27pEM-7

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2013.3.27

トポロジカル超伝導体としてのUPt_3

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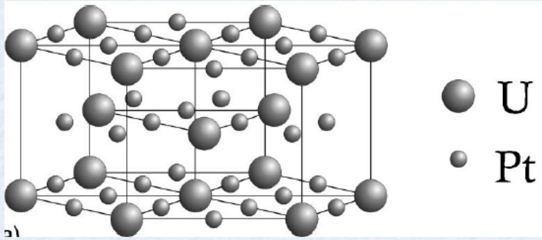
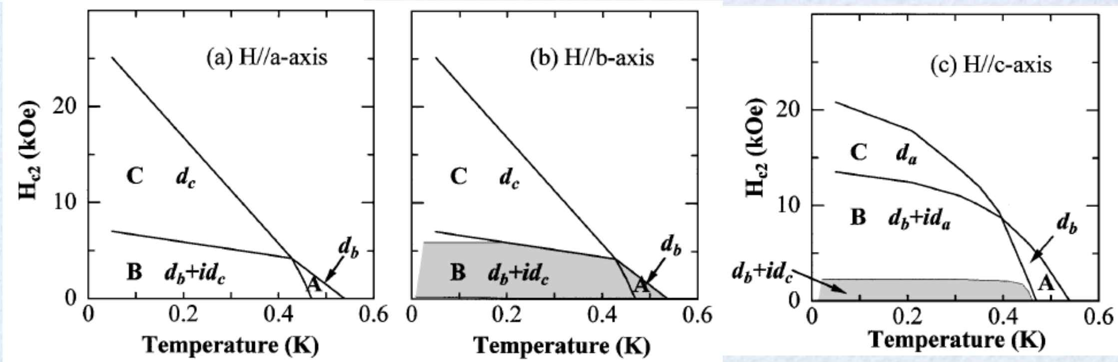
Superconductivity in UPt_3

Crystal structure



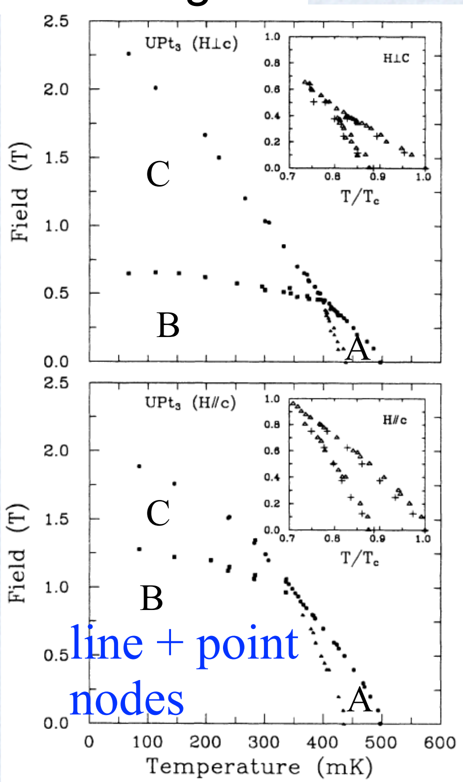
D_{6h}
hexagonal

NMR Knight shift



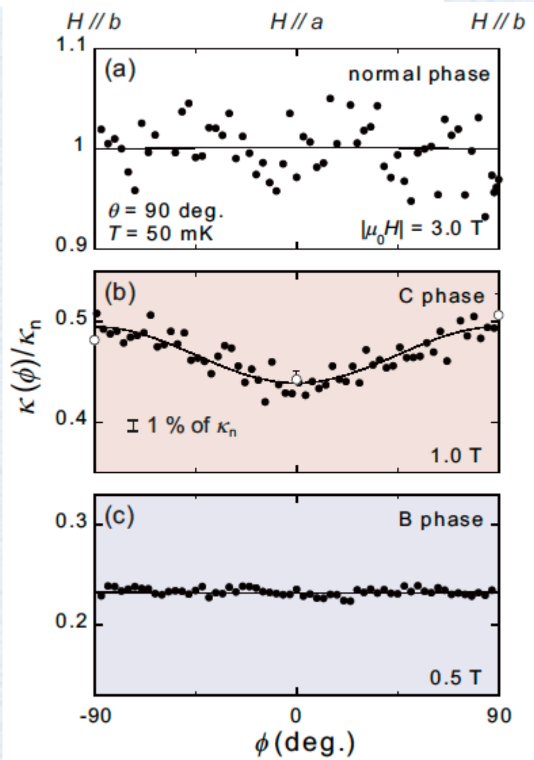
H. Tou *et al.*, PRL **80**, 3129 (1998).

Phase diagram



S. Adenwalla *et al.*, PRL **65**, 2298 (1990).

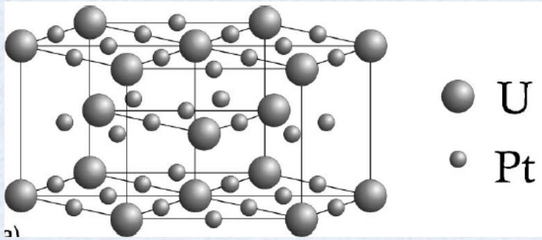
Thermal conductivity



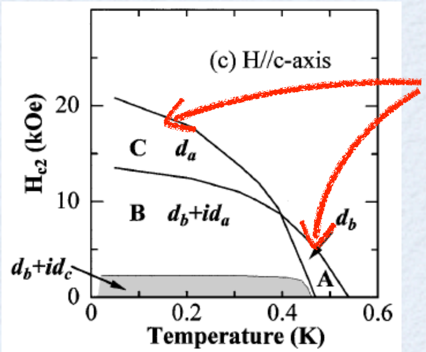
Y. Machida *et al.*, PRL **108**, 157002 (2012).

- ☑ line + point nodes in B phase
- ☑ spin-triplet
- ☑ twofold symmetry in C phase

Gap function



D_{6h}
hexagonal



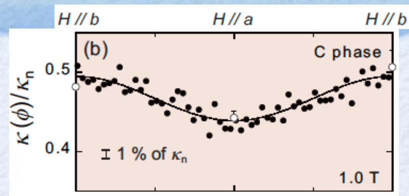
2次元表現

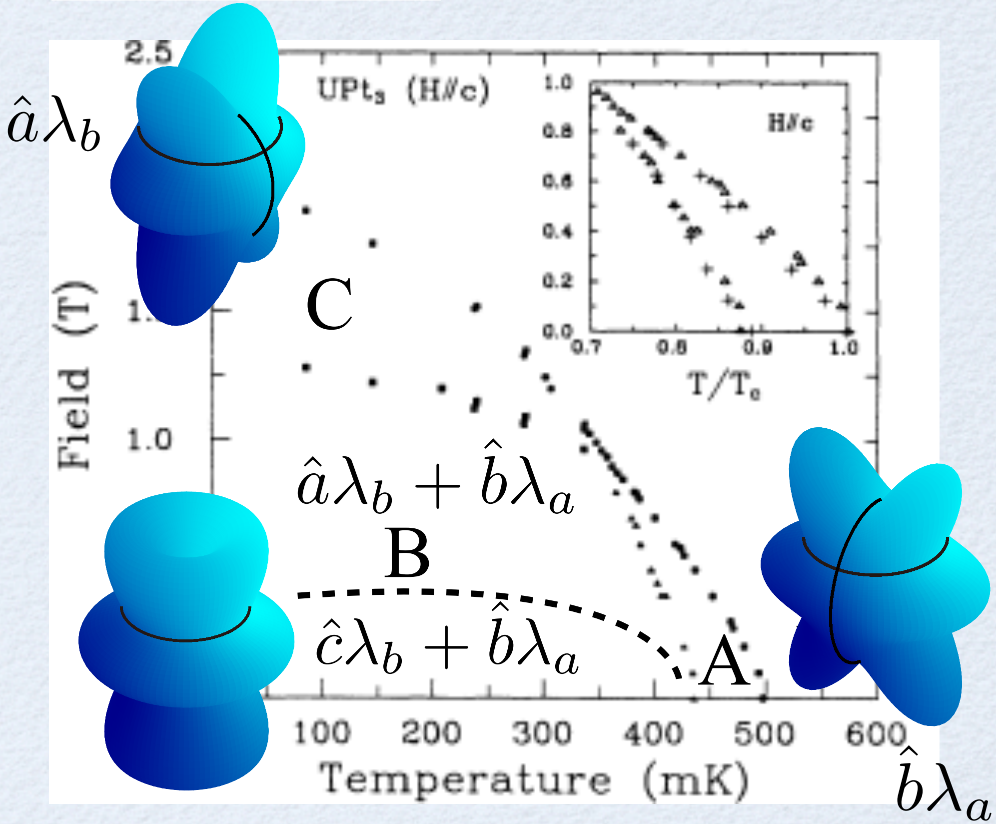
- ☑ line + point nodes
- ☑ twofold symmetry

f-wave: $Y_3^{\pm 1}(\theta,\phi) \propto \sin\theta(5\cos^2\theta - 1)e^{\pm i\phi}$

E$_{1u}$ representation

$$\lambda_a = k_a(5k_c^2 - 1),\ \lambda_b = k_b(5k_c^2 - 1)$$





Y. Tsutsumi *et al.*, JPSJ **81**, 074717 (2012).

B phase: unitary state

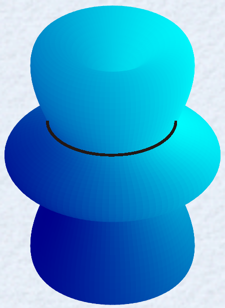
$$k_c = \pm 1/\sqrt{5}$$

tropical line nodes: $\theta \approx 66^\circ, 114^\circ$

Topological aspect

UPt_3 B phase

$(\hat{b}k_a + \hat{c}k_b)(5k_c^2 - 1)$

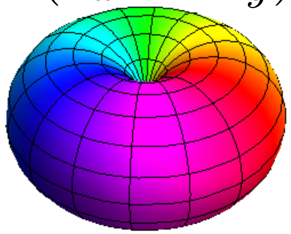


helical state
point nodes
tropical line nodes

- ☑ edge state
- ☑ vortex core state

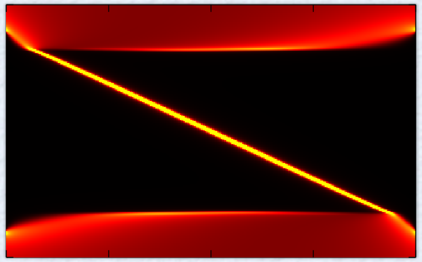
^3He A-phase

$\hat{z}(k_x + ik_y)$



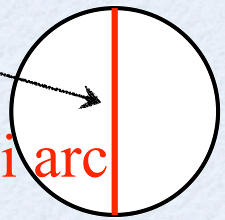
chiral superfluid

Edge state



mass current

$k_z = +k_F$



zero energy state

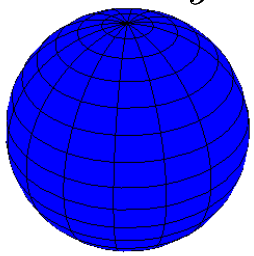
topological Fermi arc

$k_z = -k_F$

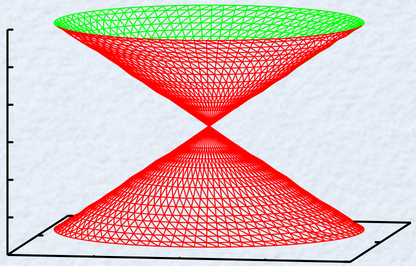
G. E. Volovik, arXiv:1110.4469.

^3He B-phase

$\hat{x}k_x + \hat{y}k_y + \hat{z}k_z$

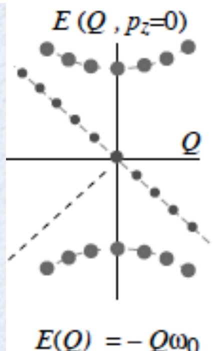


helical superfluid



Majorana cone
spin current

Vortex core state



normal core vortex

Majorana
zero energy mode

G. E. Volovik

Quasi-classical Eilenberger theory

$\Delta/E_F \ll 1$ $$\int d\xi_k \widehat{\sigma}_z \widehat{G}(\boldsymbol{k},\boldsymbol{r},\omega_n) \equiv \widehat{g}(\boldsymbol{k}_F,\boldsymbol{r},\omega_n) \equiv -i\pi \begin{pmatrix} \hat{g} & i\hat{f} \\ -i\underline{\hat{f}} & -\underline{\hat{g}} \end{pmatrix}$$

Eilenberger equation

$$-i\hbar \boldsymbol{v}_F \cdot \boldsymbol{\nabla} \widehat{g}(\boldsymbol{k}_F,\boldsymbol{r},\omega_n) = \left[\begin{pmatrix} i\omega_n \hat{1} & -\hat{\Delta}(\boldsymbol{k}_F,\boldsymbol{r}) \\ \hat{\Delta}^\dagger(\boldsymbol{k}_F,\boldsymbol{r}) & -i\omega_n \hat{1} \end{pmatrix}, \widehat{g}(\boldsymbol{k}_F,\boldsymbol{r},\omega_n) \right]$$

$\widehat{g}$ ↓ ↑ $\hat{\Delta}$

Gap equation

$$\hat{\Delta}(\boldsymbol{k}_F,\boldsymbol{r}) = N_0 \pi k_B T \sum_{-\omega_c \le \omega_n \le \omega_c} \left\langle V(\boldsymbol{k}_F,\boldsymbol{k}'_F) \hat{f}(\boldsymbol{k}'_F,\boldsymbol{r},\omega_n) \right\rangle_{\boldsymbol{k}'_F}$$

Current

$$\boldsymbol{j}_0^\mu(\boldsymbol{r}) = j_0^\mu \pi k_B T \sum_{\omega_n} \langle \boldsymbol{v}_F \mathrm{Im}[g_\mu(\boldsymbol{k}_F,\boldsymbol{r},\omega_n)] \rangle_{\boldsymbol{k}_F}$$

$$\hat{g} = \begin{pmatrix} g_0 + g_z & g_x - i g_y \\ g_x + i g_y & g_0 - g_z \end{pmatrix}$$

$\mu = 0$: charge current

$\mu = x, y, z$: spin current of μ-spin

Local density of states (LDOS)

$$N(\boldsymbol{r},E) = \underline{\langle N(\boldsymbol{k}_F,\boldsymbol{r},E) \rangle}_{\boldsymbol{k}_F} = N_0 \langle \mathrm{Re}[g_0(\boldsymbol{k}_F,\boldsymbol{r},\omega_n)|_{i\omega_n \to E + i\eta}] \rangle_{\boldsymbol{k}_F}$$

Dispersion

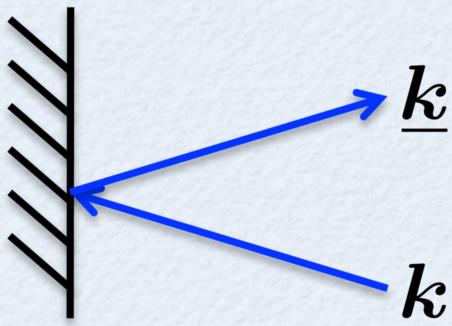
Calculation of edge state

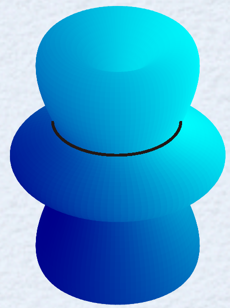
specular edge

$$\widehat{g}(\boldsymbol{k}, a=0, \omega_n) = \widehat{g}(\underline{\boldsymbol{k}}, a=0, \omega_n)$$

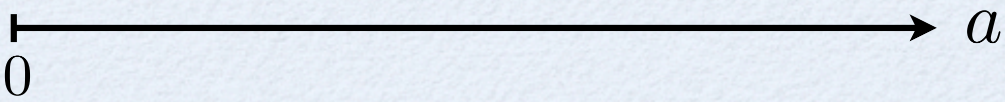
$$\boldsymbol{k} = (k_a, k_b, k_c)$$

$$\underline{\boldsymbol{k}} = (-k_a, k_b, k_c)$$





$$\hat{\Delta} = \Delta_0(\hat{b}k_a + \hat{c}k_b)(5k_c^2 - 1)$$

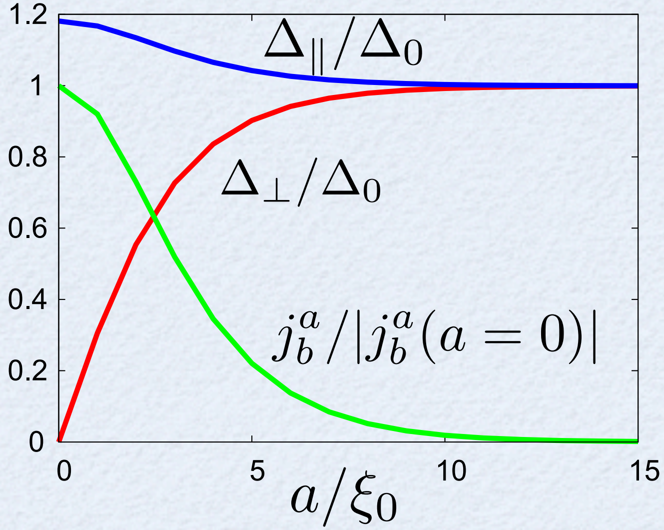


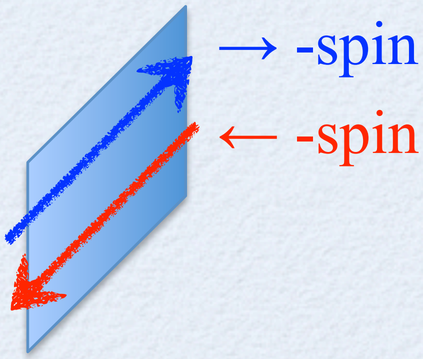
Result of edge state

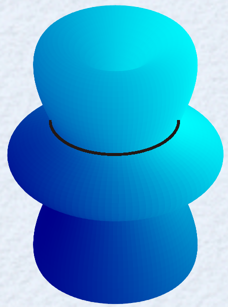
$$\hat{\Delta}(a,\boldsymbol{k}) = (\Delta_{\perp}(a)\hat{b}k_a + \Delta_{\parallel}(a)\hat{c}k_b)(5k_c^2 - 1)$$

$$\Delta_{\perp,\parallel}(a \to \infty) = \Delta_0$$

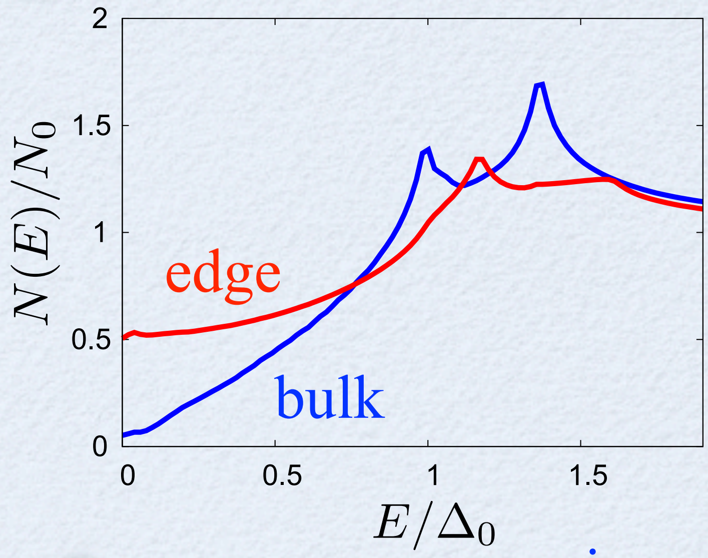
order parameter and spin current



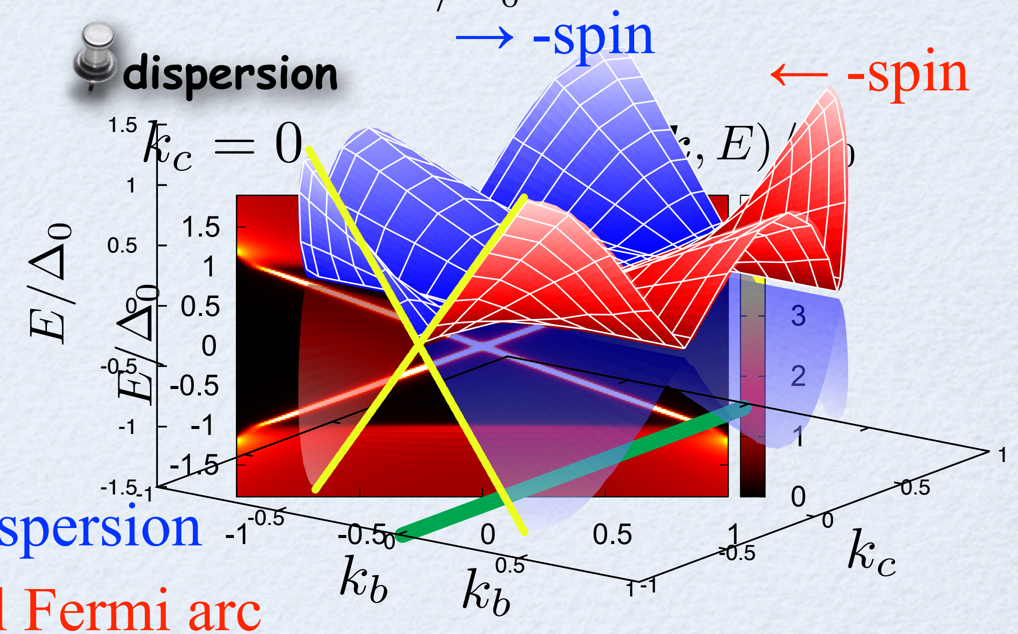




LDOS



dispersion



linear dispersion

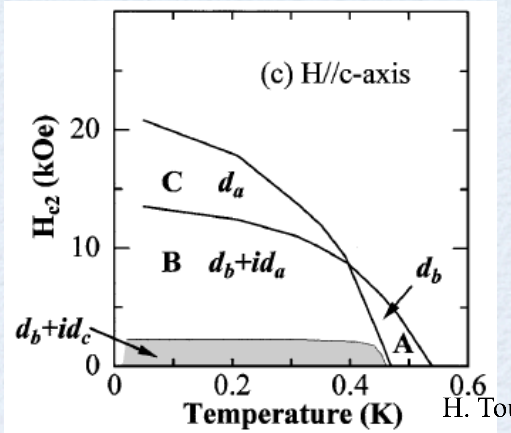
topological Fermi arc

Calculation of vortex state

$$\hat{\Delta}(\boldsymbol{r},\boldsymbol{k}) = \Delta(\boldsymbol{r})(\hat{b}k_a + \hat{c}k_b)(5k_c^2 - 1)$$

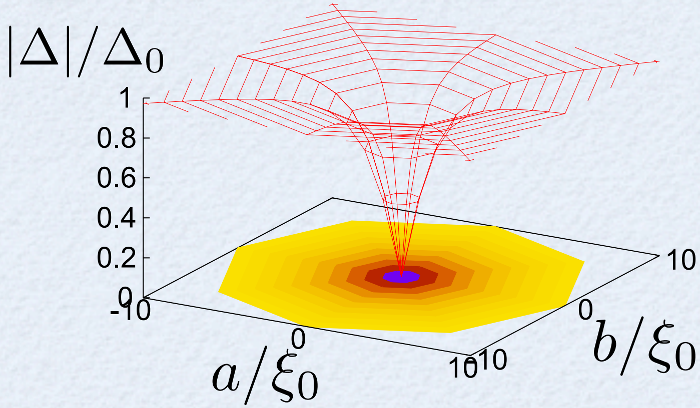
vortex // c-axis

$$\Delta(\boldsymbol{r} \to \infty) = \Delta_0 e^{i\phi}$$



H. Tou *et al.*, PRL **80**, 3129 (1998).

normal-core vortex

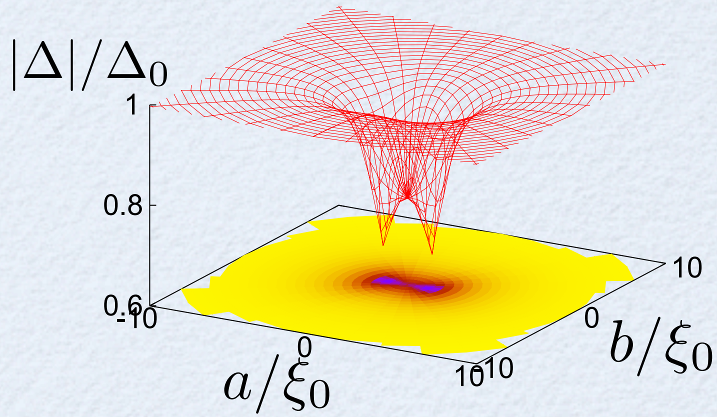


double-core vortex

$$\Delta_a \hat{a} k_b (5k_c^2 - 1)$$

stable in low-T & low-H region

Y. Tsutsumi *et al.*, JPSJ **81**, 074717 (2012).



Bogoliubov-de Gennes theory

$$\int d\boldsymbol{r}_2 \begin{pmatrix} H_0(\boldsymbol{r}_1,\boldsymbol{r}_2) & \Delta(\boldsymbol{r}_1,\boldsymbol{r}_2) \\ -\Delta(\boldsymbol{r}_1,\boldsymbol{r}_2)^* & -H_0^*(\boldsymbol{r}_1,\boldsymbol{r}_2) \end{pmatrix} \begin{pmatrix} u(\boldsymbol{r}_2) \\ v(\boldsymbol{r}_2) \end{pmatrix} = E \begin{pmatrix} u(\boldsymbol{r}_1) \\ v(\boldsymbol{r}_1) \end{pmatrix}$$

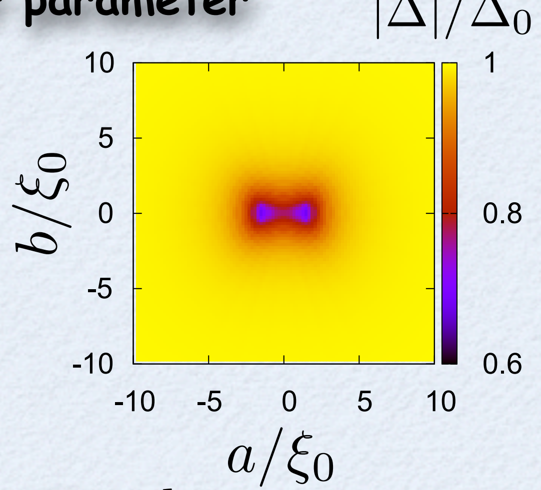
$u = v^*$: Majorana zero energy mode

Result of vortex state

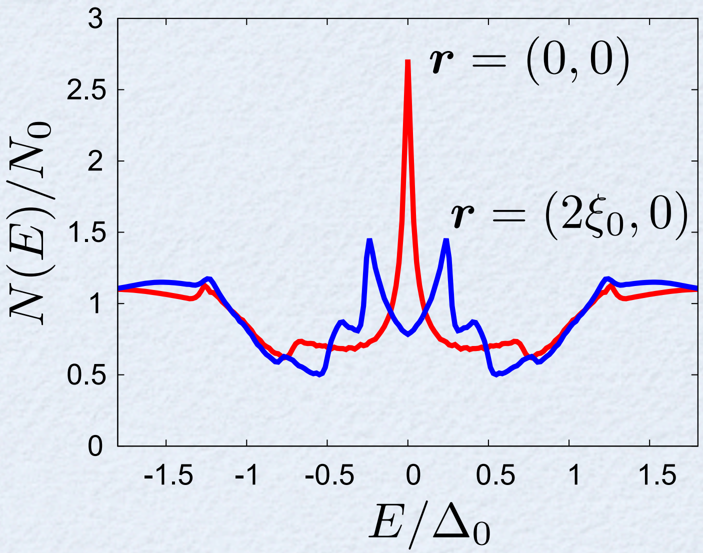
bulk: $\Delta_{bc}(\hat{b}k_a + \hat{c}k_b)(5k_c^2 - 1)$

vortex core: $\Delta_a \hat{a} k_b (5k_c^2 - 1)$

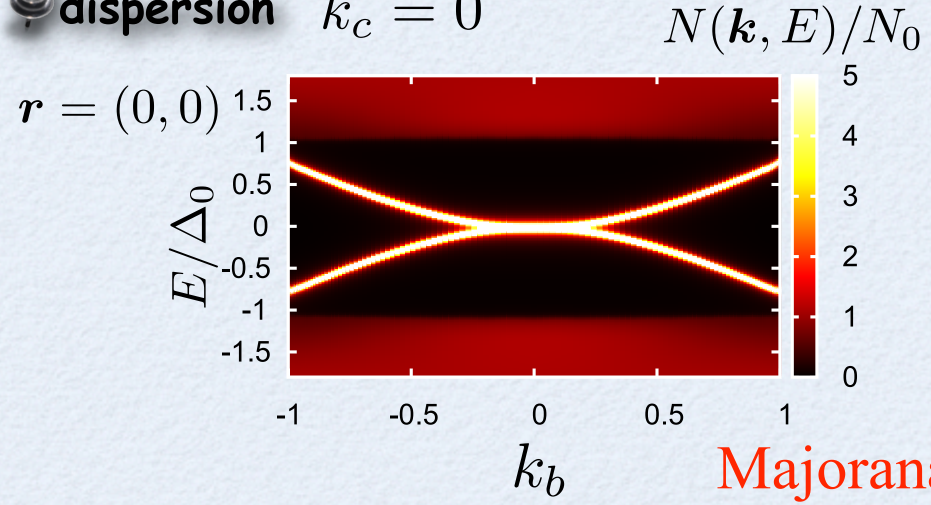
order parameter

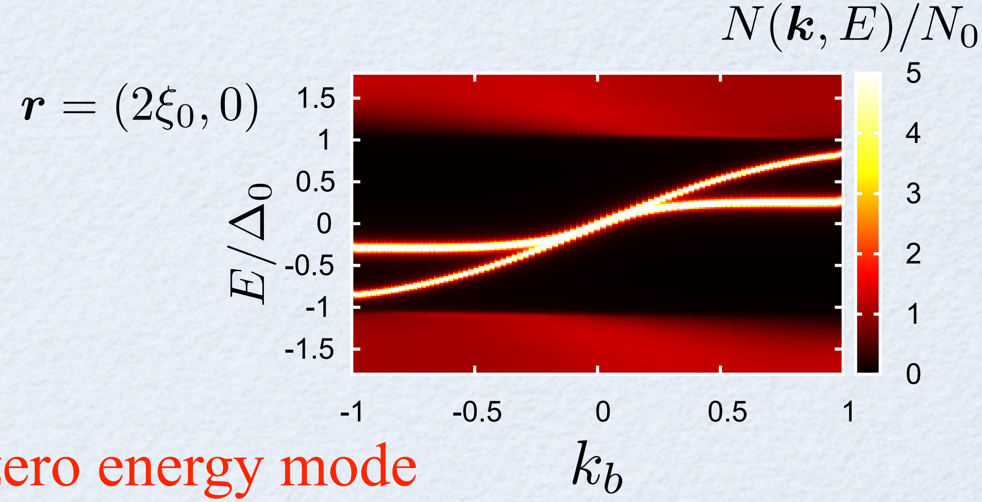


LDOS



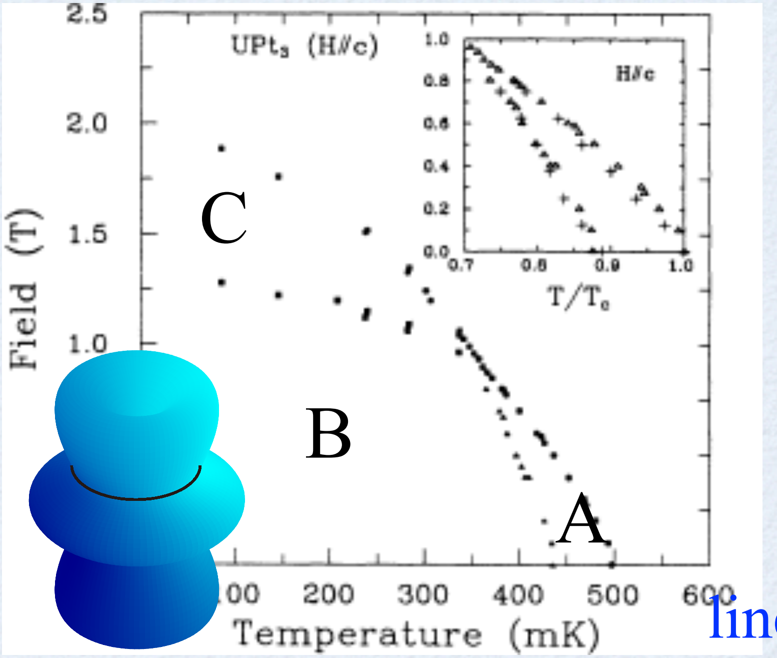
dispersion $k_c = 0$





Majorana zero energy mode

Summary



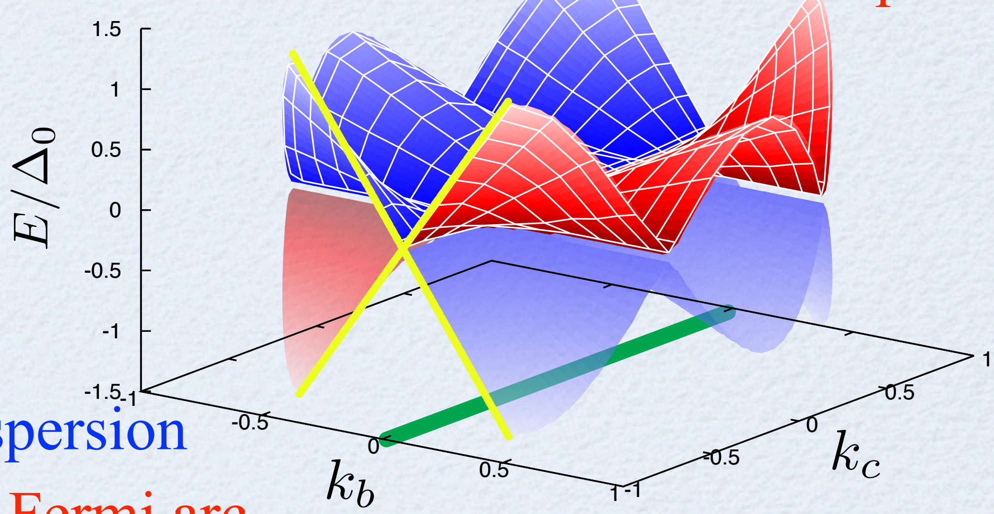
$(\hat{b}k_a + \hat{c}k_b)(5k_c^2 - 1)$

- Edge state

spin current

$\rightarrow$ -spin

$\leftarrow$ -spin

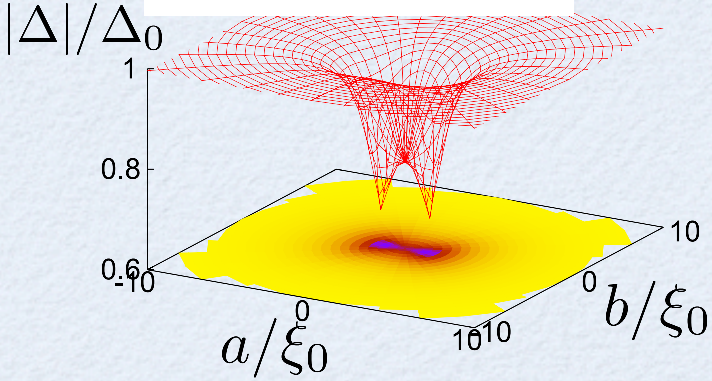


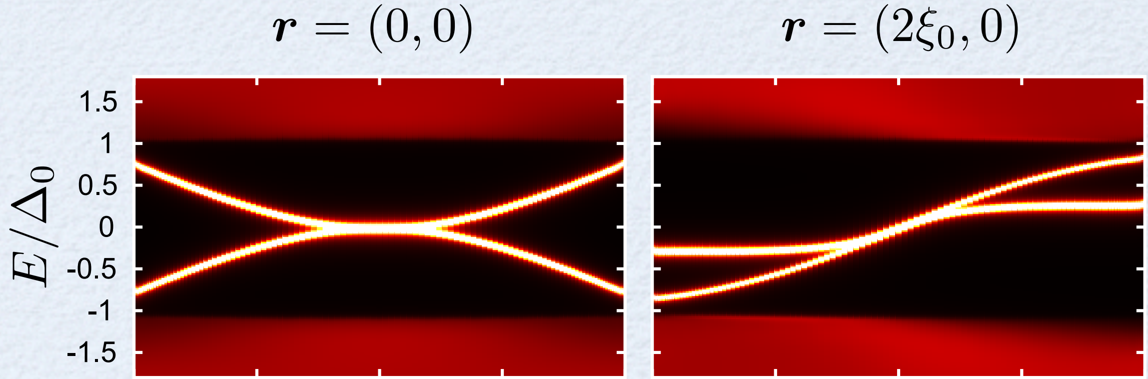
linear dispersion

topological Fermi arc

- Vortex state

double-core vortex





Majorana zero energy mode