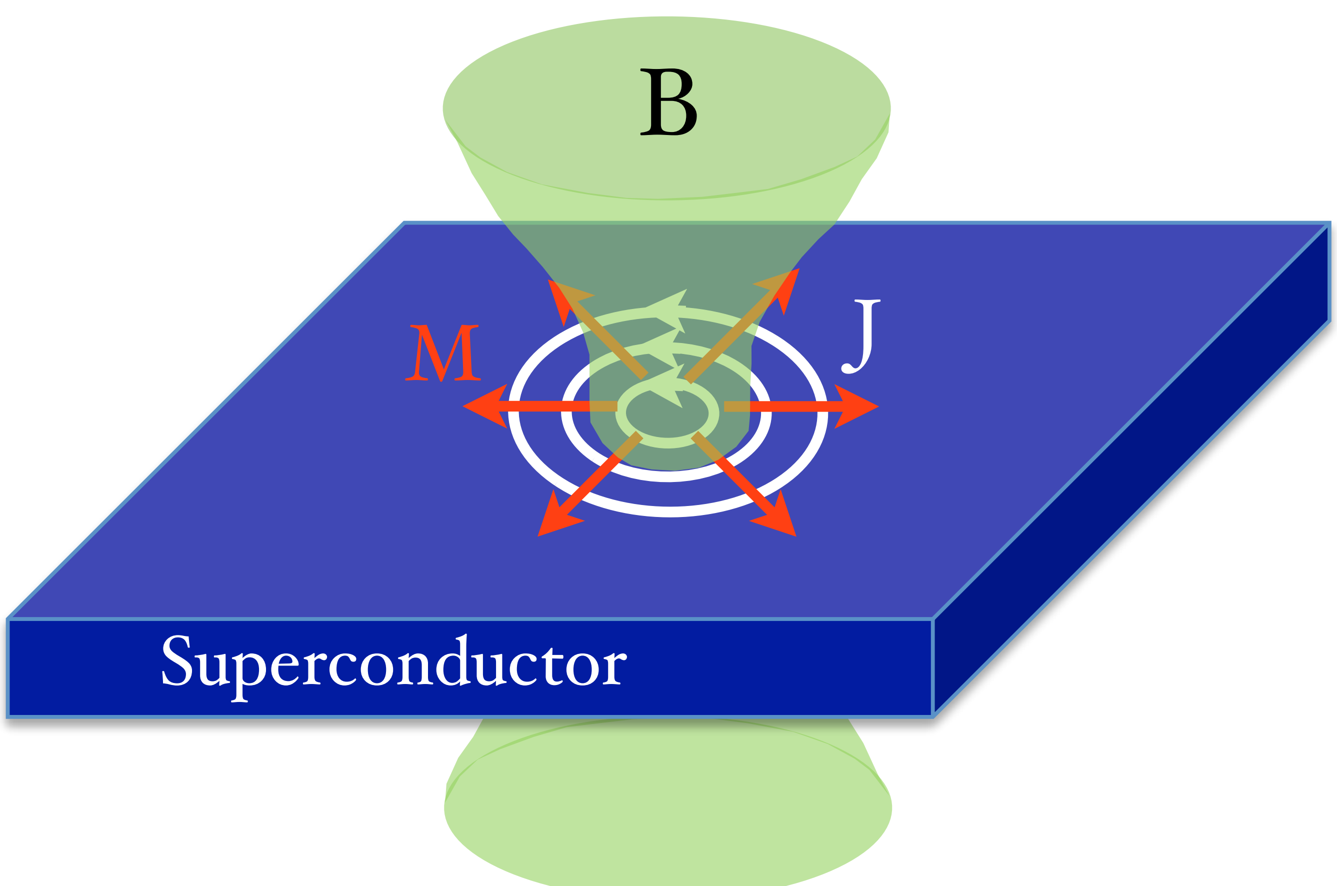
$$\chi = \frac{\chi_s}{1 - \chi_s U/g^2\mu_B^2}$$



S.-K. Yip, 2005

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

Free energy

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

$$-\frac{\chi_s}{2}H_T^2 \; + \frac{U}{2\mu_B^2}M^2$$

A. Steinbok and KM, in preparation

Free energy

$$F = -\rho_s \sum_{\vec{i},\hat{\mu}} \cos\left(\Phi_{\vec{i}+\hat{\mu}} - \Phi_{\vec{i}}\right) + \kappa \sum_{\vec{i},\hat{\mu},\hat{\eta}} \varepsilon_{\mu\eta z} \sin\left(\Phi_{\vec{i}+\hat{\mu}} - \Phi_{\vec{i}}\right) \frac{H^{\eta}_{\vec{i}} + H^{\eta}_{\vec{i}+\hat{\mu}}}{2}$$

$$-\frac{\chi_s}{2} H^2 + \frac{U}{2\mu_B^2} M^2$$

A. Steinbok and KM, in preparation

Free energy

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

$$-\kappa^2 \frac{\chi U}{2\chi_s \mu_B^2} \sum_{\vec{i},\hat{\mu}} \left[\sin\left(\Phi_{\vec{i}+\hat{\mu}} - \Phi_{\vec{i}}\right) + \sin\left(\Phi_{\vec{i}} - \Phi_{\vec{i}-\hat{\mu}}\right)\right]^2$$

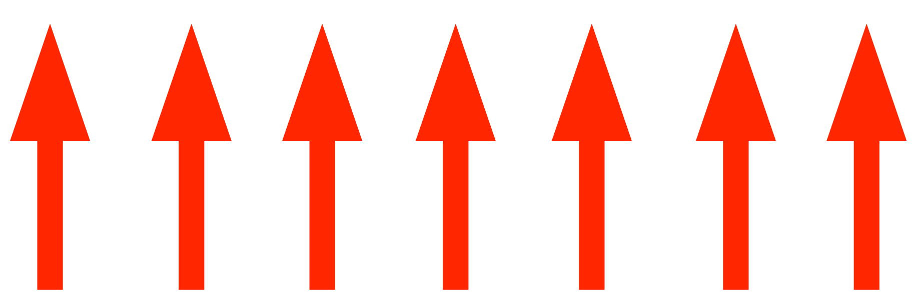
$$\vec{S}_{\vec{i}} = \begin{pmatrix} \cos\Phi_{\vec{i}} \\ \sin\Phi_{\vec{i}} \end{pmatrix}$$

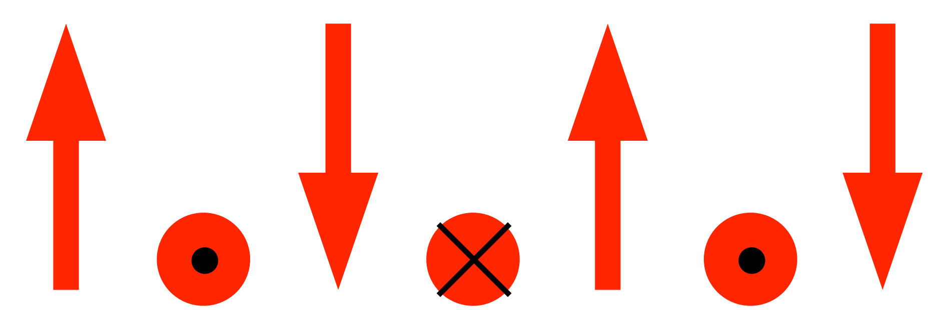
A. Steinbok and KM, in preparation

Free energy

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

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

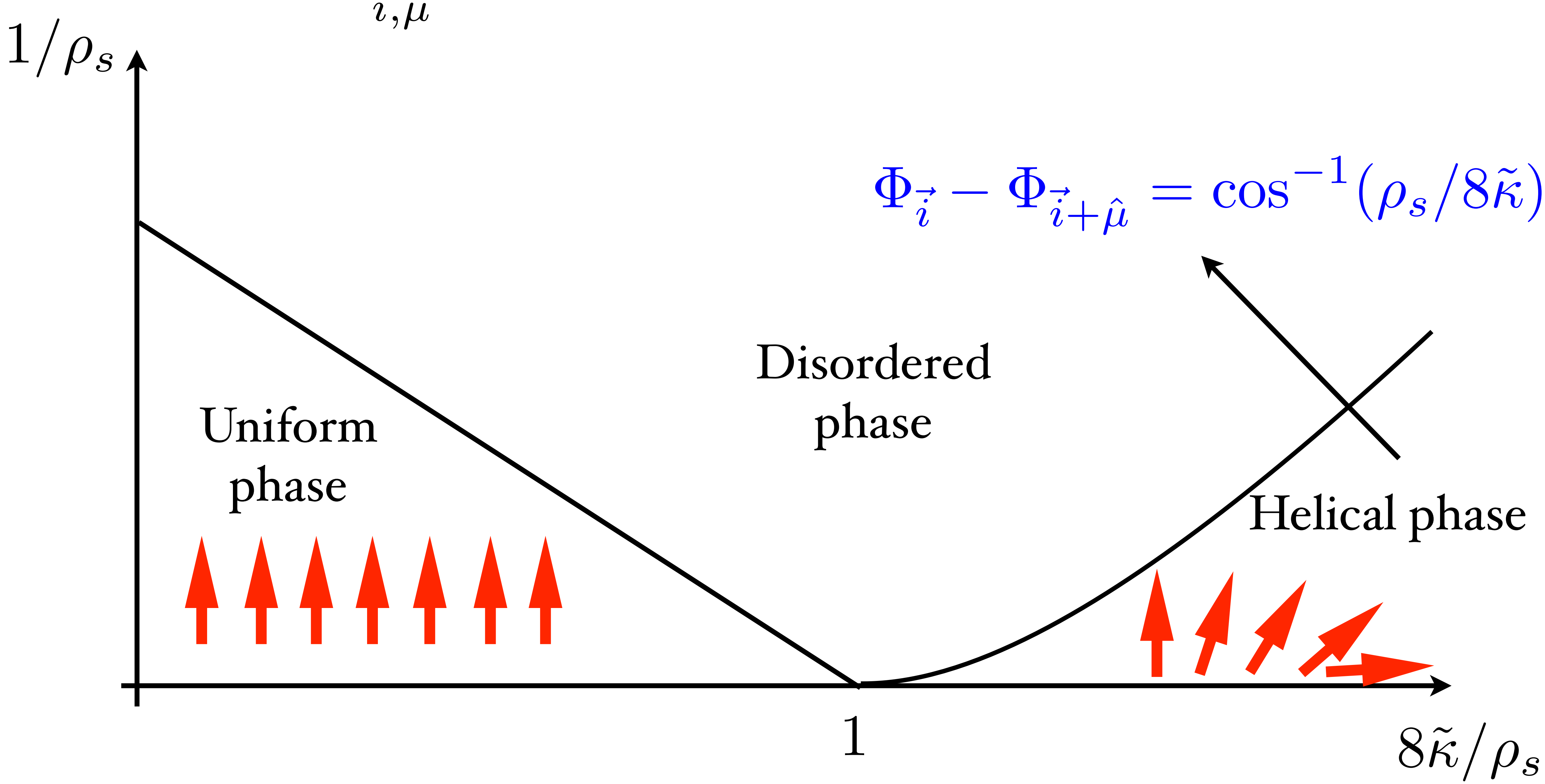




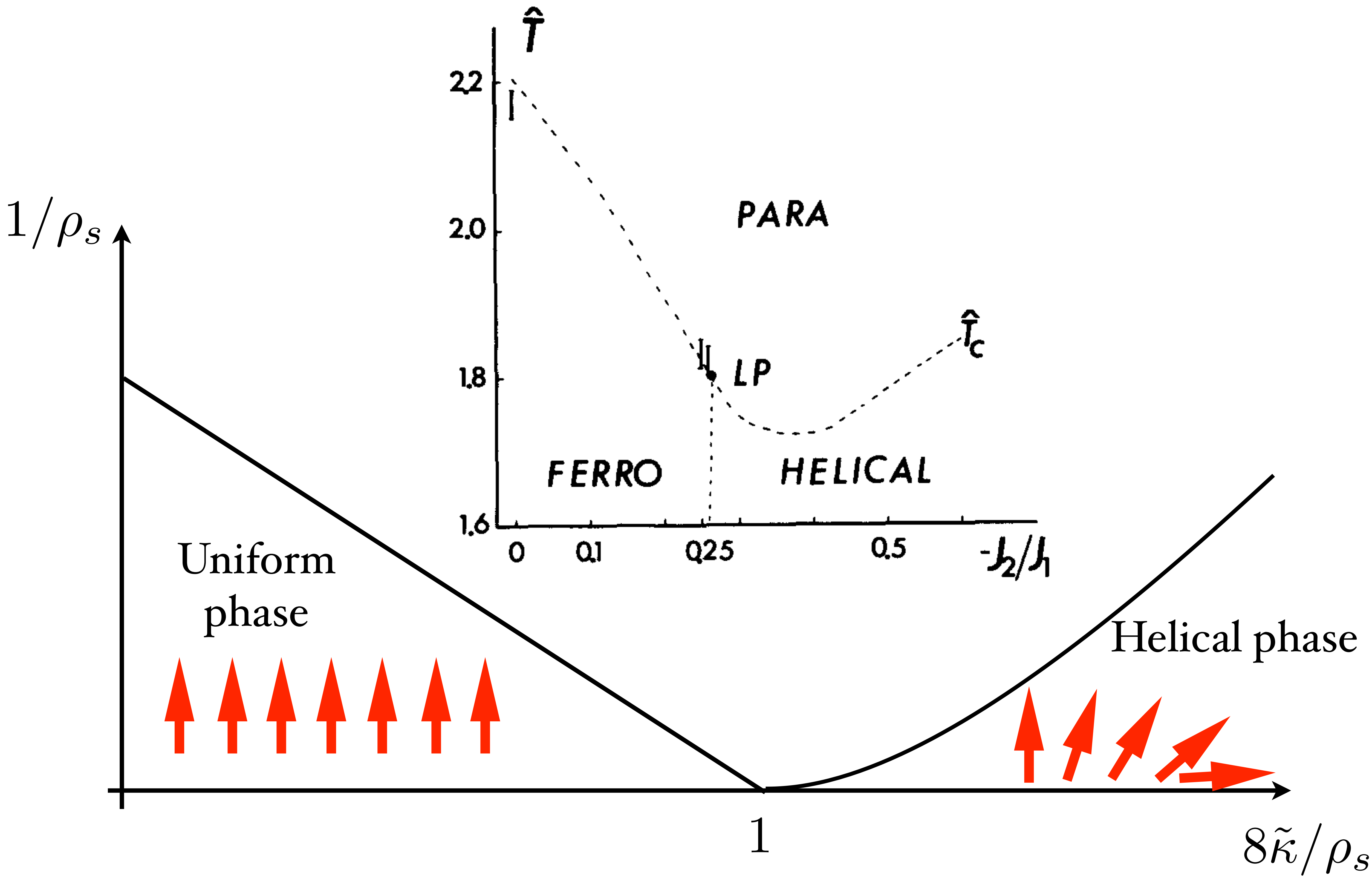
A. Steinbok and KM, in preparation

Phase diagram

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



Phase diagram



Magnetic Field

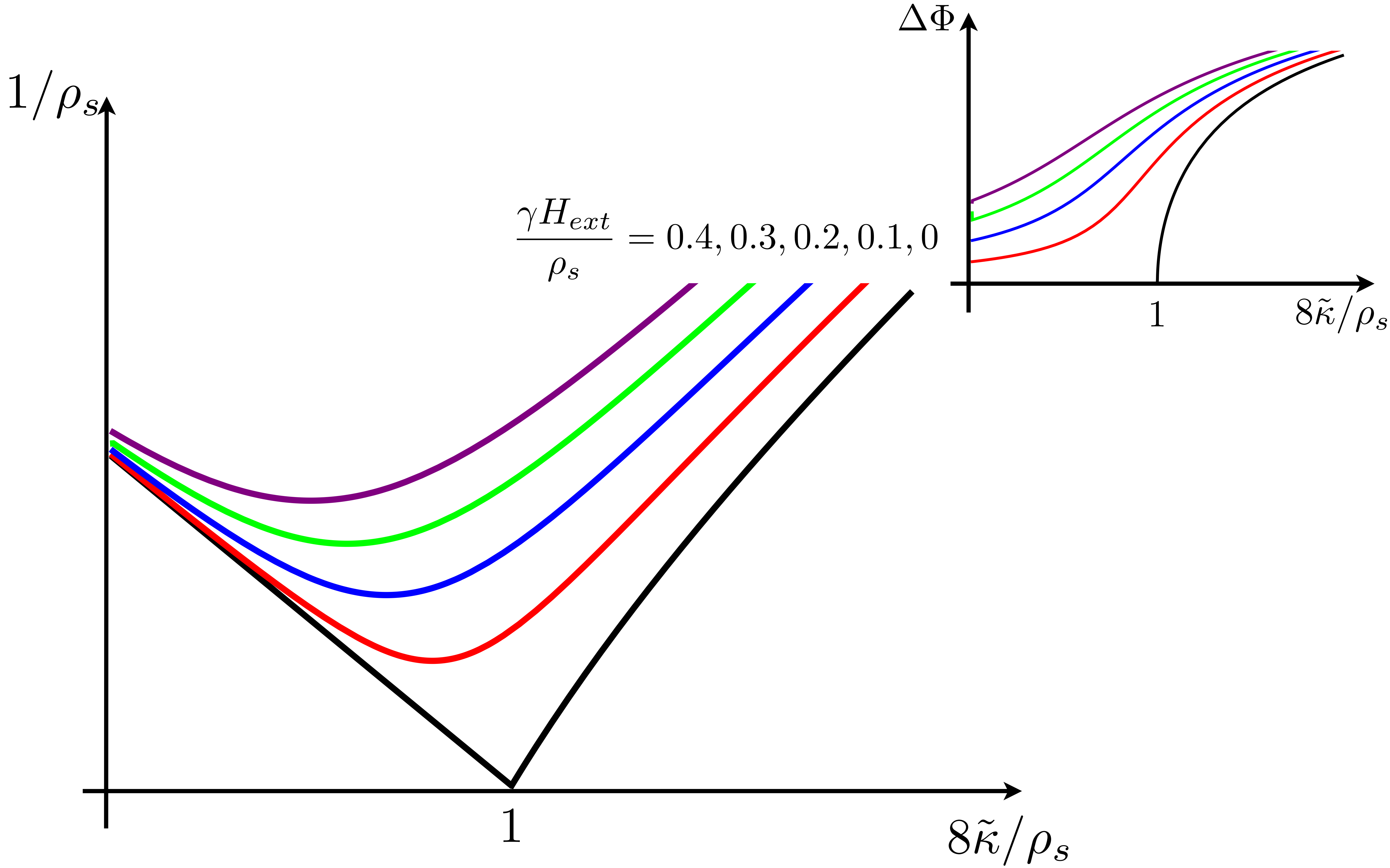
$$F = -\rho_s \sum_{\vec{i},\hat{\mu}} \left\{ \vec{S}_i \cdot \vec{S}_{i+\hat{\mu}} + \frac{\tilde{\kappa}}{\rho_s} \left[\vec{S}_{\vec{i}+\hat{\mu}} \times \vec{S}_{\vec{i}} + \vec{S}_{\vec{i}} \times \vec{S}_{\vec{i}-\hat{\mu}} \right]^2 \right\}$$

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

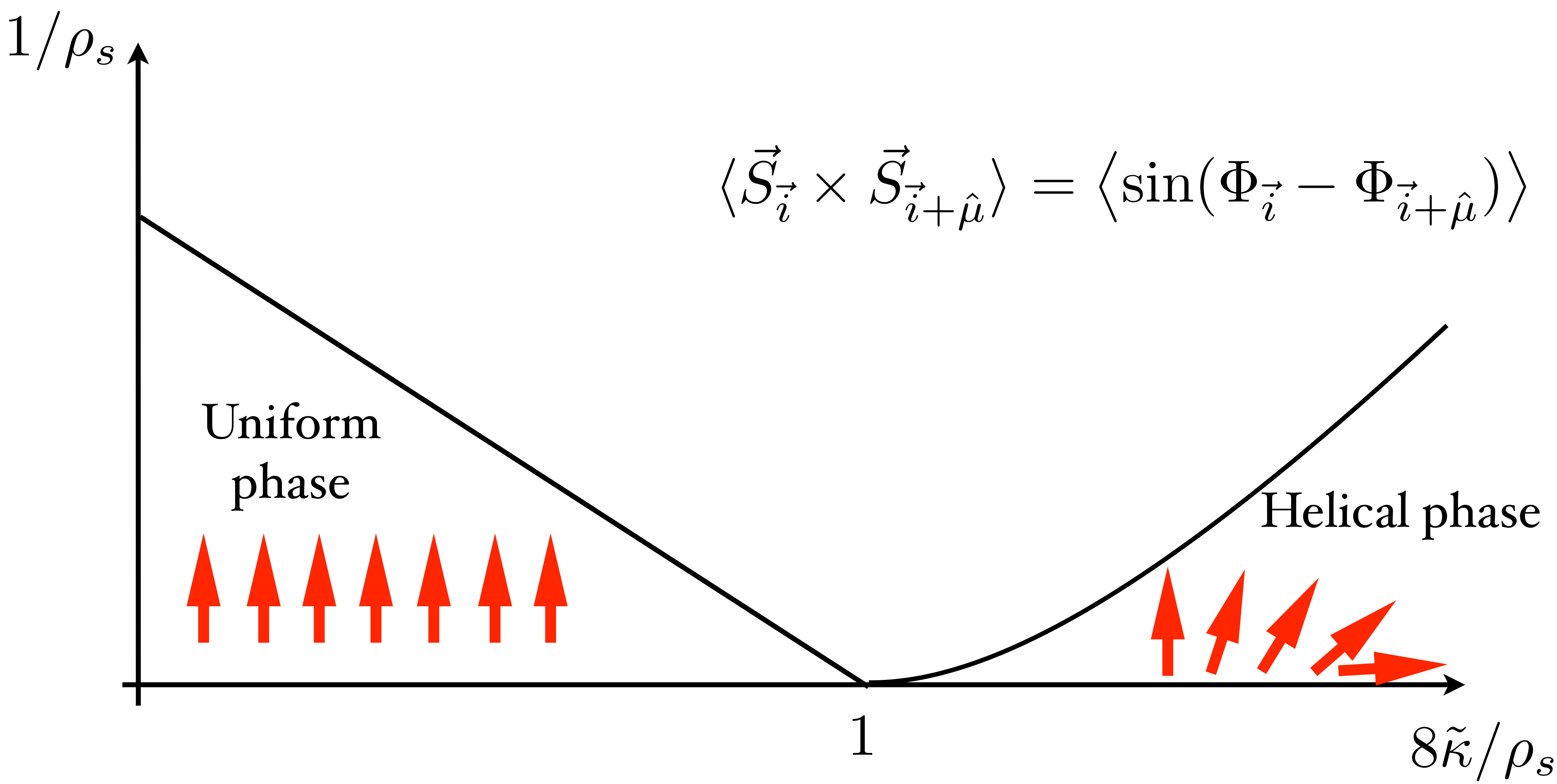
$$\rho_s \rightarrow \sqrt{\rho_s^2 + (\gamma H_{ext})^2}$$

Helical phase for all values of $\tilde{\kappa}$

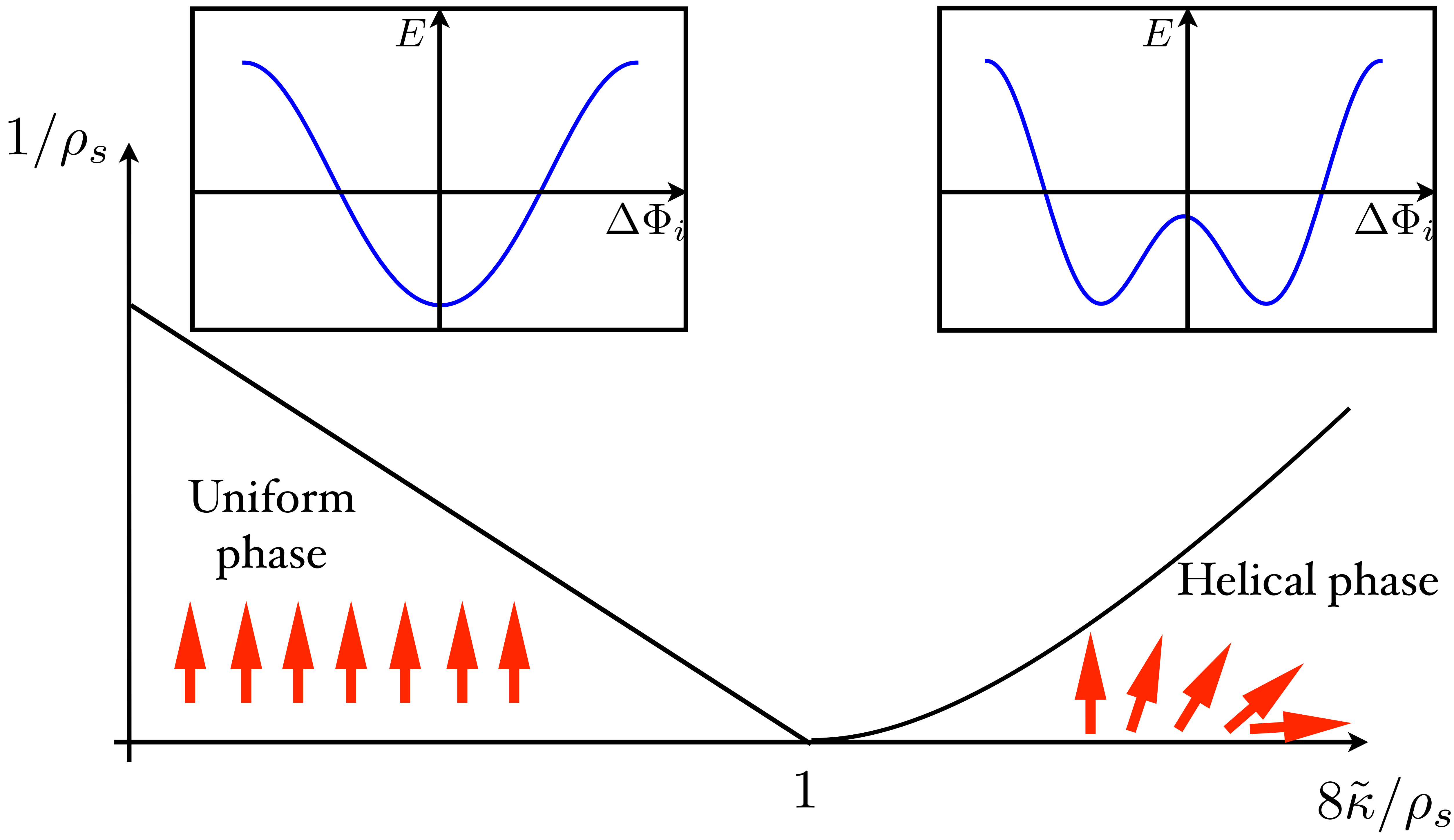
Magnetic Field



Phase diagram



Phase diagram



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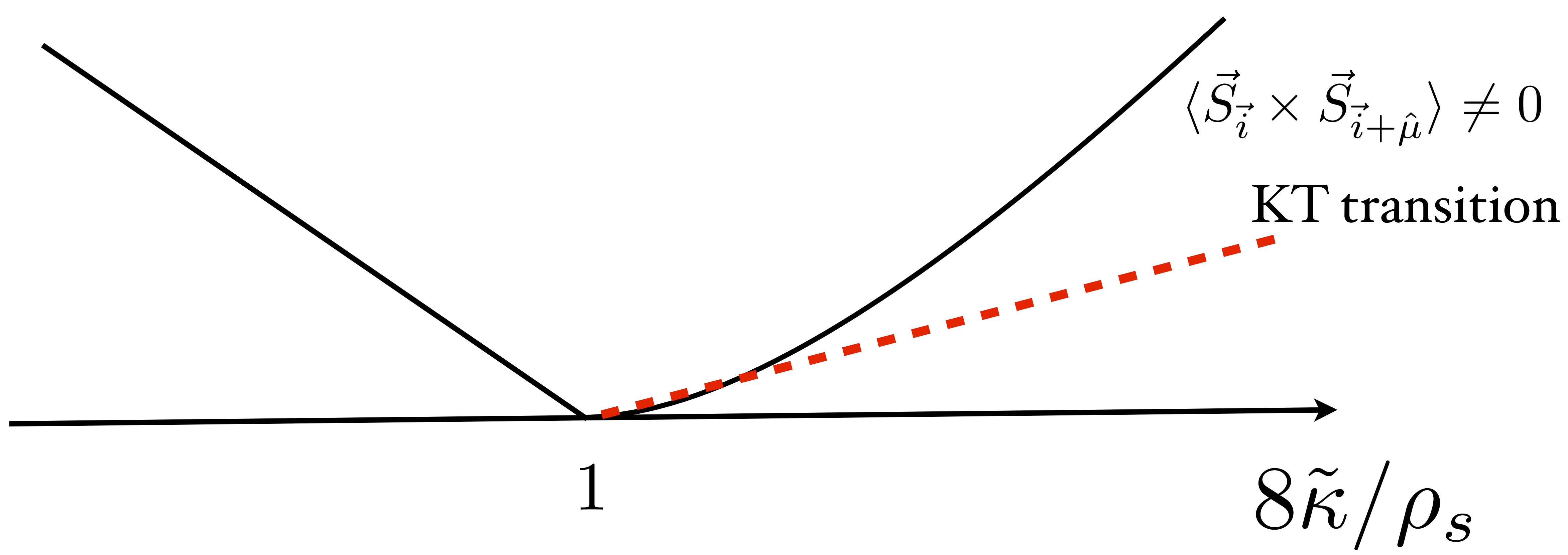

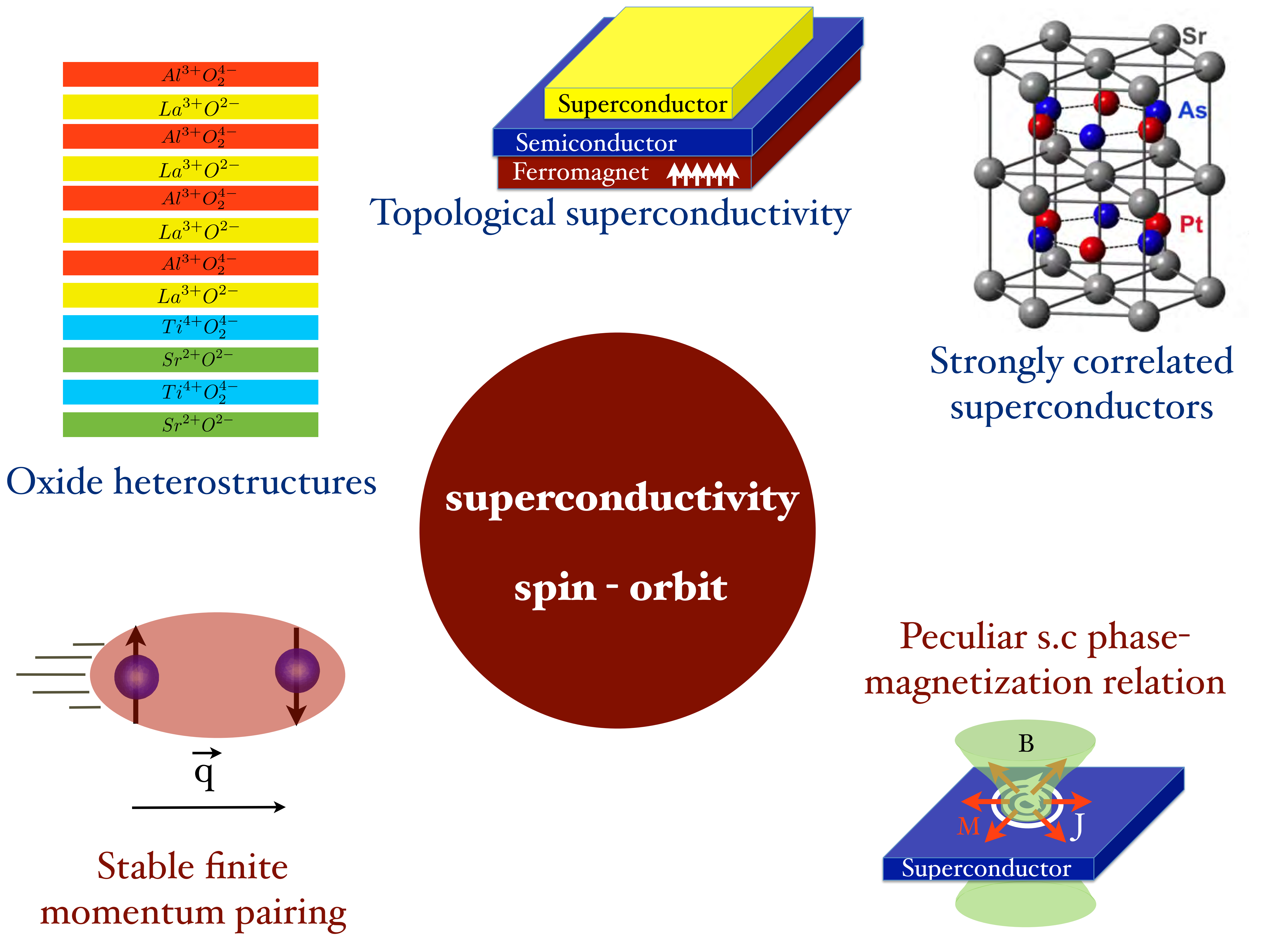

$Al^{3+}O_2^{4-}$
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Stable finite momentum pairing
Peculiar s.c phase-magnetization relation
B
M
J
Superconductor