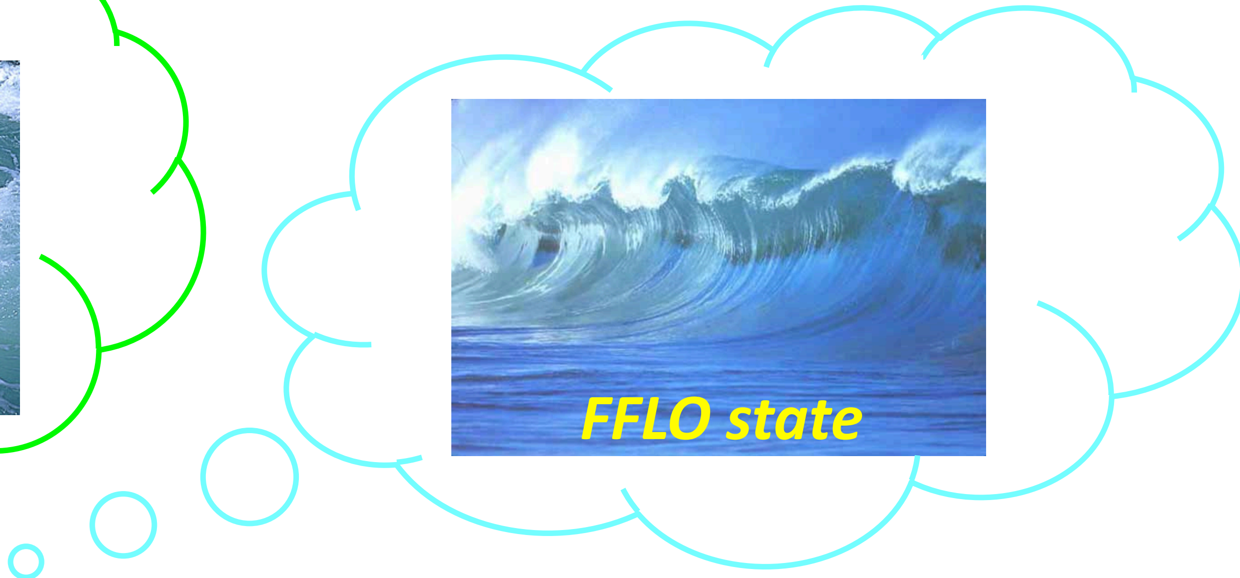
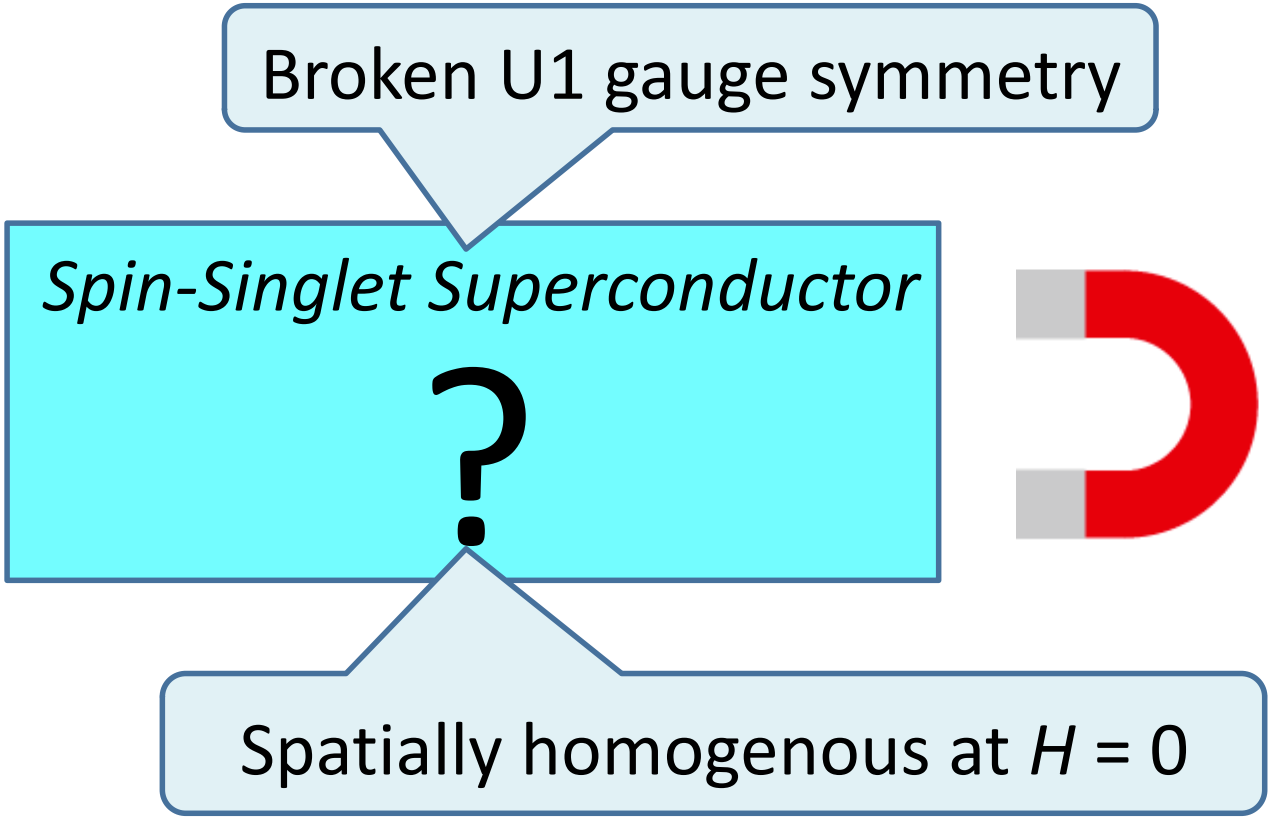
Superconductivity and magnetic fields
- competition and interplay -



Quantum Materials Laboratory
Kyoto University

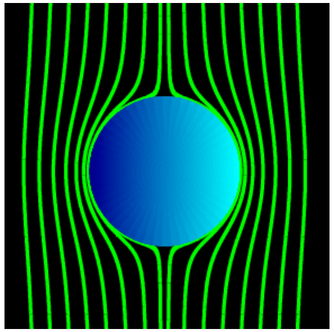
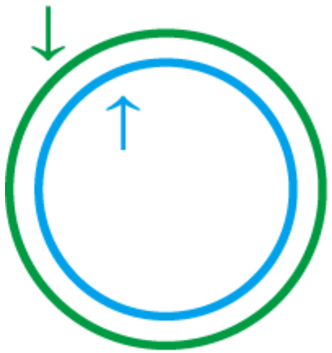
Shingo Yonezawa

Overview



What happens if a magnetic field is applied to a singlet superconductor?

Overview
~ Competition and Interplay ~

	Competition	***Interplay***
Flux Expulsion	Meissner Effect 	
Spin Polarization	Zeeman Effect 	

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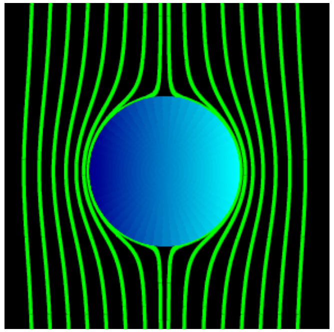
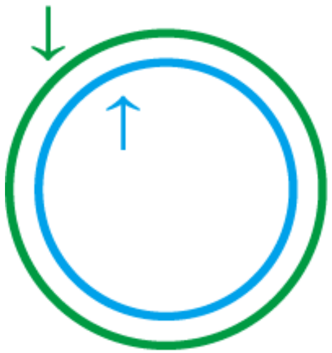
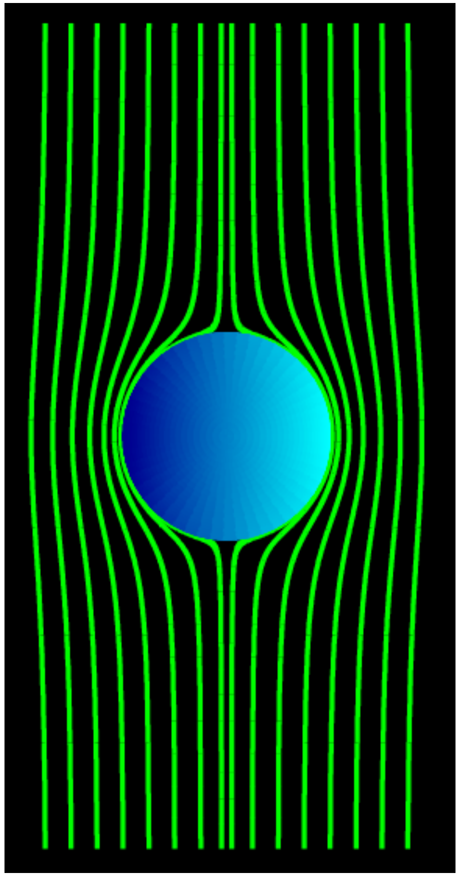
Flux Expulsion	Meissner Effect 	
Spin Polarization	Zeeman Effect 	

Meissner Effect



Meissner Effect:

Expelling magnetic flux inside a superconductor

Energy is required.

$(1/2)\mu_0 H^2$ / unit volume

When this energy is equal to the condensation energy U_c, superconductivity is broken.

Meissner Effect

Meissner Effect:
Expelling magnetic flux inside a superconductor

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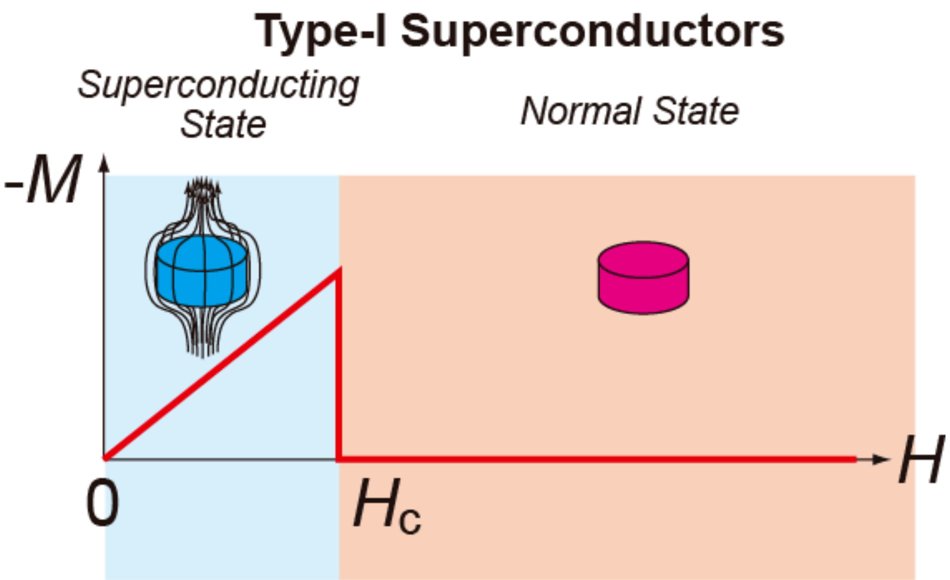
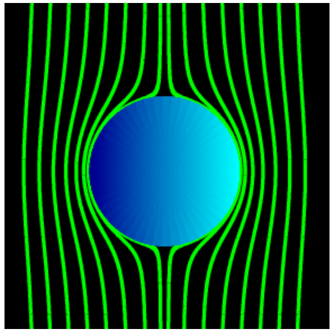
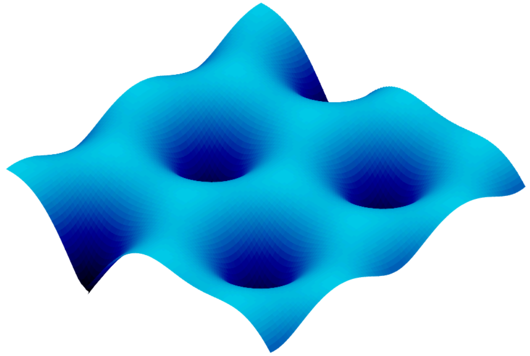
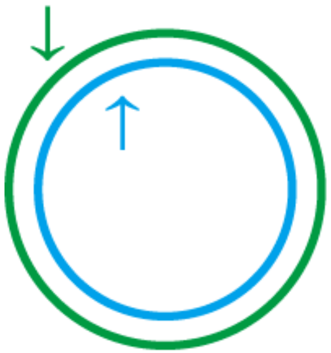


When this energy is equal to the condensation energy U_c, superconductivity is broken.

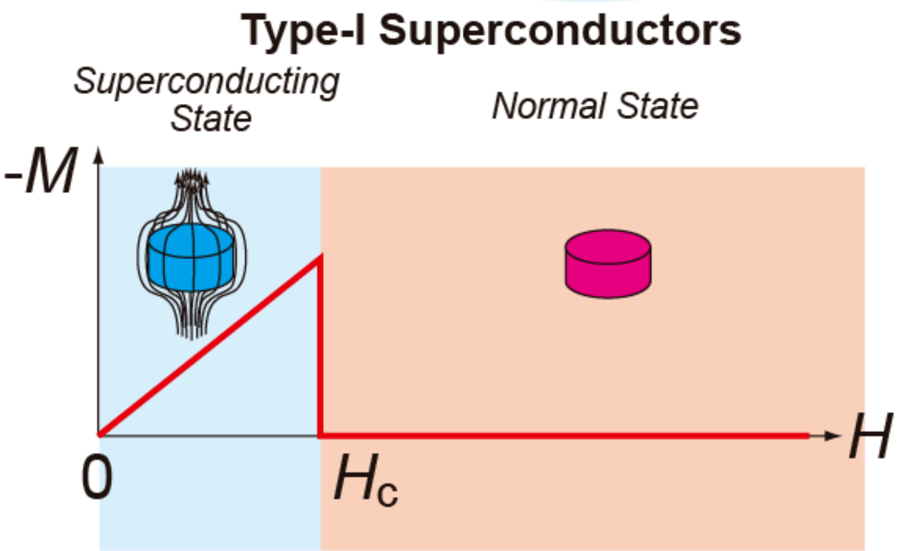
The critical field: H_c

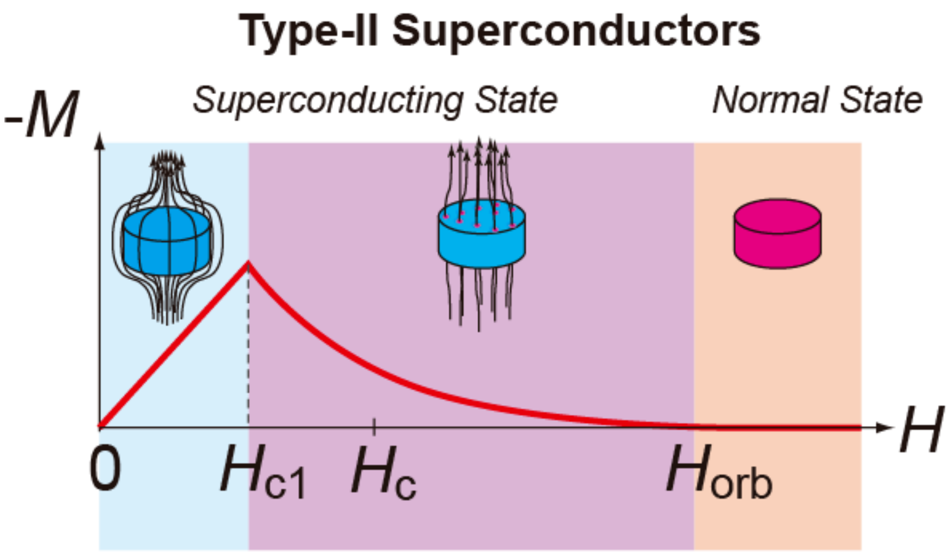
$$U_c = (1/2)\mu_0 H_c^2$$

Overview
~ Competition and Interplay ~

	Competition	***Interplay***
Flux Expulsion	Meissner Effect 	Vortex State 
Spin Polarization	Zeeman Effect 	

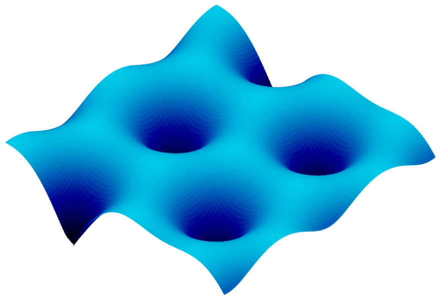
Vortex State

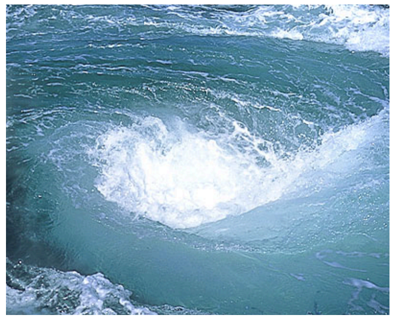




A. A. Abrikosov, Sov. Phys. JETP **5**, 1174(1957).

Type-II superconductors:
Vortices penetrate above H_{c1}

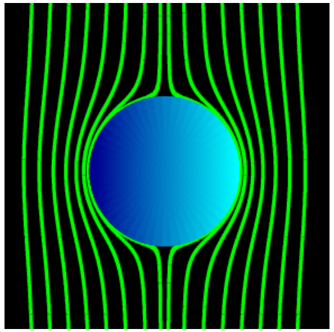
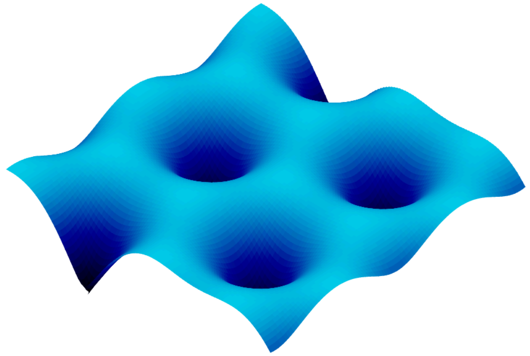
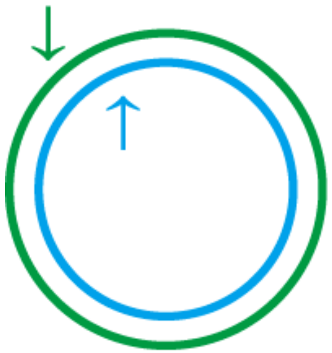




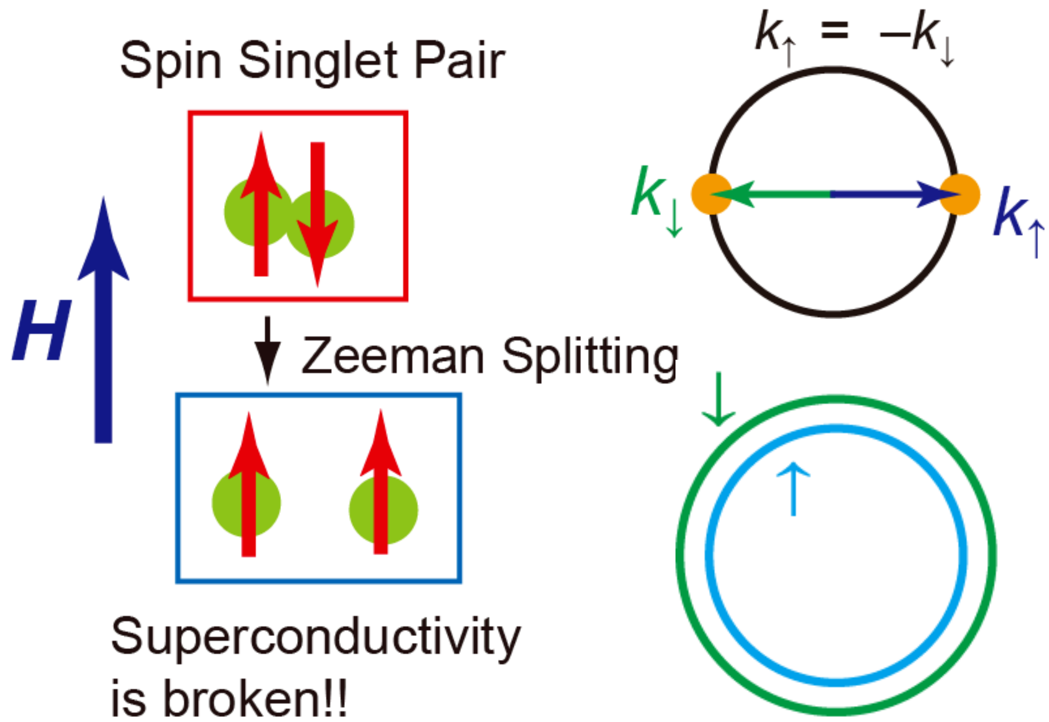
Superconductivity can survive up to much higher field H_{orb}

$$H_{orb}(T=0) = \Phi_0 / (2\pi\xi^2)$$

Overview
~ Competition and Interplay ~

	Competition	***Interplay***
Flux Expulsion	Meissner Effect 	Vortex State 
Spin Polarization	Zeeman Effect 	

Zeeman (Pauli) effect



Singlet pairs become unstable against the Zeeman splitting

Pauli limiting field H_p:

$$U_c = (1/2)\chi_p H_p^2$$

χ_P: Spin susceptibility in the normal state

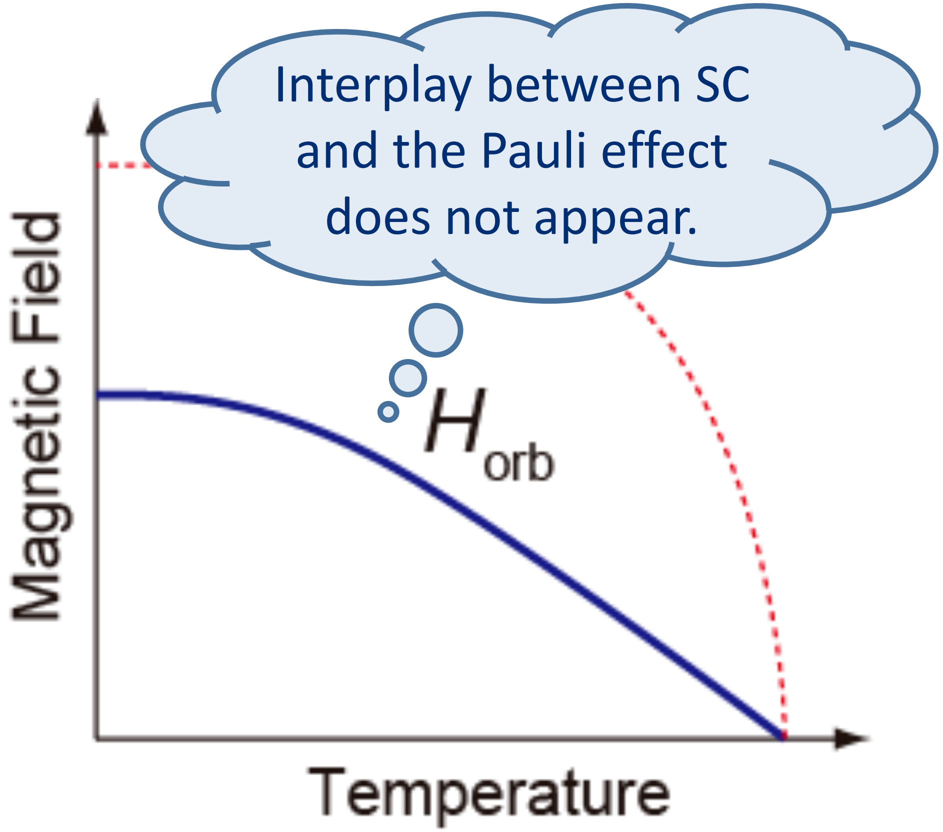
More useful relation:

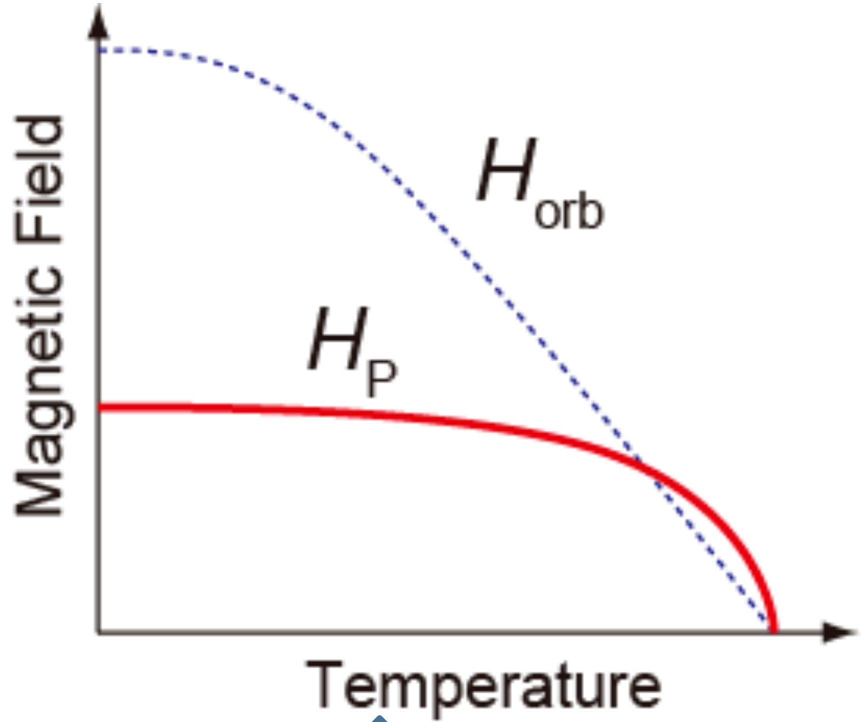
$H_P / T_c \sim 1.84$ T/K

A. M. Clogston, Phys. Rev. Lett. **9**, 266 (1962).

Comparison between H_{orb} and H_P

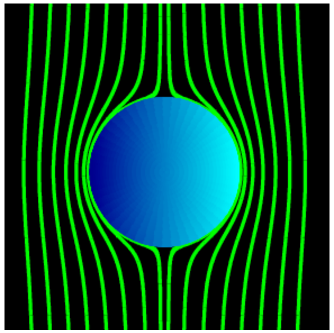
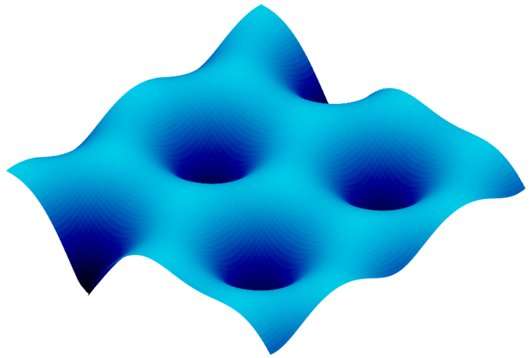
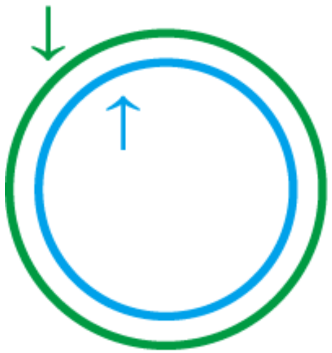
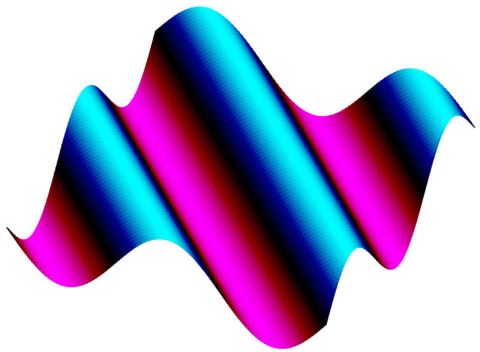
In most type-II singlet superconductors, $H_{orb} << H_P$





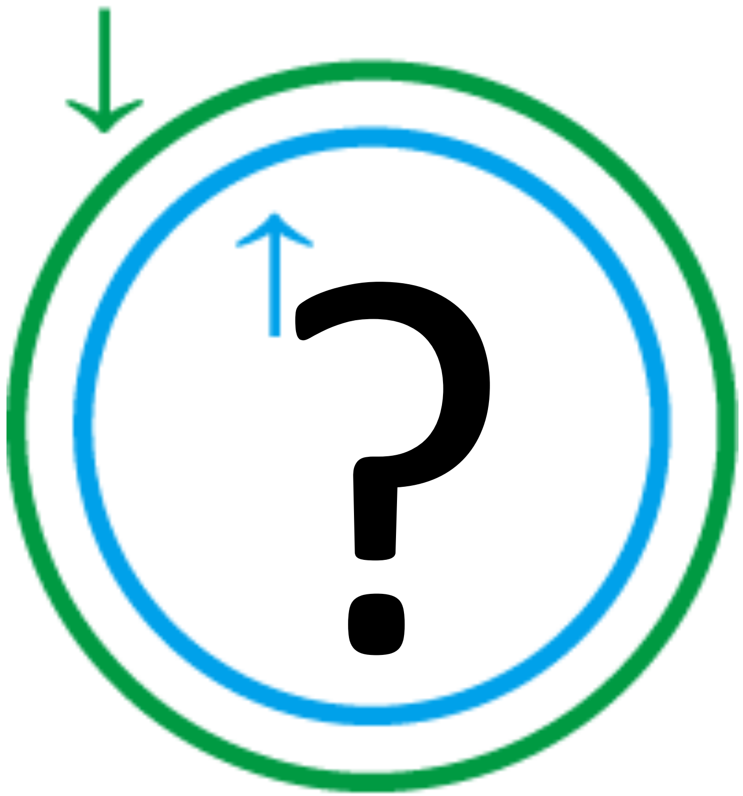
What happens in this situation?

Overview
~ Competition and Interplay ~

	Competition	***Interplay***
Flux Expulsion	Meissner Effect 	Vortex State 
Spin Polarization	Zeeman Effect 	FFLO State 

FFLO state

Question:
Can pair be formed on Zeeman-split Fermi surfaces??



FFLO state

1964, Fulde & Ferrell [Phys. Rev. **135**, A550]

Larkin & Ovchinnkov [Sov. Phys. JETP **20**, 762]

PHYSICAL REVIEW VOLUME 135, NUMBER 3A 3 AUGUST 1964

Superconductivity in a Strong Spin-Exchange Field*

PETER FULDE AND RICHARD A. FERRELL
University of Maryland, College Park, Maryland

(Received 23 December 1963; revised manuscript received 17 April 1964)

SOVIET PHYSICS JETP VOLUME 20, NUMBER 3 MARCH, 1965

INHOMOGENEOUS STATE OF SUPERCONDUCTORS

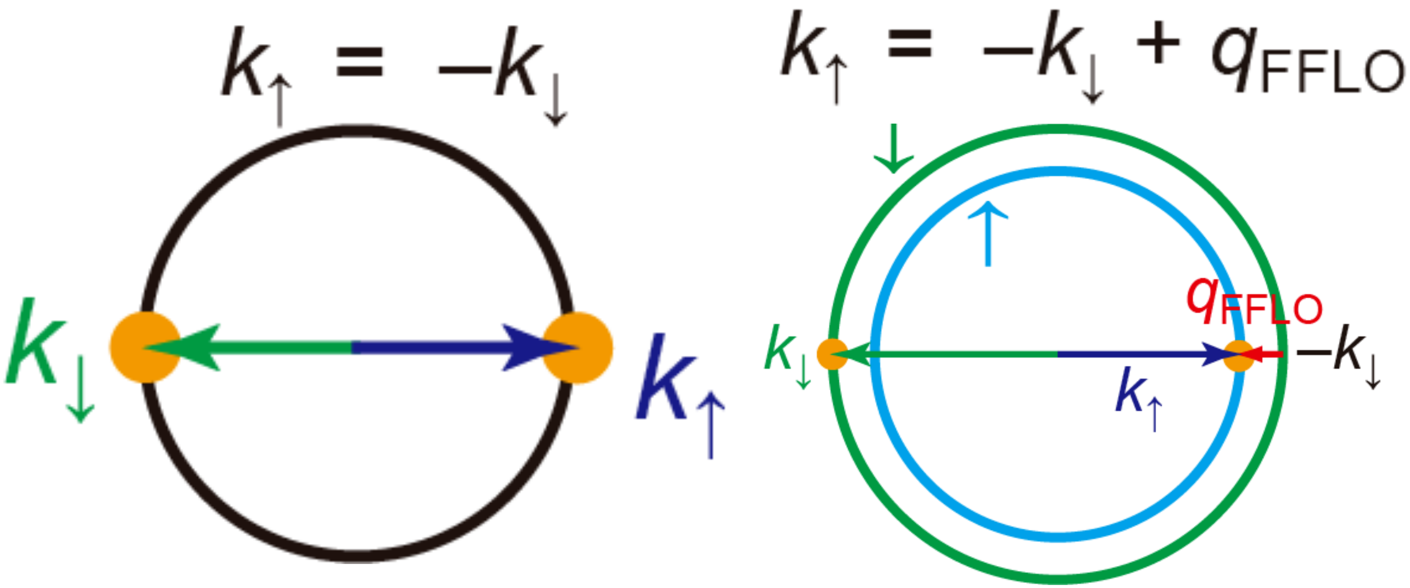
A. I. LARKIN and Yu. N. OVCHINNIKOV
Moscow Physico-technical Institute

Submitted to JETP editor April 16, 1964
J Exptl. Theoret. Phys. (U.S.S.R.) 47, 1136-1146 (September, 1964)

FFLO state

Question:
Can pair be formed on Zeeman-split Fermi surface??

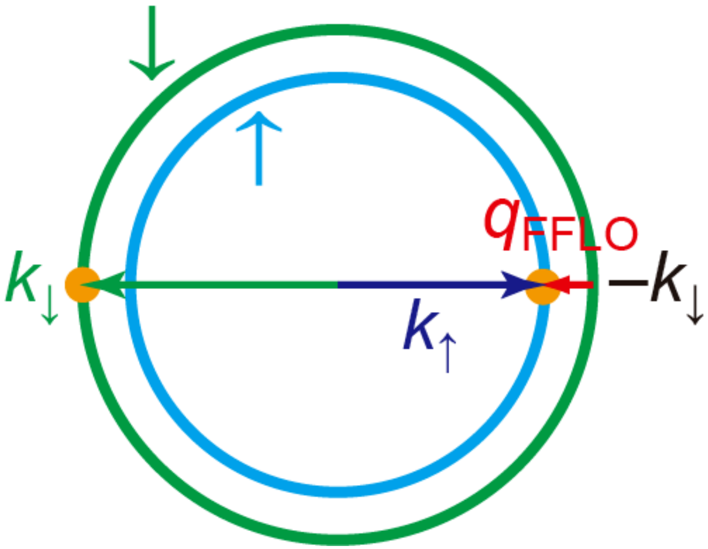
Answer: Theoretically possible! But not usual BCS state.



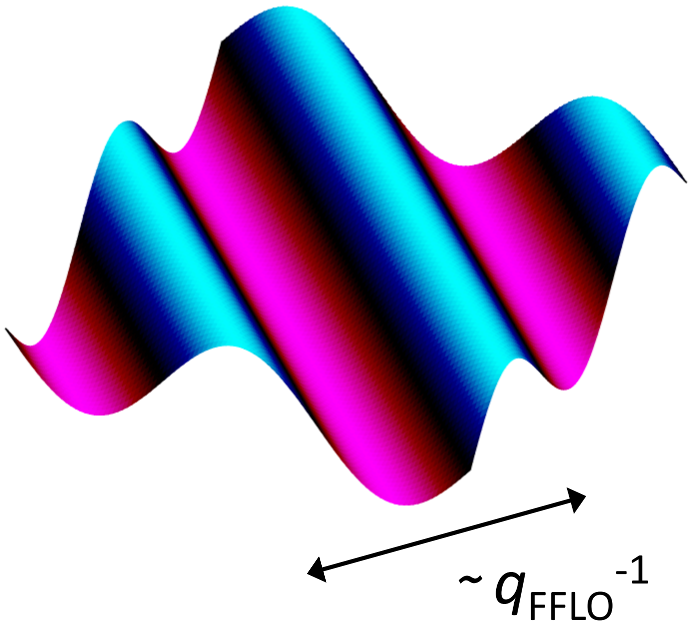
The center-of-mass momentum of the pair is non-zero

Fulde & Ferrell, Phys. Rev. **135**, A550 (1964).
Larkin & Ovchinnkov, Sov. Phys. JETP **20**, 762 (1964).

FFLO state:
Spatial modulation



$$k_\uparrow = -k_\downarrow + q_{\rm FFLO}$$



Spatial modulation of the order parameter $\Delta(r)$

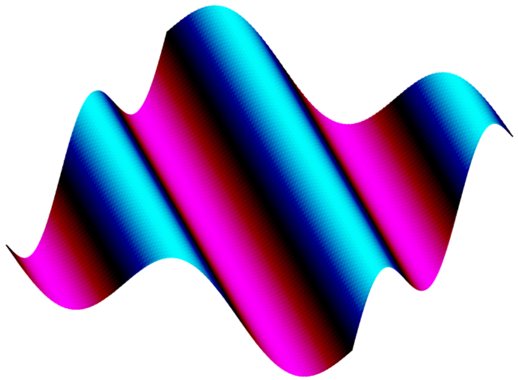
$\Delta(\boldsymbol{r}) = \Delta_0 \exp(i\boldsymbol{q}_{\rm FFLO}\boldsymbol{r})$ [Fulde & Ferrell]

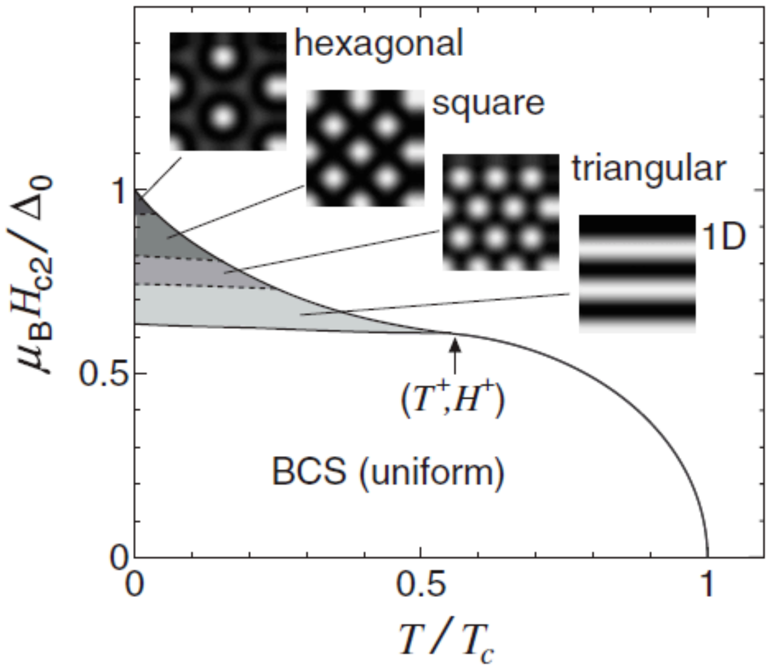
or $\Delta_0 \cos(\boldsymbol{q}_{\rm FFLO}\boldsymbol{r})$ [Larkin & Ovchinnikov]

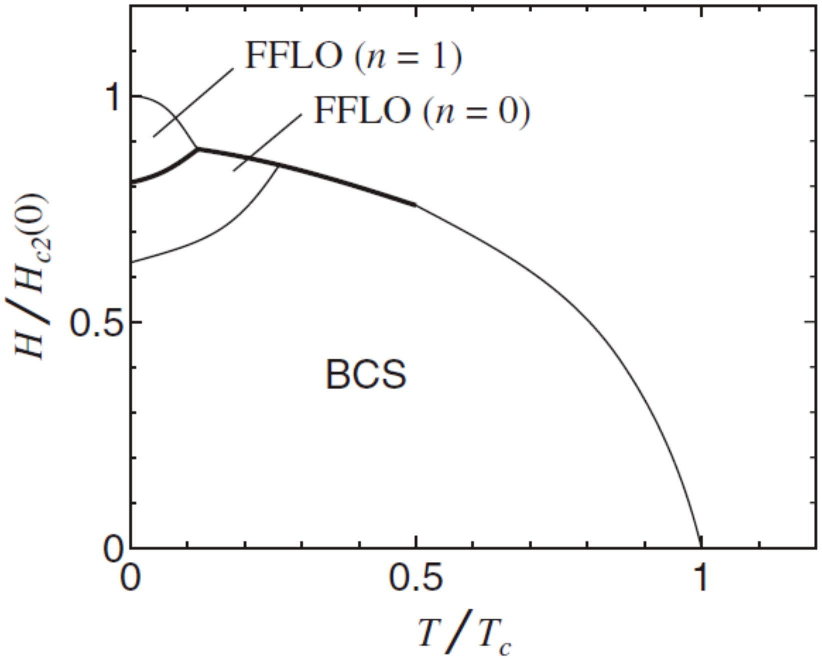
$$q_{\rm FFLO} \sim 2\mu_B H / \hbar v_F$$

FFLO state: Phase Diagram

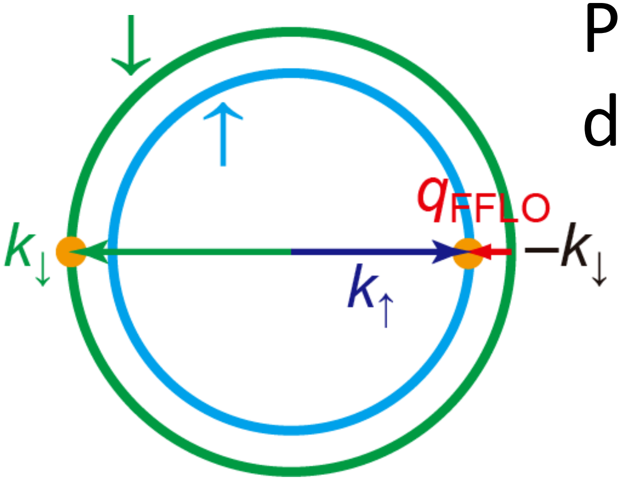
FFLO state locates
high-field low-temperature region
of the superconducting phase





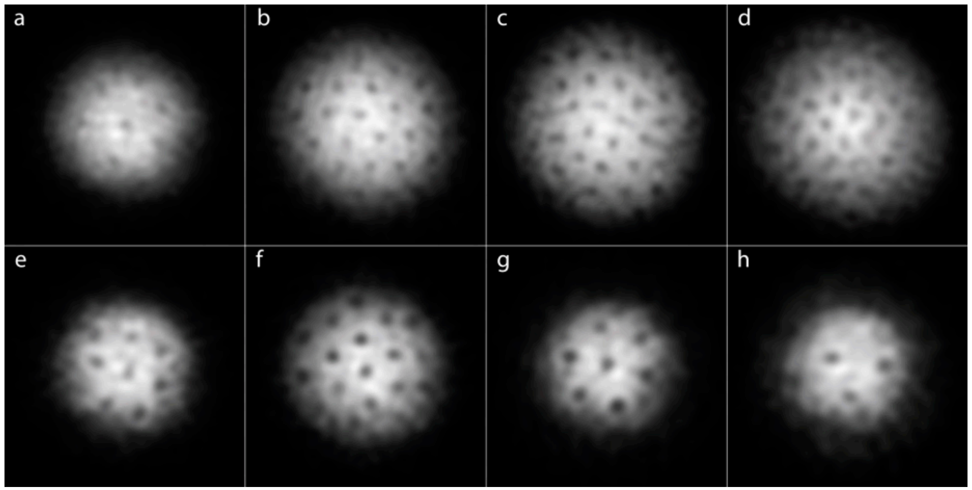


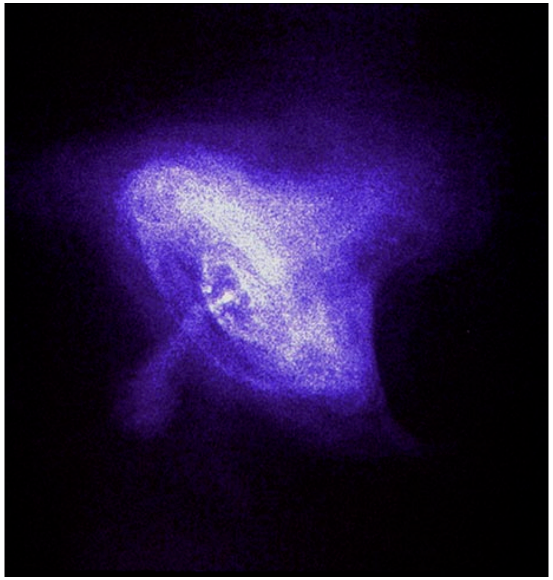
FFLO-related physics in other research fields



Pairing state of particles with different chemical potentials

- ↑Spin- ↓ Spin Imbalanced Atomic Gas
- Color Superconductivity in pulsars





R. Casalbuoni and G. Nardulli, Rev. Mod. Phys. **76**, 263 (2004)

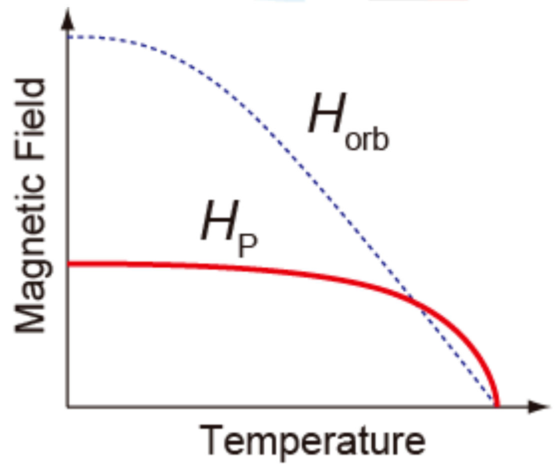
Required conditions for FFLO states

1. $H_P < H_{orb}$

Maki parameter:

$\alpha \equiv \sqrt{2}H_{orb} / H_P > 1.8$

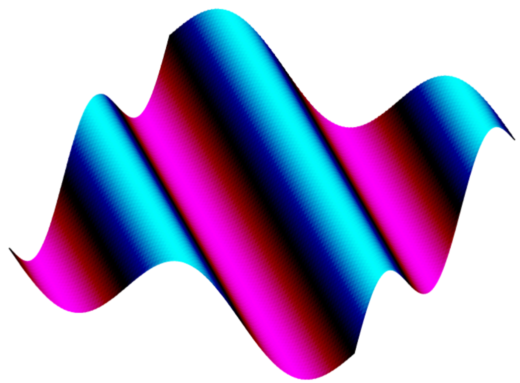
Accurate field alignment is often required.



2. Very clean material

Mean free path >> coherence length

Very clean sample is required.

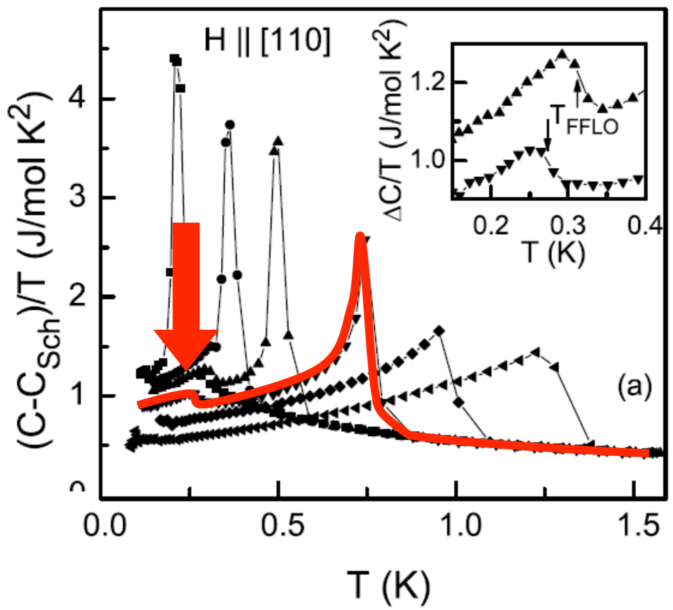


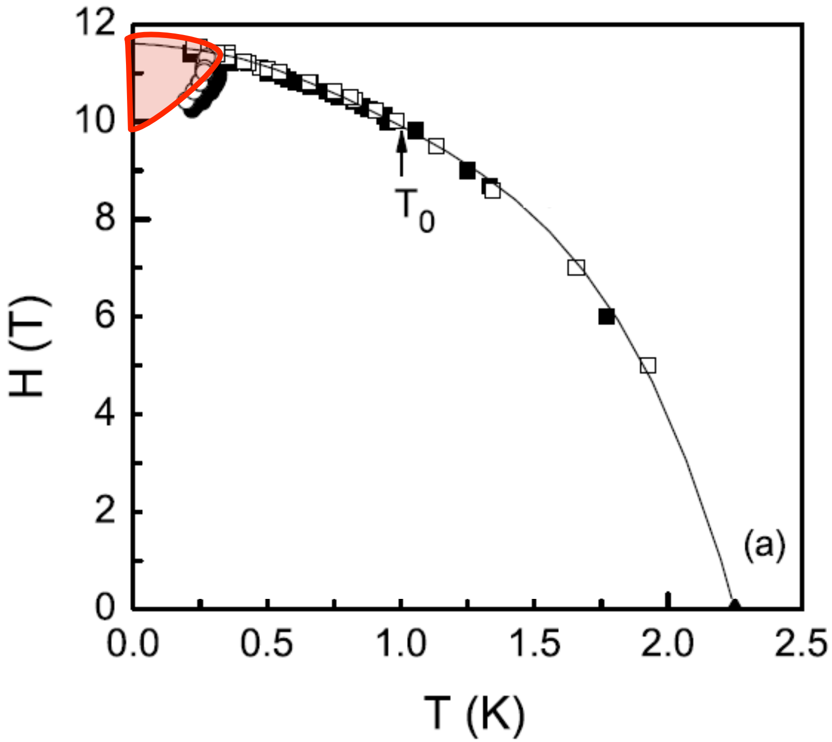
Despite long history and much effort devoted,
FFLO state had not been observed for nearly 40 years!!

Candidate for FFLO states (1)
Heavy-Fermion $CeCoIn_5$

Heavy Fermion superconductor $CeCoIn_5$

$\alpha = \sqrt{2} H_P / H_{orb} \sim 4.5$

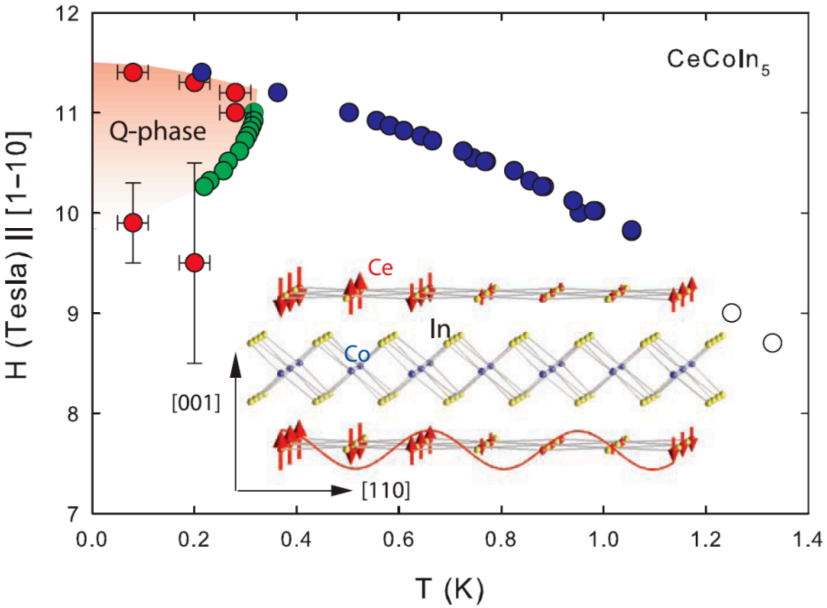


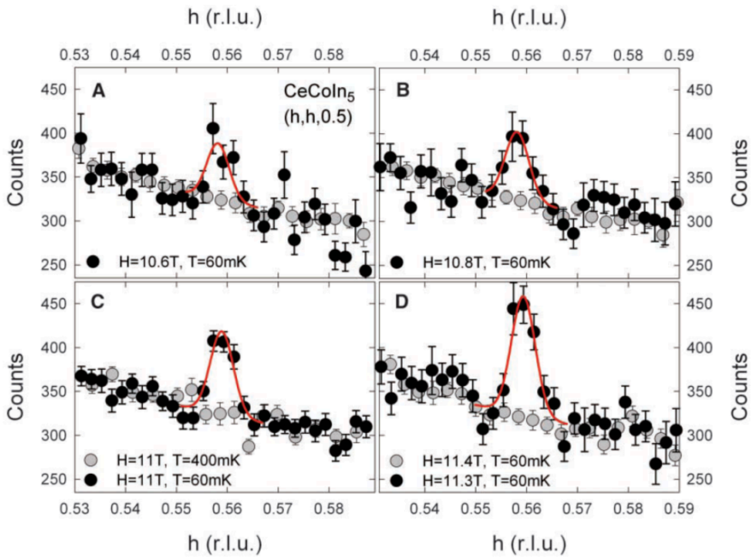


At high field,
another SC phase is observed!

Candidate for FFLO states (1)

Heavy-Fermion $CeCoIn_5$





However....

Recent experiments revealed that antiferromagnetic order coexists with the "FFLO" state.

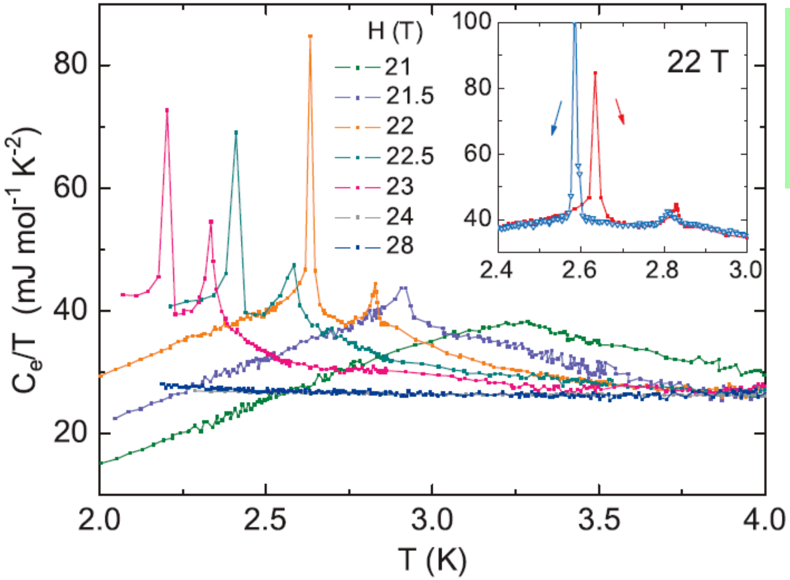
M. Kenzelmann *et al.*, Science **321**, 5896 (2008)

The "FFLO" state is not a text-book like modulated state.

Quantum criticality is involved??

Candidate for FFLO states (2)

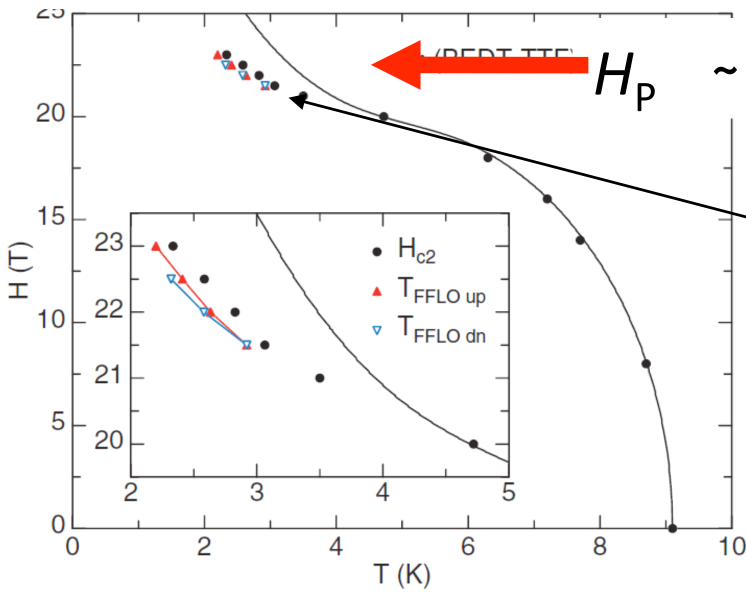
Q2D Organic Superconductor



Quasi-two-dimensional organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$

- $\alpha = \sqrt{2}H_P / H_{orb} \sim 8$

  H // conductive plane



H_P ~ 21-23 T

Two phase transitions in high fields

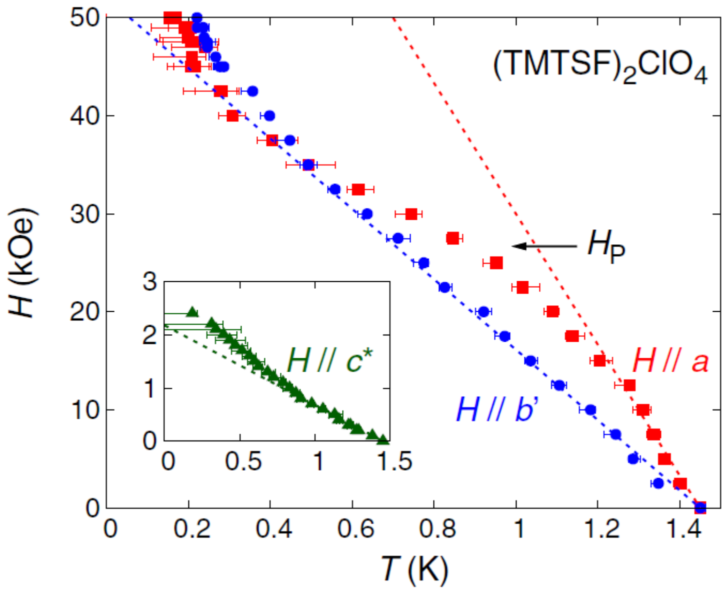
FFLO state??

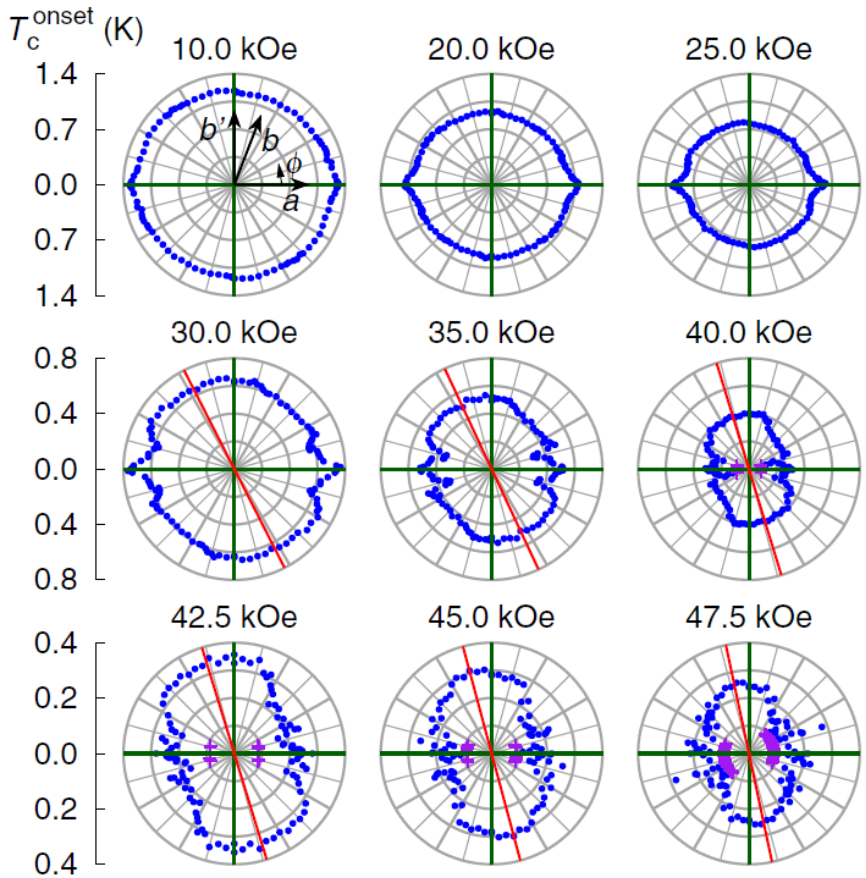
Lortz *et al*., Phys. Rev. Lett. **99**, 187002 (2007).

Candidate for FFLO states (3)

Q1D Organic Superconductor

Quasi-one-dimensional organic superconductor $(TMTSF)_2ClO_4$



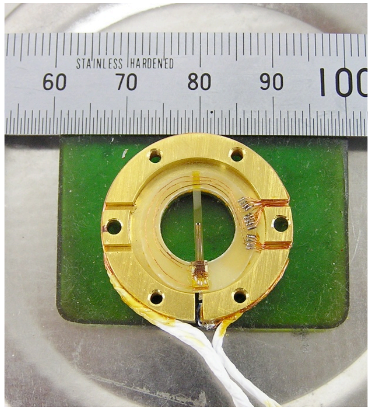


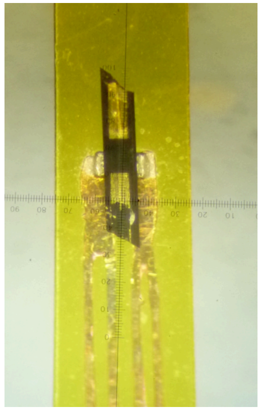
- $\alpha = \sqrt{2}H_P / H_{orb}$ ~ 3.7 (H // a)
- Resistivity onset T_c^{onset} remains finite in high fields.
- Unusual in-plane field angle dependence of T_c^{onset}

S. Yonezawa *et al.*, Phys. Rev. Lett. **100**, 117002 (2008).

Our recent specific-heat study on $(TMTSF)_2ClO_4$

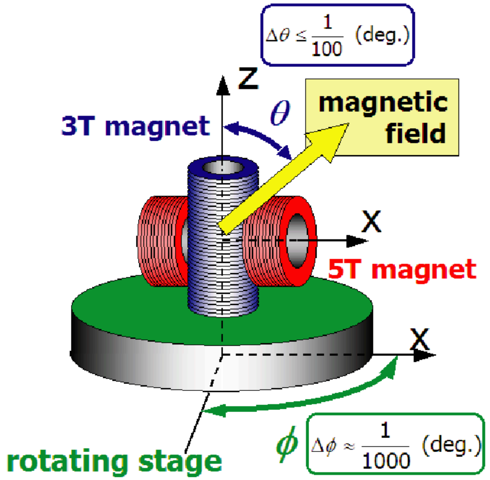
Sensitive calorimeter for further studies of the high-field SC state





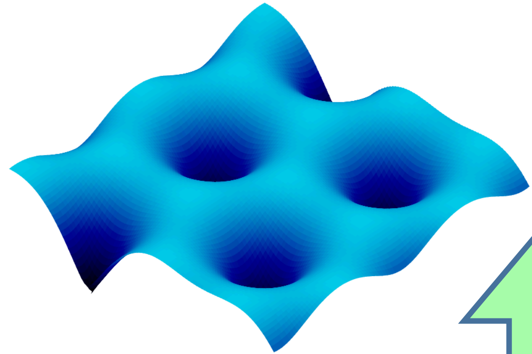
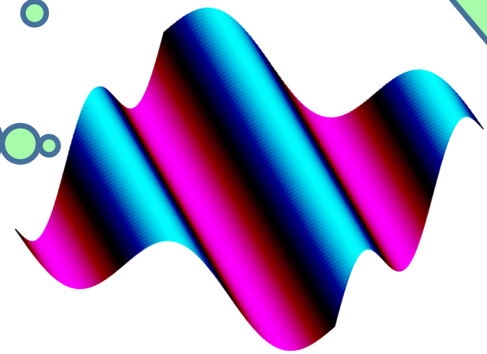
mass: 0.102 mg

→ $\Delta C / T_c = 1.7$ nJ/K^2



Phase Diagram of $(TMTSF)_2ClO_4$

Summary
~ Competition and Interplay ~

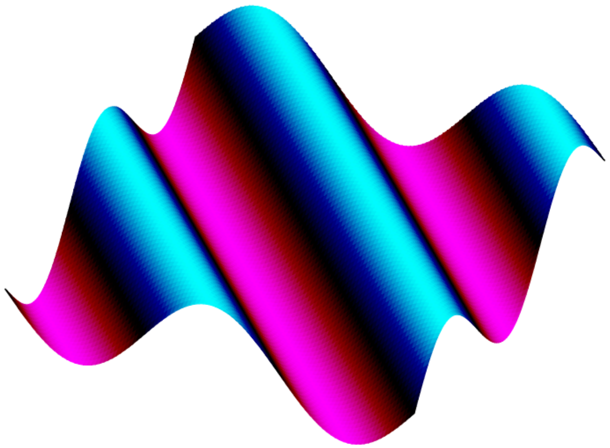
	Competition	***Interplay***
Flux Expulsion	Meiss 	Vortex State 
Spin Polarizatio	Ze 	FFLO State 

Quantum Criticality & Magnetism ?

Low Dimensionality and Fluctuations ?

Concluding Remark

We are almost catching the "FFLO wave",
40 years after the first prediction,



But....

We need more effort to really enjoy it!