FFLO-like state in oxide interface superconductors

Daniel F. Agterberg, U. Wisconsin – Milwaukee

J. Garaud, E. Babaev (KTH, U. Mass-Amherst)

M. Sigrist (ETH-Zurich), H. Tsunetsugu (ISSP)

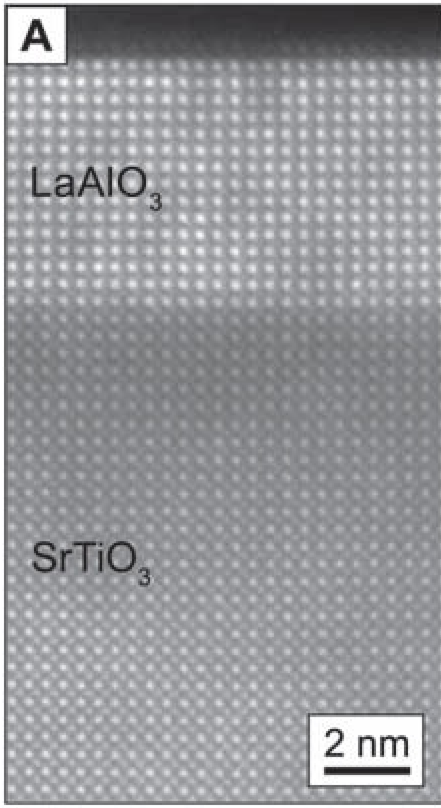
R.P. Kaur, S. Mukherjee, Z. Zheng (UWM)

NSF DMR-0906633 and NSF DMR-1335215

1- Relevant Materials
2- Superconductivity with Rashba spin-orbit
3- FFLO-like state in magnetic fields
4- Abrikosov, Fractional, Skyrmion vortices (arXiv:1403.6655)

2D Superconductors

Ohtomo, Hwang, Nature 427, 423 (2004):
2D electron gas at $LaAlO_3$ and $SrTiO_3$ interface



Superconductivity in the 2D electron gas
Reyren et al, Science 317, 1196 (2007):

Many 2D superconducting materials:

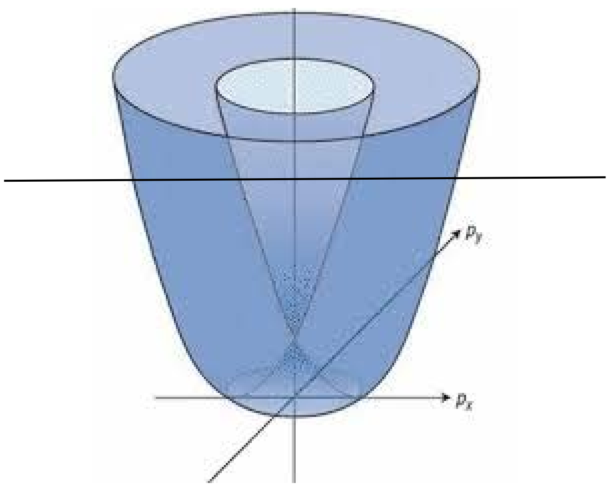
MoS_2: Science 338, 1193 (2012)
Pb on GaAs: PRL 111, 057005 (2013)
$KTaO_3$: Nat. Nano 6, 408 (2011)

All these materials lack spatial parity symmetry and allow for a Rashba spin-orbit interaction

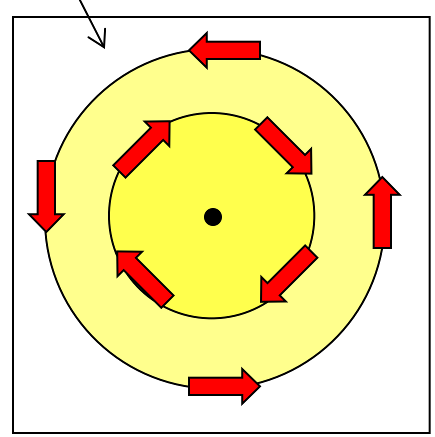
Microscopic Model

$$H = \sum_{k,s} \xi_k c^t_{ks} c_{ks} + \frac{1}{2} \sum_{k,k',q,s,s'} V c^t_{k+qs} c^t_{-k+qs'} c_{-k'+qs'} c_{k'+qs}$$

$$H_{spin} = \sum_{k,s,s'} (\mu_B \vec{h} + \vec{g}_k) \cdot \vec{\sigma}_{s,s'} c^t_{ks} c_{ks'}$$



$$\vec{g}_k = \alpha(\hat{x}k_y - \hat{y}k_x)$$



$$\delta N = \frac{N_1 - N_2}{N_1 + N_2} (\cong 0.05)$$

Free Energy: Broken Parity

GLW free energy: constrained by symmetry:

$$f = -\alpha |\psi|^2 + \beta |\psi|^4 + \frac{\hbar^2}{2m}(\nabla \psi)(\nabla \psi)^*$$

Broken parity symmetry allows a new term (Lifshitz invariant)

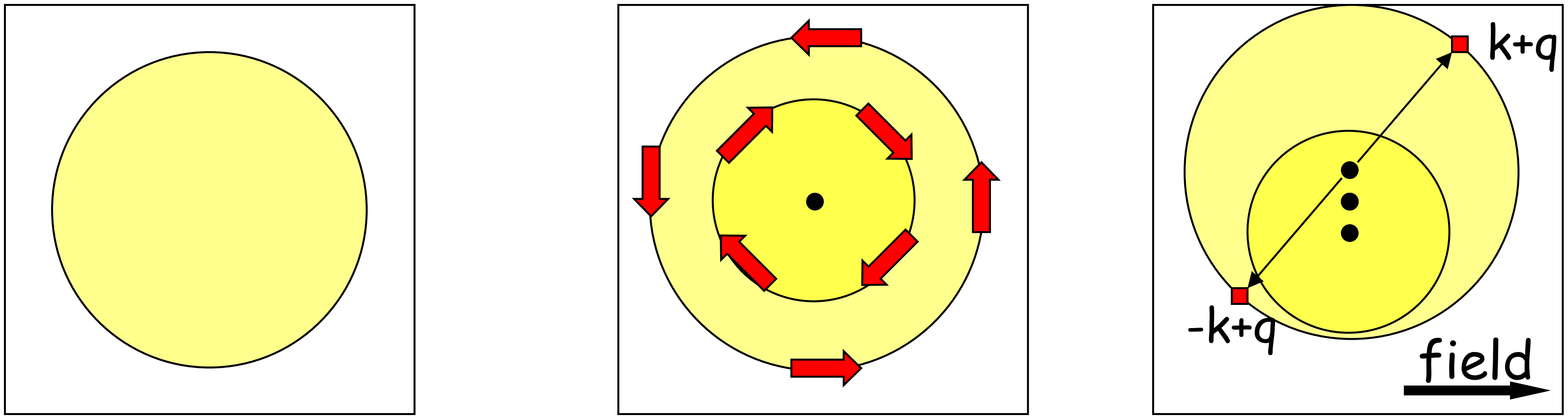
$$\varepsilon \hat{z} \cdot \vec{B} \times [\psi (\nabla \psi)^* + \psi^* (\nabla \psi)] = \varepsilon \hat{z} \cdot \vec{B} \times \vec{j}_{s,0}$$

$$\Rightarrow \psi = \psi_0 e^{i2\vec{q}\cdot\vec{r}} \qquad \vec{q} = -m\varepsilon \hat{z} \times \vec{B}$$

- finite momentum pairing solution in a uniform magnetic field when $|\Psi|$ is uniform (this state carries no current)
- finite momentum pairing guaranteed with in-plane field

DFA, Physica C 387, 13 (2003) and Kaur, DFA, Sigrist, PRL 94, 13702 (2005)

Finite Momentum Pairing



No Rasba | With Rashba | With Rasba and Zeeman Field

$$\xi_{\pm}(k) = \varepsilon(k) \pm |\alpha \vec{g}(k) + \mu_B \vec{B}|$$

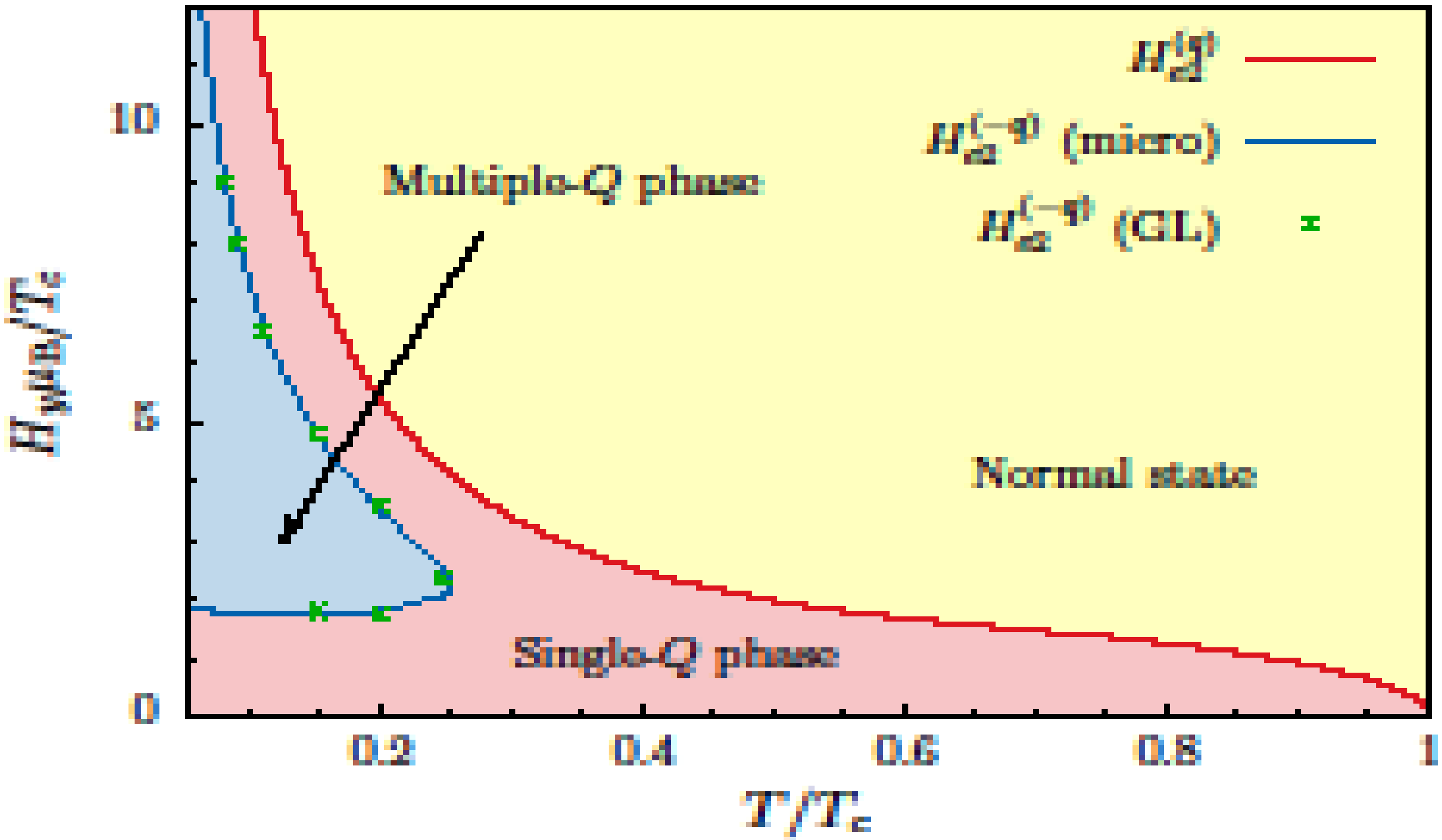
$$\xi_{\pm}(k) \approx \varepsilon(k) \pm \alpha \pm \mu_B \vec{B} \cdot \hat{g}(k)$$

$$\mu_B \vec{B} \cdot \hat{g}(k) = \mu_B B_x k_y / k_F$$

$$\Delta(\vec{\boldsymbol{r}}) = \Delta_0 \boldsymbol{e}^{\boldsymbol{i} 2 \vec{\boldsymbol{q}} . \vec{\boldsymbol{r}}}$$

The two bands prefer opposite q vectors.

Phase Diagram



Single-Q phase: $\psi(\vec{r}) = \psi_0 e^{i2\vec{q}.\vec{r}}$

Multiple-Q phase: $\psi(\vec{r}) = \psi_q e^{i2qr} + \psi_{-q} e^{-2iqr}$

Theory of ψ_q and ψ_{-q}

$$\psi = \psi_q e^{iqx} + \psi_{-q} e^{-iqx}$$

$$f = \alpha_+ |\psi_q|^2 + \alpha_- |\psi_{-q}|^2 + \beta_+ |\psi_q|^4 + \beta_- |\psi_{-q}|^4$$
$$+ \beta_m |\psi_q|^2 |\psi_{-q}|^2 + \kappa_+ |\nabla \psi_q|^2 + \kappa_- |\nabla \psi_{-q}|^2$$

$$\boxed{\boldsymbol{U}(1) \times \boldsymbol{U}(1) \text{ symmetry!}}$$

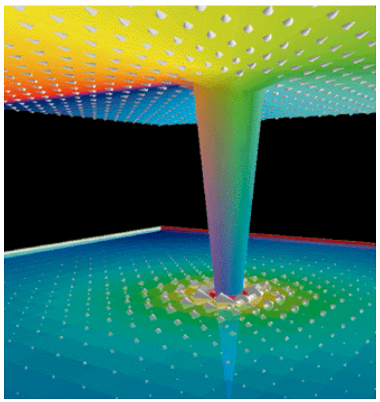
General feature: $$(\psi_{Qx})^{n} (\psi^*_{Qx})^{m} (\psi_{-Qx})^{p} (\psi^*_{-Qx})^{k}$$

$\boldsymbol{n} - \boldsymbol{m} + \boldsymbol{p} - \boldsymbol{k} = 0$ Gauge invariance $\boldsymbol{n} = \boldsymbol{m}$

$\boldsymbol{n} - \boldsymbol{m} - \boldsymbol{p} + \boldsymbol{k} = 0$ Translational invariance $\boldsymbol{p} = \boldsymbol{k}$

Fractional Vortices

(n,m) $\psi_q(r,\phi) = |\psi_q(r)|e^{in\phi}$ $\psi_{-q}(r,\phi) = |\psi_q(r)|e^{im\phi}$



Consider (1,0) vortex:

$$\vec{j} = i\hbar m[\psi_q(\nabla\psi_q)^* - \psi_q^*(\nabla\psi_q)] - \frac{2me}{c}(|\psi_q|^2 + |\psi_{-q}|^2)\vec{A}$$

$$\oint A\cdot dl = \frac{|\psi_1|^2}{|\psi_1|^2 + |\psi_2|^2}\Phi_0$$

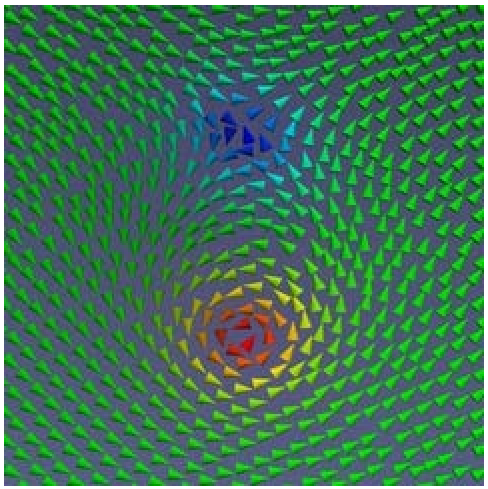
Fractional Flux vortices have line energies that diverge as logR

(1,1) vortex has usual flux Φ_0 and finite line energy

Two kinds of (1,1) vortices: Abrikosov vortices and Skyrmion vortices

Abrikosov/Skyrmion Vortices

$$\Psi = \begin{pmatrix} \psi_q \\ \psi_{-q} \end{pmatrix} \qquad \hat{n} = \frac{\Psi^t \vec{\sigma} \Psi}{\Psi^t \Psi} \qquad S_2 \rightarrow S_2 \text{ Map}$$



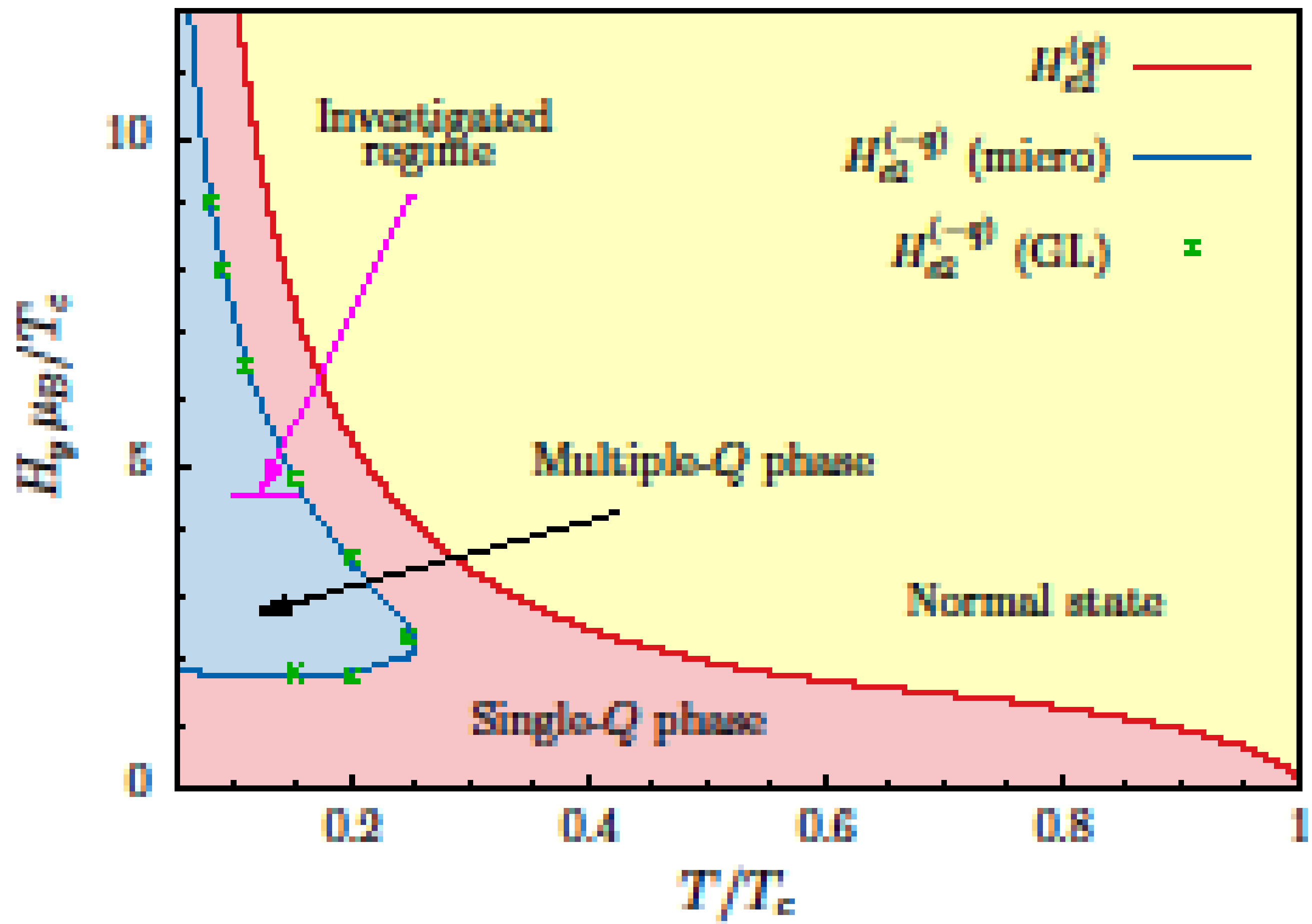
$$Q = \frac{1}{4\pi} \int_{R^2} (\hat{n} \cdot \partial_x \hat{n} \times \partial_y \hat{n}) dxdy$$

Q is non-zero (integer) when the two components have different core positions (Skyrmion)

Q =0 when the cores coincide (Abrikosov)

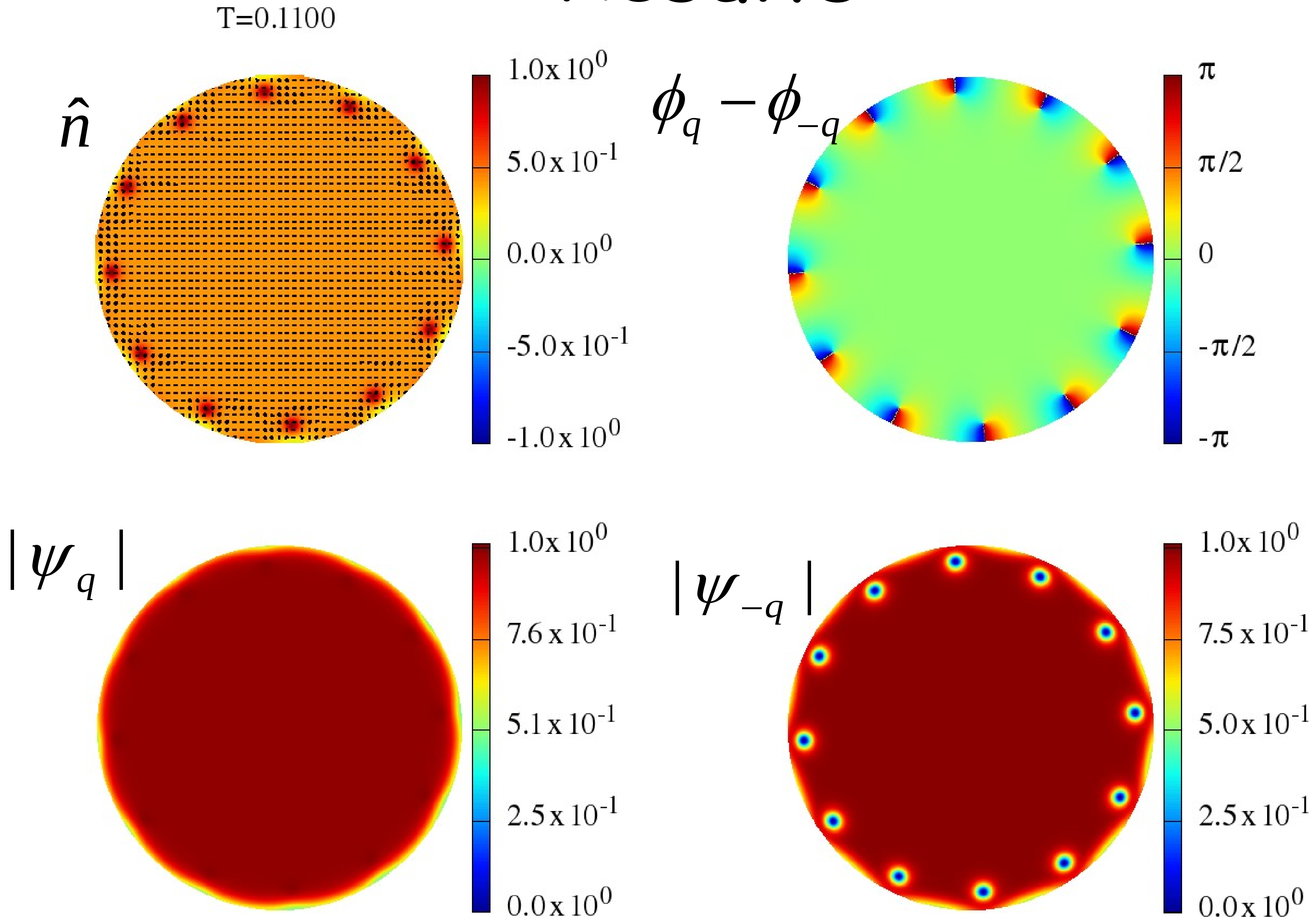
- Which defects are stable in field a c-axis field, fractional vortices, Abrikosov vortices, or Skyrmion vortices?

c-axis Field



For parameters investigated GL theory is valid since $1/q << \xi_0$

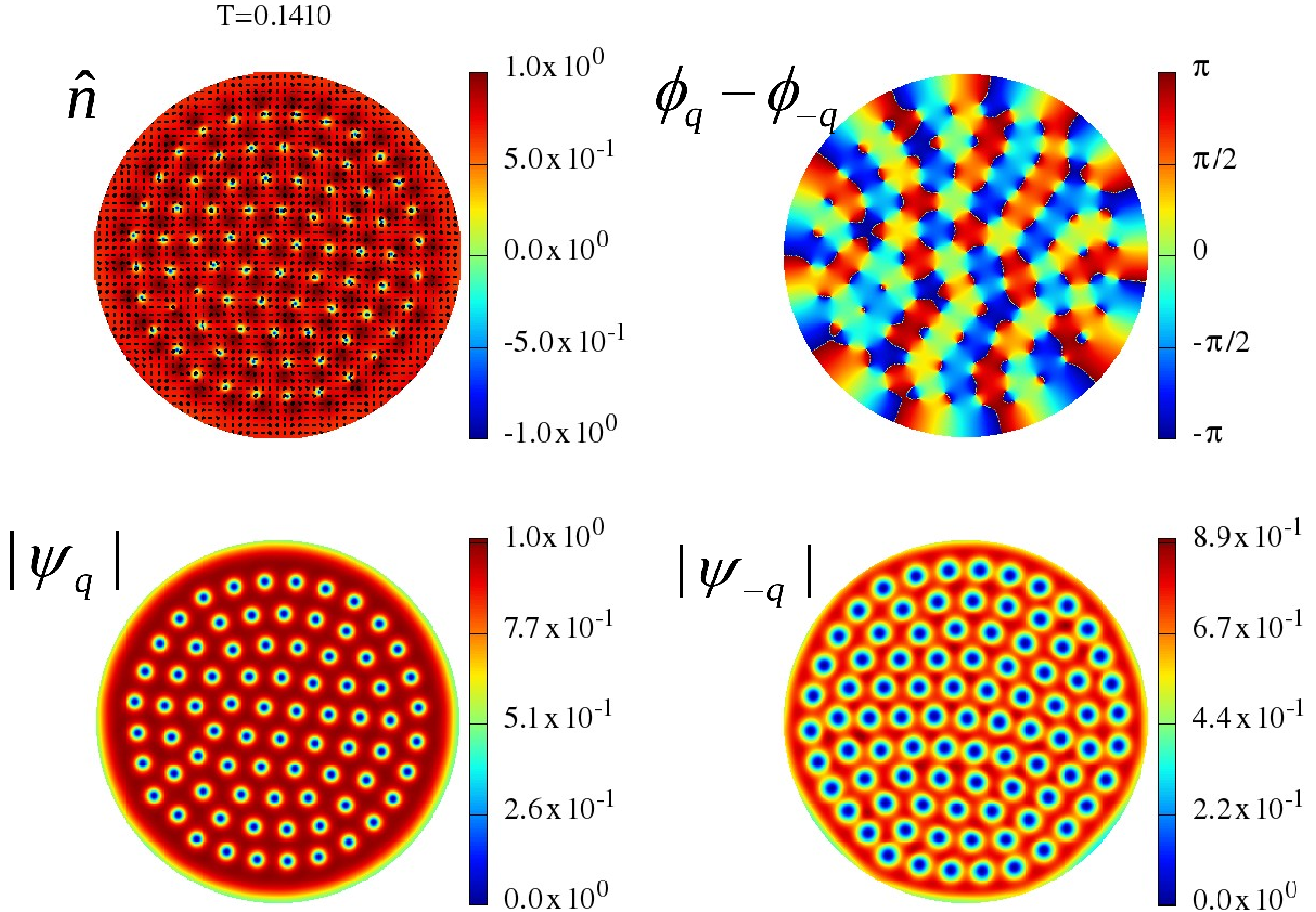
Results



Fractional vortices near the boundary

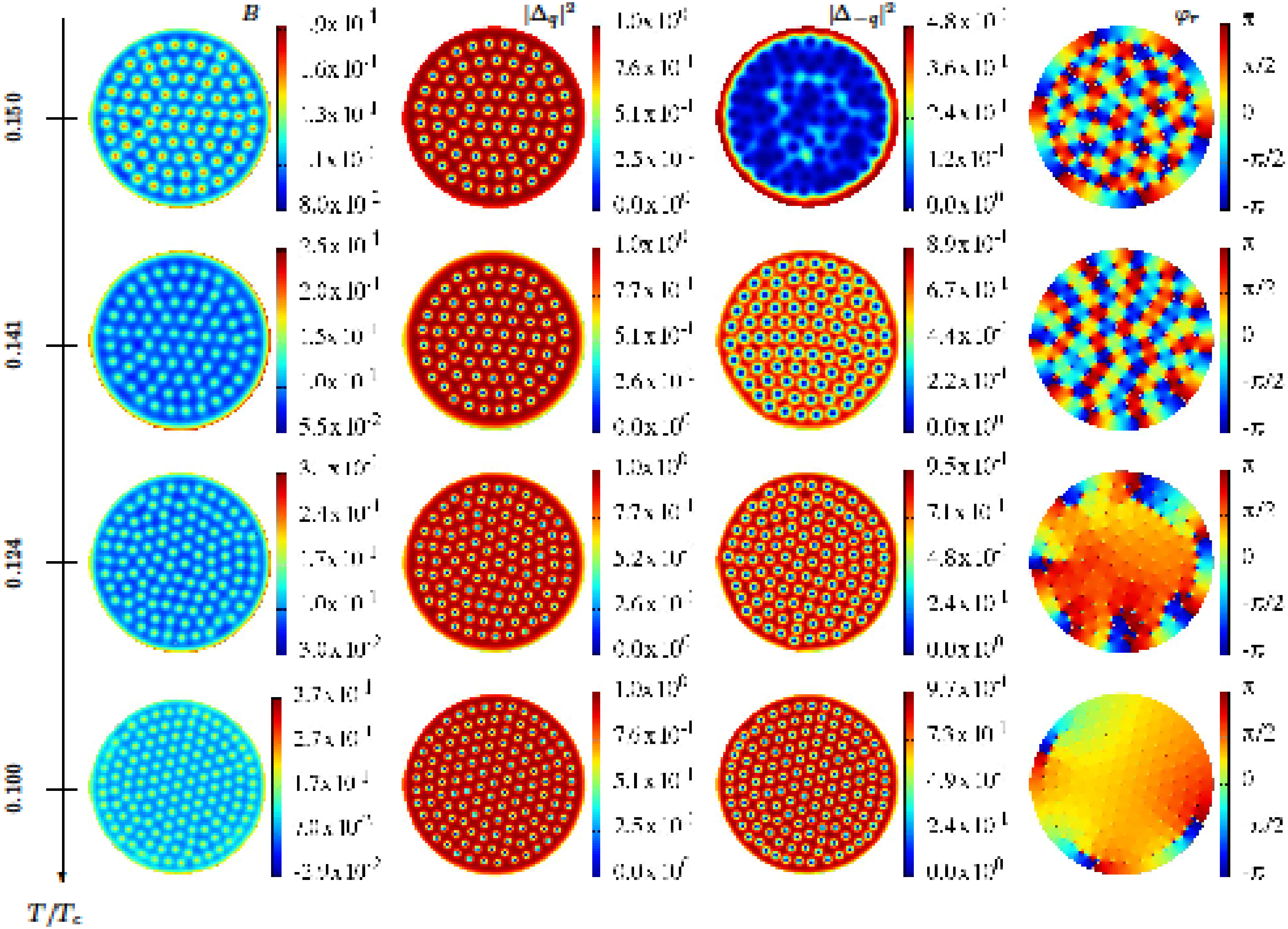
Boundary Fractional Vortices

- Stable because condition that no current flows through boundary.
- Can be implemented by image fractional anti-vortex.
- Fractional vortex anti-vortex pair does not have divergent line energy
- Fractional vortices stay near boundary because line energy grows with log L, L = vortex separation



Skyrmion vortex lattice at high fields

Moderate Field: Temperature Evolution



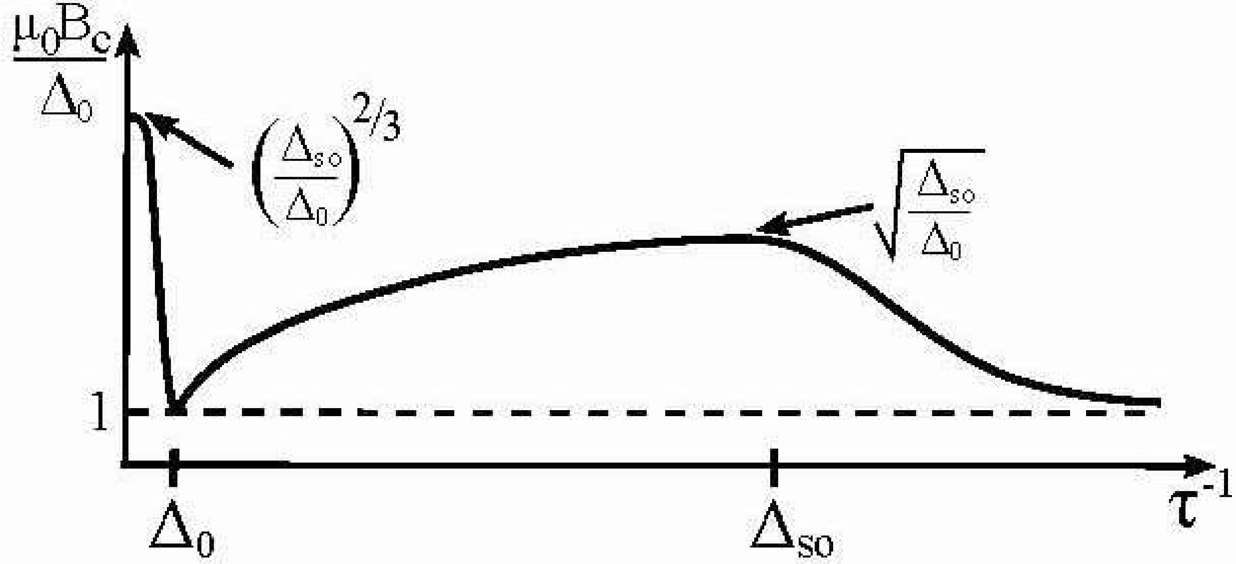
Conclusions

- 2D superconductors with Rashba spin-orbit coupling has finite momentum phases with in-plane fields.
- In clean limit, FFLO-like phase exists that supports fractional vortices, Abrikosov vortices, and Skyrmion vortices.
- Microscopic weak-coupling theory shows fractional vortices are stable near boundaries and Skyrmion vortex lattices appear when c-axis fields are applied

Results in-plane field Rashba Spin-Orbit

Barzykin and Gorkov, PRL (2002); DFA, Physica C (2003); Kaur, DFA, Sigrist PRL (2004); DFA and Kaur PRB (2007); Dimitrova and Feigel'man , PRB (2007); Yanase and Sigrist JPSJ (2007); Samokhin, PRB (2008); Mineev and Samokhin PRB (2008); Zhang et al. Nat. Comm. (2013)

Michaeli, Potter, PRL (2012)

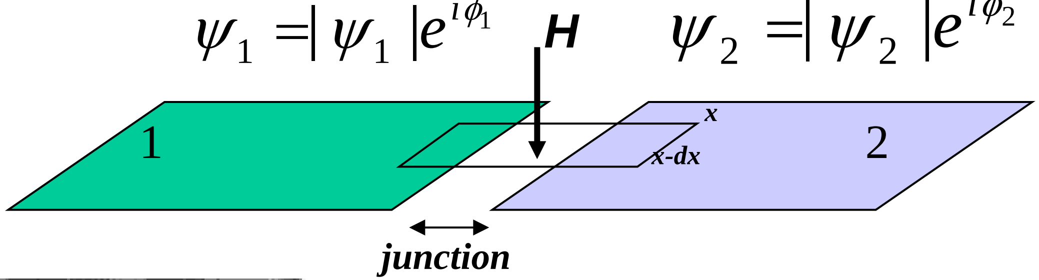


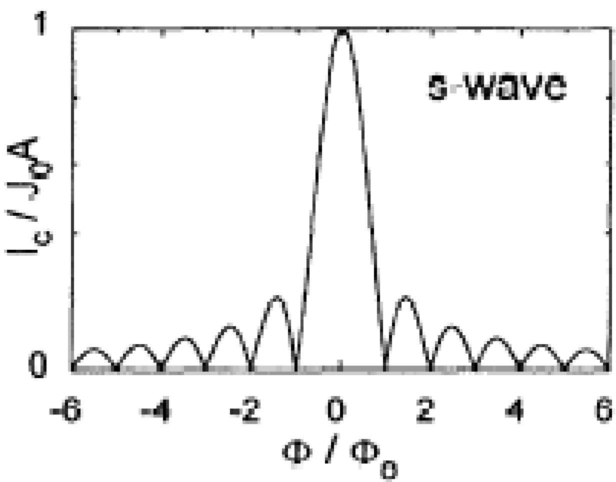
Survives to high Fields in disordered 2D Rashba

Josephson detection of helical phase

- The Helical phase can be *unambiguously* detected by a Josephson experiment

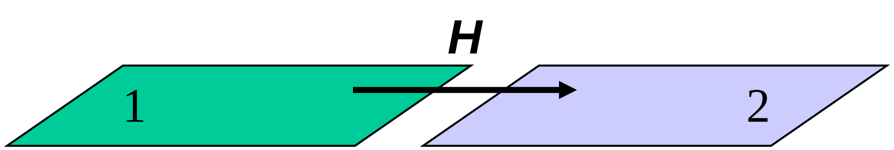
$$\psi_1 = |\psi_1| e^{i\phi_1} \qquad \psi_2 = |\psi_2| e^{i\phi_2}$$





Fraunhofer pattern

$$I = I_c \sin(\gamma_0) \frac{|\sin(\pi\Phi/\Phi_0)|}{|\pi\Phi/\Phi_0|}$$

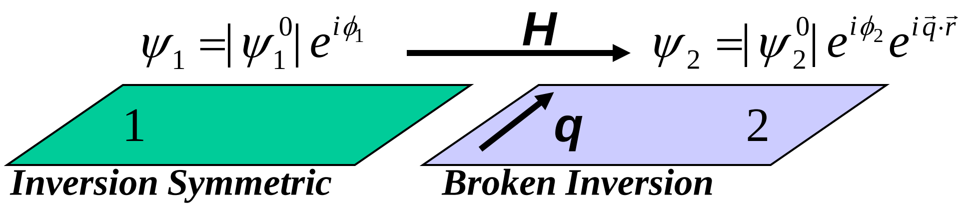


For this field in the plane, no Fraunhofer pattern

If one superconductor has single-q phase order parameter (say 2). The Josephson current will exhibit a *Fraunhofer pattern for field in the plane.*

$$I = \tilde{I}_c \frac{\sin(qL)}{qL}$$

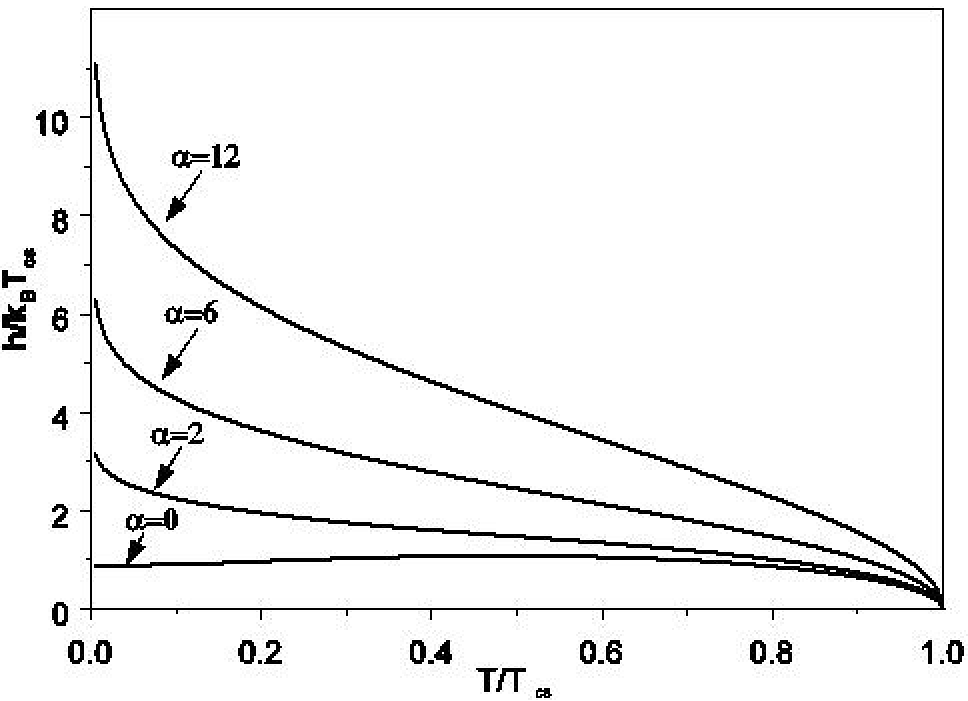
$$\vec{q} = -2m\varepsilon \hat{n} \times \vec{H}$$



For verification of helical phases by Josephson experiment, uniform $|\Psi|$ and in-plane *H* are required.

Enhancement of Pauli field

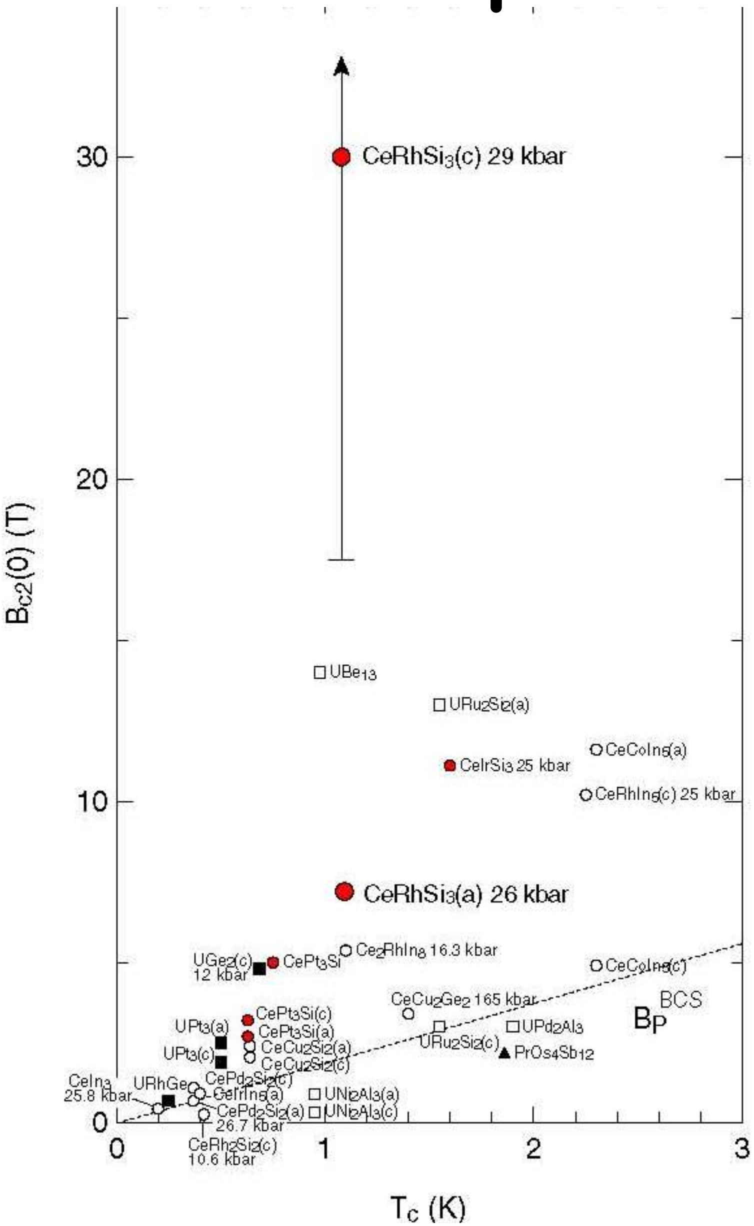
- Pauli field for **spin-singlet** case is strongly enhanced (also found by Bulaevski):



for $\vec{g} \cdot \vec{h} = 0$

Spin singlet pairing:
Paramagnetic limit diverge for T=0:
Spin triplet pairing:
No limitation if $\hat{g}_{\vec{k}} \parallel \vec{d}$

Experimental Results

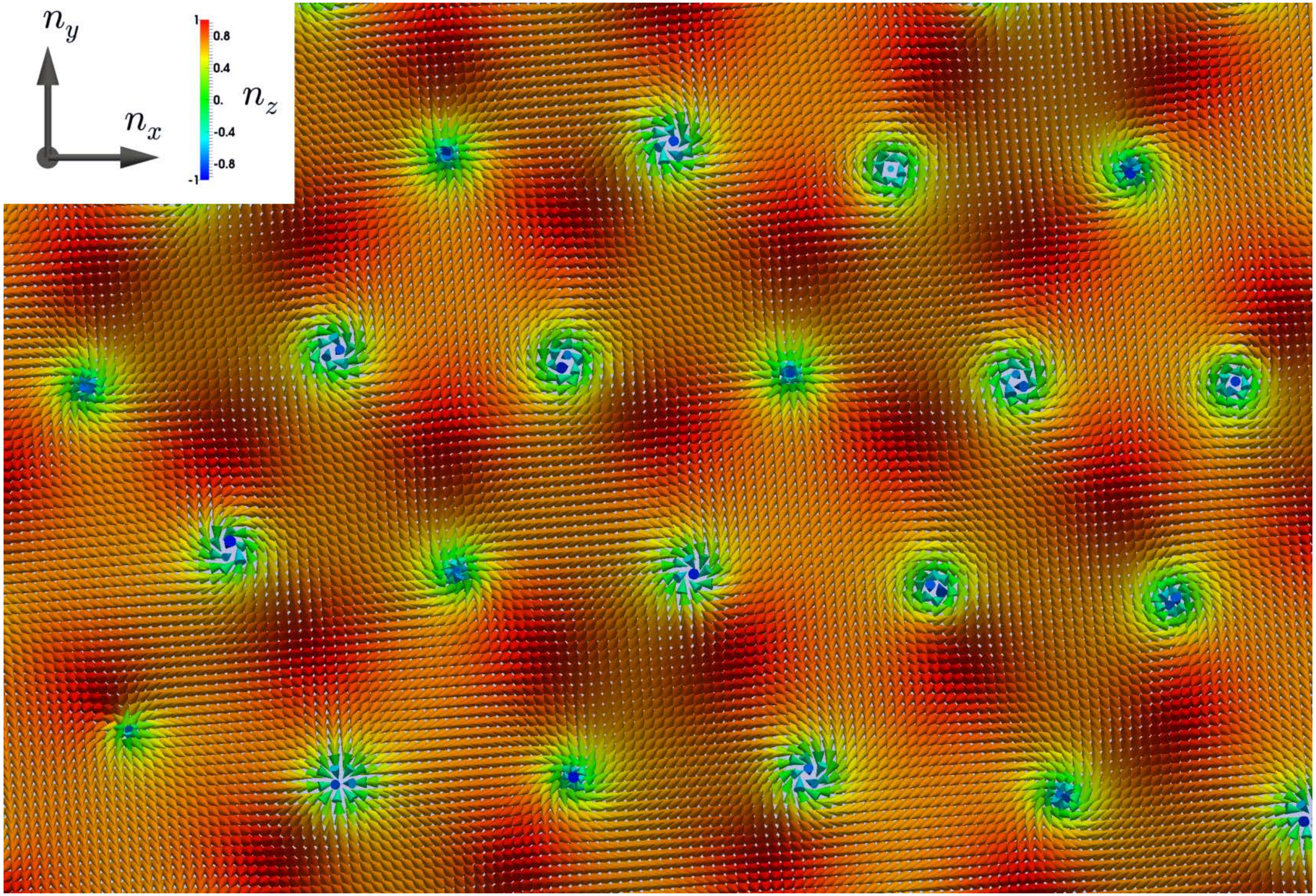


Kimura et al, PRL (2007)

Red dots are non-centrosymmetric materials with a Rashba spin-orbit.

They all surpass the Pauli field.

Critical field determined by vortex physics



n_y
n_x
n_z
1
0.8
0.4
0.
-0.4
-0.8
-1