Finite momentum pairing states in non-centrosymmetric superconductors

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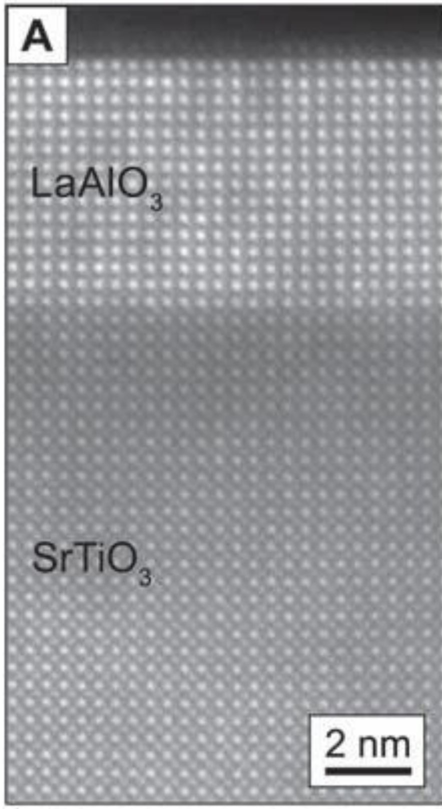
1- Relevant Materials – 2D interface superconductors
2- Superconductivity with Rashba spin-orbit coupling
3- “Most stable” weak-coupling pair density wave state
4- Abrikosov, Fractional, Skyrmion vortices (c-axis fields)
5- PDW broken time reversal symmetry in pseudo-gap phase.

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. Spin orbit large energy scale for SC.

Free energy without parity symmetry

GLW free energy with parity symmetry

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

Broken parity symmetry allows a new term in magnetic field

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

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

- Since f is minimized with q, this state carries no current
- finite momentum pairing guaranteed with in-plane field

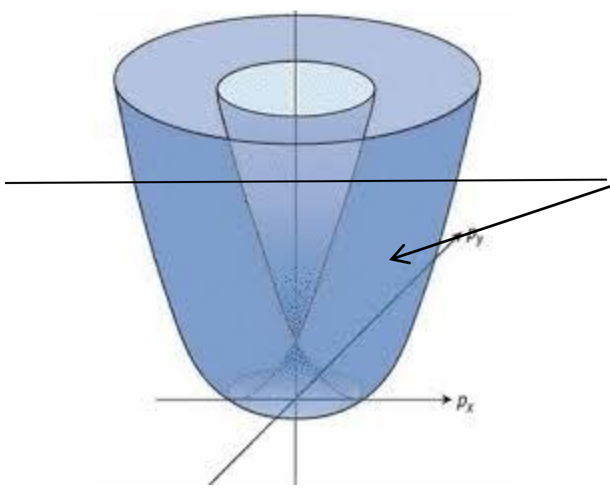
In q-space: $\varepsilon(\hat{n}\times\vec{B})\cdot\vec{q}\left(|\psi_q|^2 - |\psi_{-q}|^2\right)$ (cuprates)

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

Microscopic Model

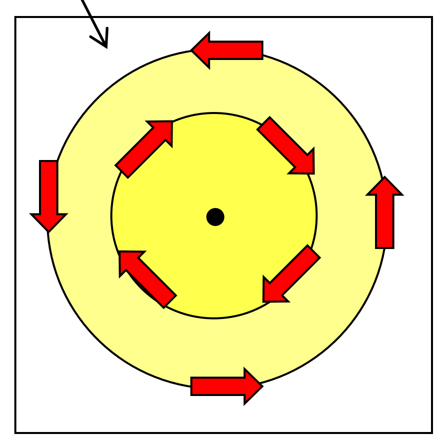
$$H = \sum_{k,s} \xi_k c^t_{ks} c_{ks} + \frac{1}{2} \sum_{k,k',q,s,s'} V c^t_{k+qs} c^t_{-k+qs'} c_{-k'+qs'} c_{k'+qs}$$

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



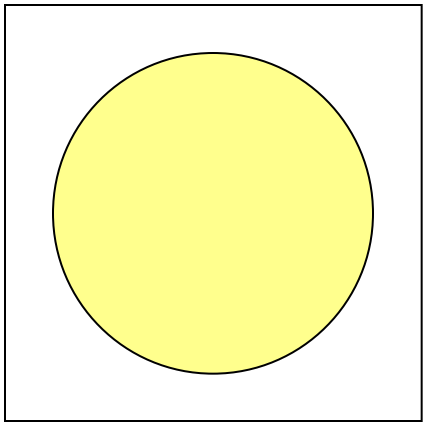
$$\vec{g}_k = \alpha(\hat{x}k_y - \hat{y}k_x)$$

$$\vec{h} = 0$$

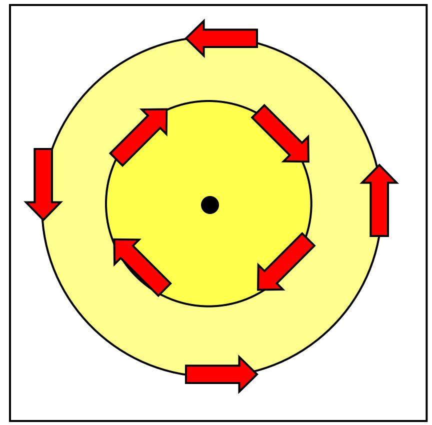


$$\delta N = \frac{N_1 - N_2}{N_1 + N_2} (\cong 0.05)$$

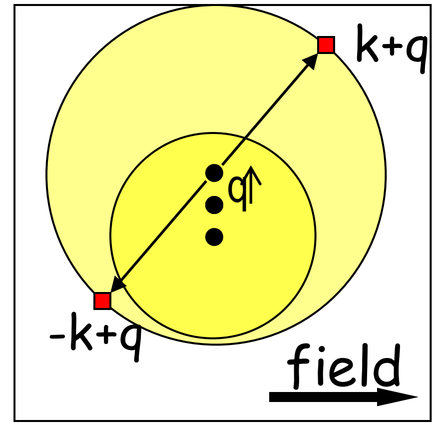
Finite Momentum Pairing



No Rashba



With Rashba



With Rashba and Zeeman Field

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

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

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

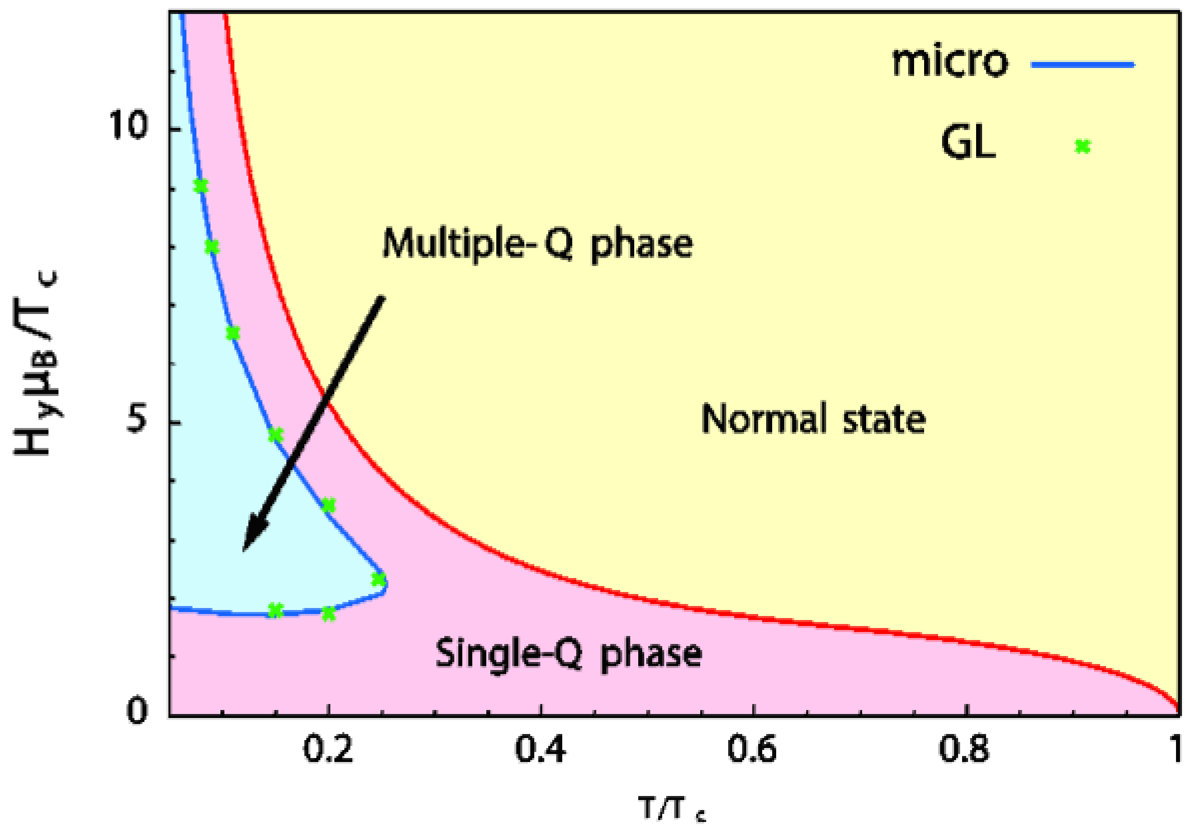
$$\Delta(\vec{r}) = \Delta_0 e^{i2\vec{q}.\vec{r}}$$

All states on one FS are paired

The two bands prefer opposite q vectors.

Barzykin, Gorkov, Dimitrova, Feigel'man, Samokhin, Mineev, Michaeli, Potter,Lee, Loder, Kampf, Kopp

Phase Diagram



Single-Q phase: $\psi(\vec{r}) = \psi_{2q} e^{i2\vec{q}.\vec{r}}$

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

Theory of ψ_q and ψ_{-q}

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

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

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

Important for PDW and FFLO

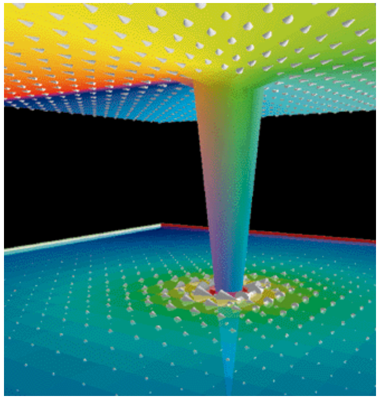
General feature: $(\psi_q)^n (\psi_q^*)^m (\psi_{-q})^p (\psi_{-q}^*)^k$

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

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

$$\oint A \cdot dl = \frac{|\psi_q|^2}{|\psi_q|^2 + |\psi_{-q}|^2}\Phi_0$$

Fractional Flux vortices have line energies that diverge as logR

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

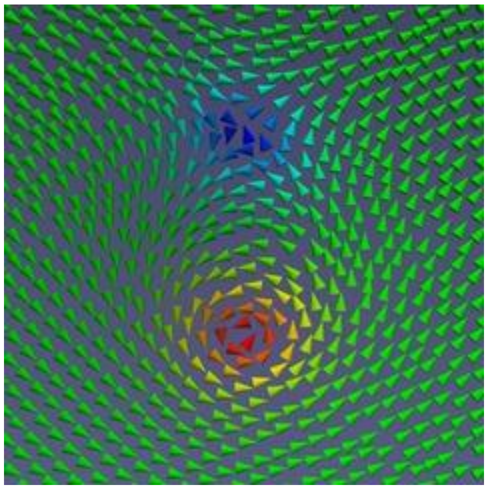
Two kinds of (1,1) vortices: Abrikosov vortices and Skyrmion vortices

Abrikosov/Skyrmion Vortices

$$\Psi = \begin{pmatrix} \psi_q \\ \psi_{-q} \end{pmatrix}$$

$$\hat{n} = \frac{\Psi^t \vec{\sigma} \Psi}{\Psi^t \Psi}$$

$S_2 \to S_2$ Map



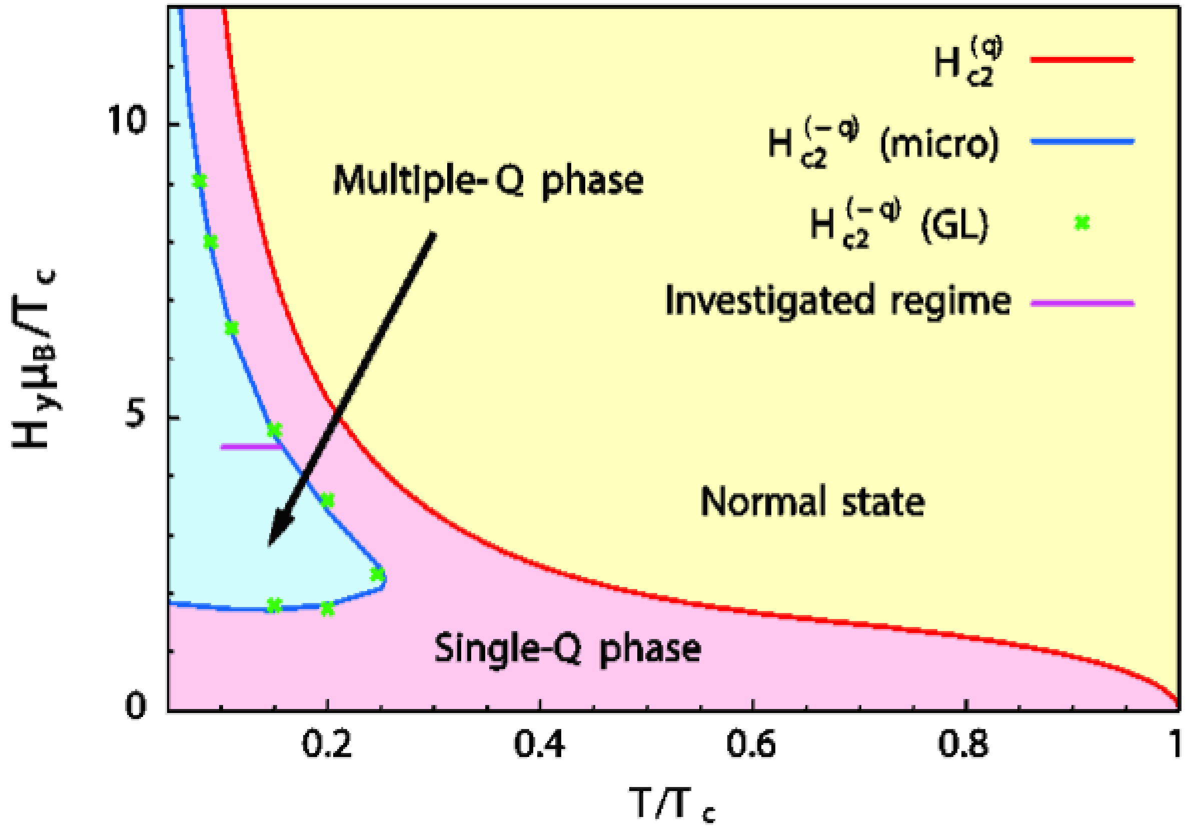
$$Q = \frac{1}{4\pi} \int_{R^2} (\hat{n} \cdot \partial_x \hat{n} \times \partial_y \hat{n}) dxdy$$

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

Q =0 when the cores coincide (Abrikosov)

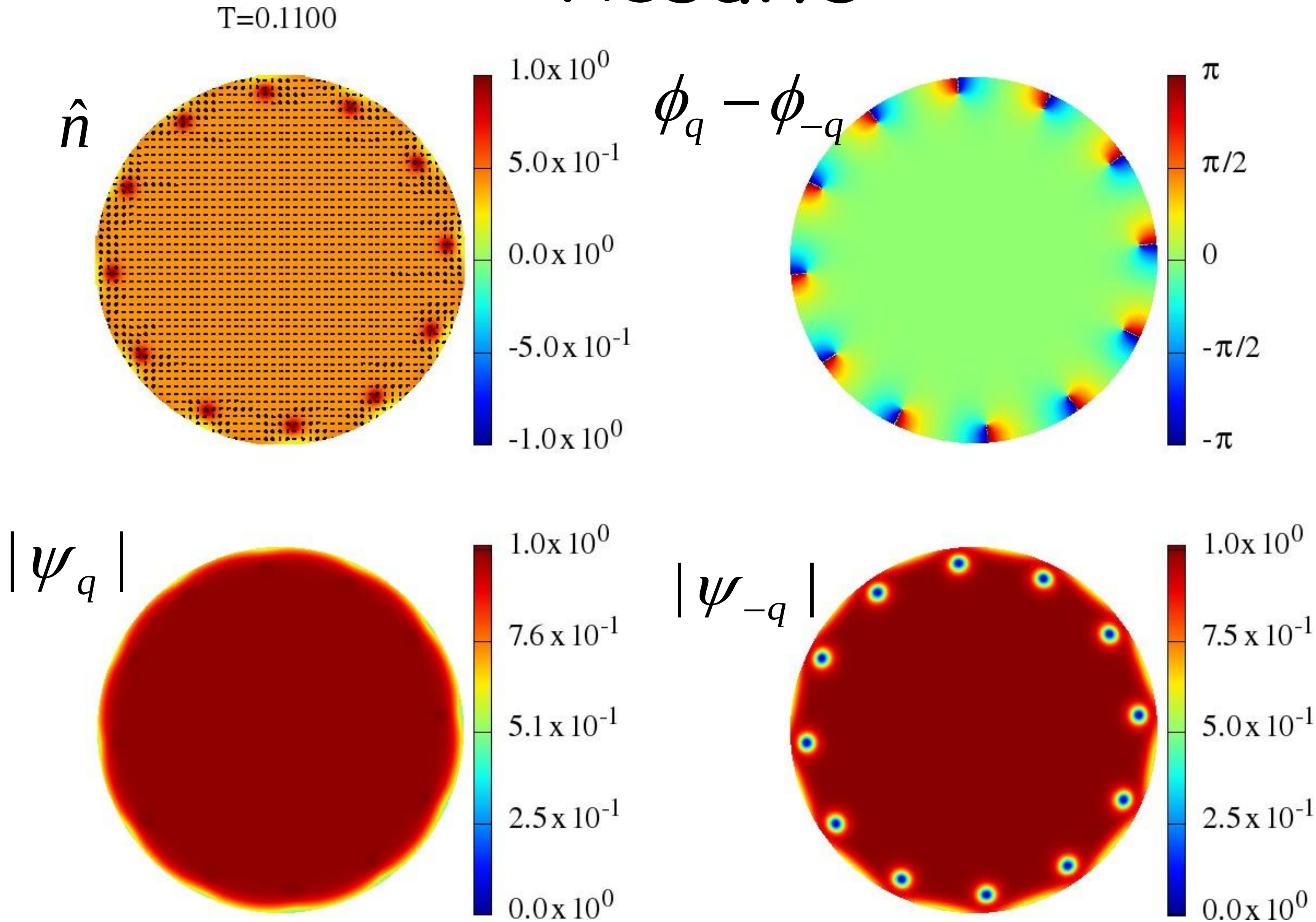
- Which defects are stable in a c-axis field, fractional vortices, Abrikosov vortices, or Skyrmion vortices?

c-axis Field

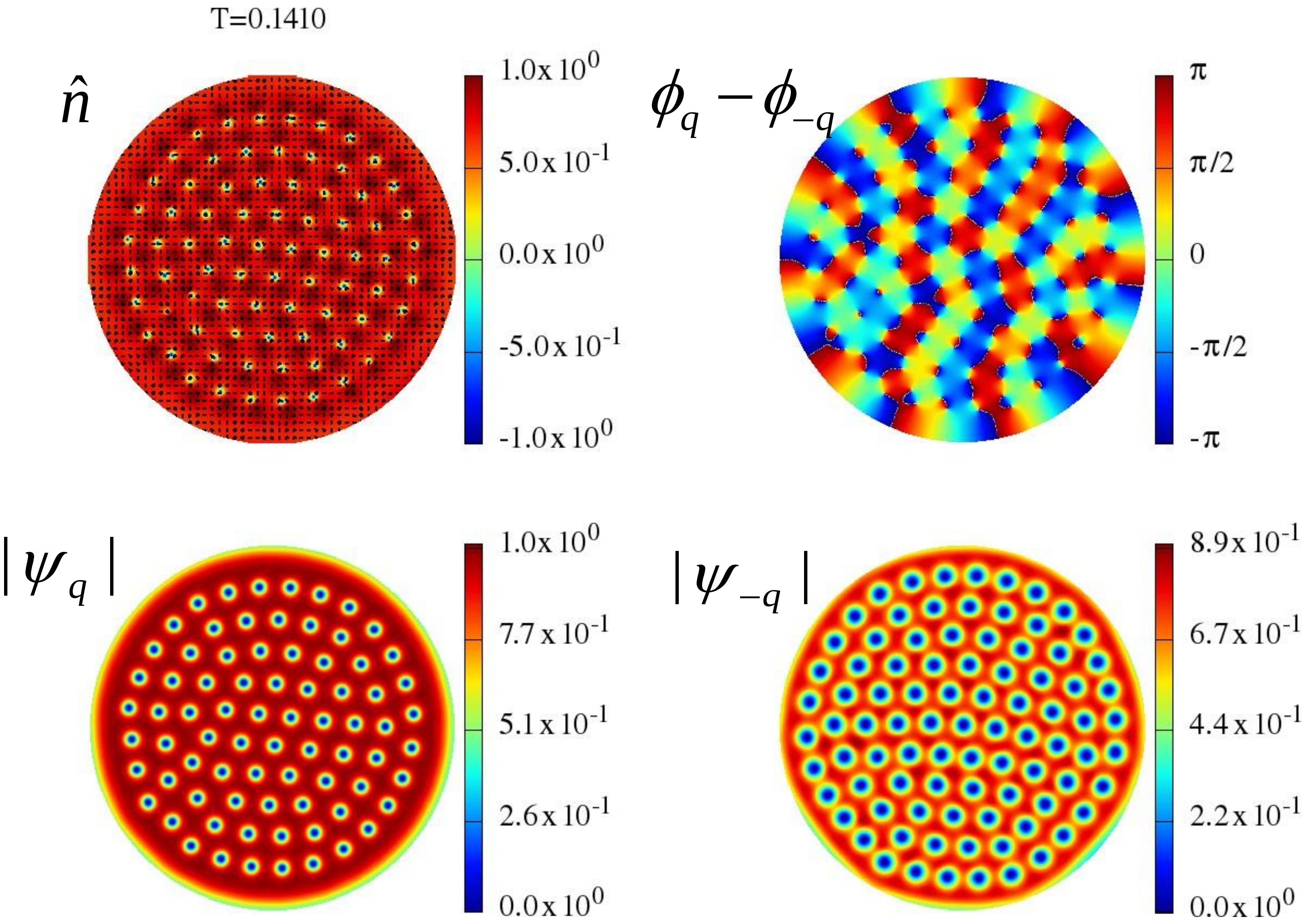


For parameters investigated GL theory is valid since $1/q << \xi_0$

Results

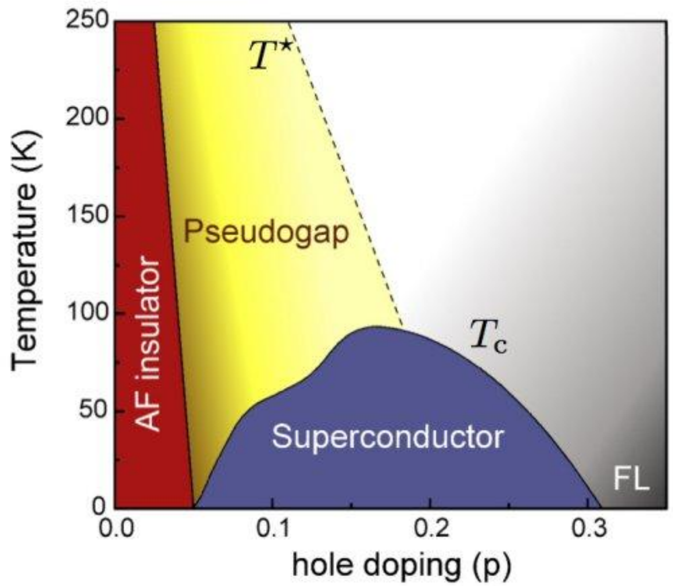


Fractional vortices near the boundary, sometimes two rings



Skyrmion vortex lattice at high fields

Pseudogap Phase

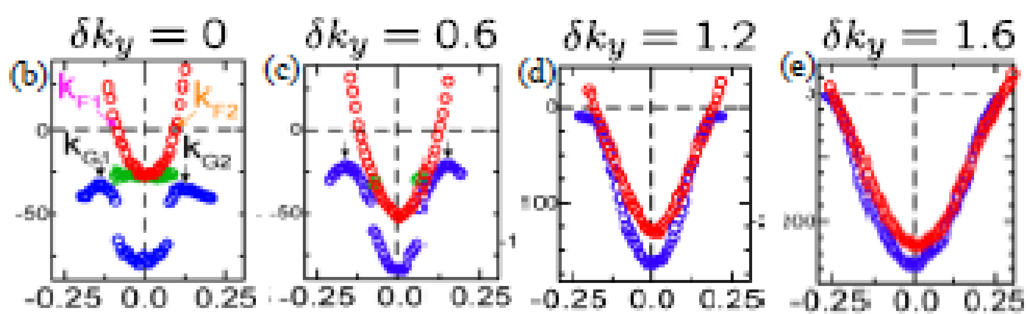


PDW/Amperean pairing proposal for cuprates:
(Lee, Berg, Fradkin, Kivelson, Loder, Kampf, Kopp, Ogata, Corboz, DFA, Tsunetsugu, Troyer, Rice, Himeda…)

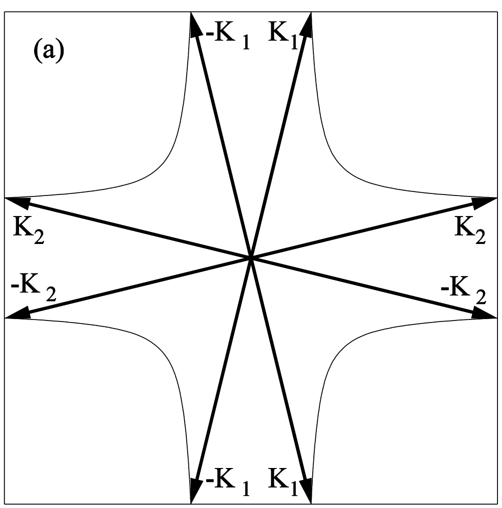
1- CDW order (near T*)

2- Superconducting fluctuations well above Tc

3- ARPES in pseudogap (Lee, PRX 2014)



R.H. He et al, Science 2011



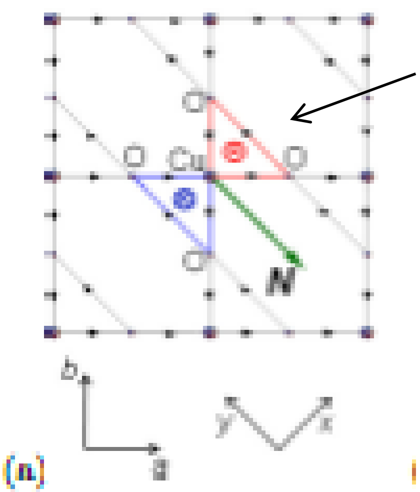
Most PDW proposals cannot account for broken time reversal

Specific proposal of PA Lee

$$|\Delta_{2K_1}| = |\Delta_{-2K_1}| = |\Delta_{2K_2}| = |\Delta_{-2K_2}|$$

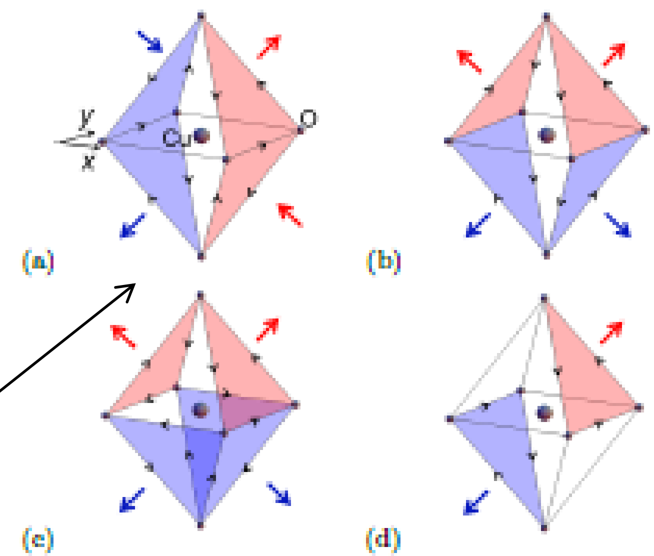
Broken Time Reversal in the Pseudogap Phase

- Spin polarized neutron scattering sees intra-cell magnetic order with in-plane and c-axis components [Sidis and P. Bourges, J. Phys.: Conf. Ser. **449**, 012012 (2013)].
- Polar Kerr effect is measured near CDW order onset (Karapetyan et al. PRL **112**, 047003).
- Both explained by tilted loop current state (V.M. Yakovenko, arXiv:1409.2183)



Original in-plane loop current proposal of Varma and Simon – has no Kerr effect

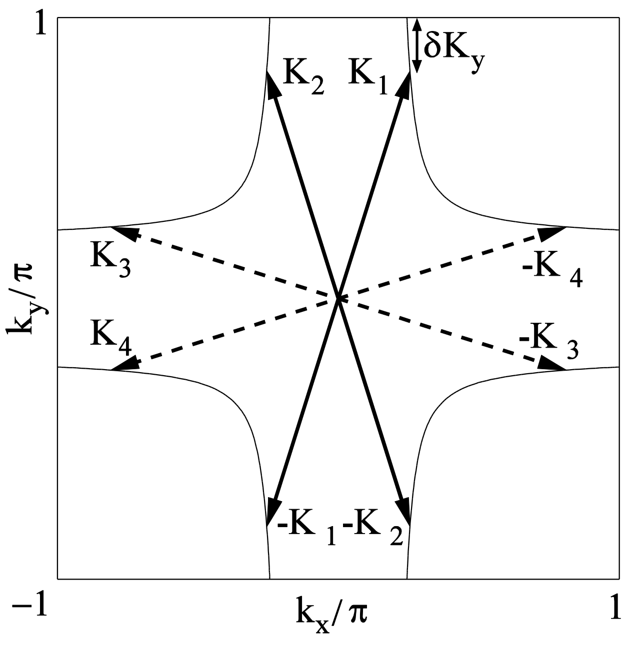
Possible generalizations: only (d) is consistent with neutrons and polar Kerr.



Broken time reversal from PDW order

Key observation: The following Q=0 order is odd under time reversal (T) and parity (P) but even under TP: $l_Q = |\Delta_Q|^2 - |\Delta_{-Q}|^2$

(discrete order parameter independent of U(1)'s)



arXiv:1406.4959

Specific PDW proposal that accounts for broken T:

$$\Delta_{2K_1} = \Delta_{2K_3}; \Delta_{2K_2} = \Delta_{2K_4}$$

$$\Delta_{-2K_1} = \Delta_{-2K_2} = \Delta_{-2K_3} = \Delta_{-2K_4} = 0$$

-This state has the same symmetries as the in-plane loop current phase.

-The titled loop current can be found by adding the same Kz component to all Ki.

-It is closely related to the proposal of P.A. Lee (and can account for ARPES)

-This state is a minimum of GLW theory

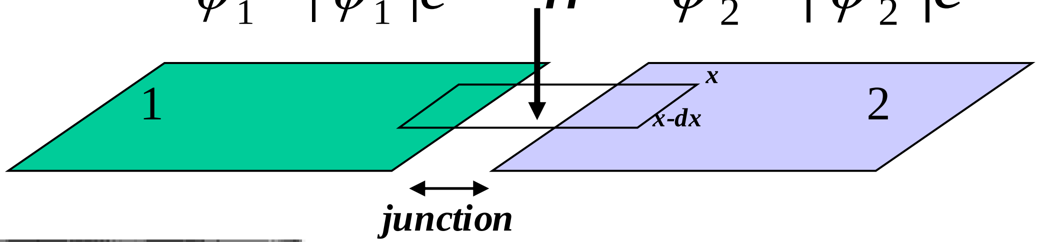
Conclusions

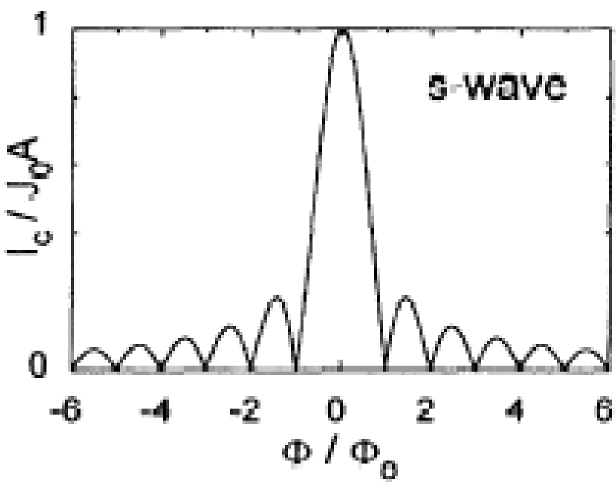
- 2D superconductors with Rashba spin-orbit coupling has finite momentum phases with in-plane fields.
- In clean limit, FFLO-like phase exists that, in principle, supports fractional vortices, Abrikosov vortices, and Skyrmion vortices.
- Microscopic weak-coupling theory shows fractional vortices are stable near boundaries and Skyrmion vortex lattices appear when c-axis fields are applied
- There exists a PDW phase that is consistent with CDW order, SC fluctuations, signatures of broken time reversal symmetry, and ARPES measurements in the pseudogap phase.

Josephson detection of helical phase

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

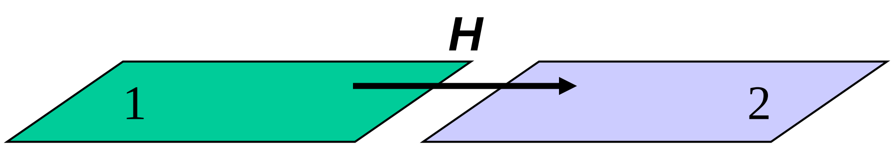
$$\psi_1 = |\psi_1| e^{i\phi_1} \qquad \psi_2 = |\psi_2| e^{i\phi_2}$$





Fraunhofer pattern

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

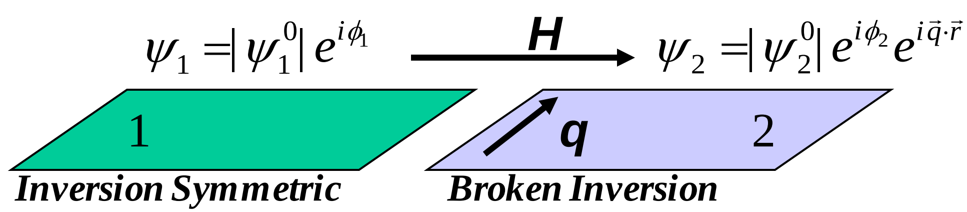


For this field in the plane, no Fraunhofer pattern

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.

PRL 94, 13702 (2005)