2009年4月19日　スーパークリーン特定領域A03A04班合同会議、ホテル箱根パウエル

Angular-FFLO state in cold fermion gases near BCS-BEC crossover

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M. Machida, M. Okumura (JAEA)
K. Machida, K. Mizushima (Okayama)

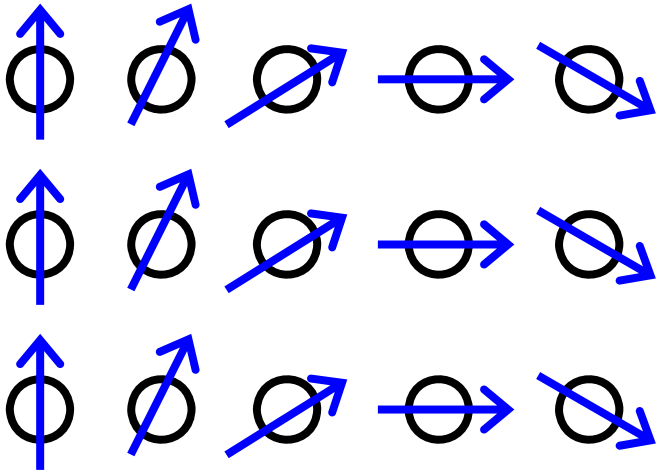
FFLO Superfluidity/Superconductivity

Condesate of Cooper pairs with finite total momentum

Theory: Fulde-Ferrel (1964), Larkin-Ovchinnikov (1964)

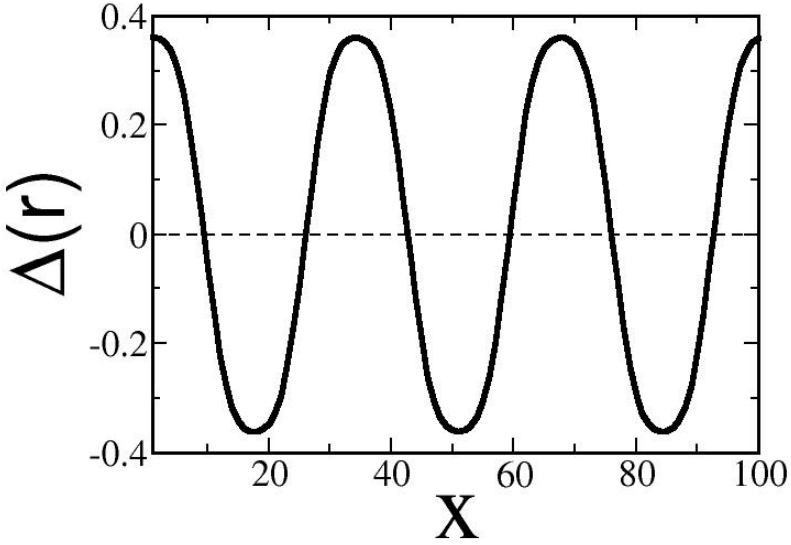
Fulde-Ferrel state

$\Delta(r) = \Delta \exp(iqx)$



Larkin-Ovchinnikov state

$\Delta(r) = \Delta \cos(qx)$



Thin film, Currect, Non-centro. SC

Broken inversion symmetry

^{3}He thin film, Superconductor

Broken translation symmetry

FFLO Superfluidity/Superconductivity

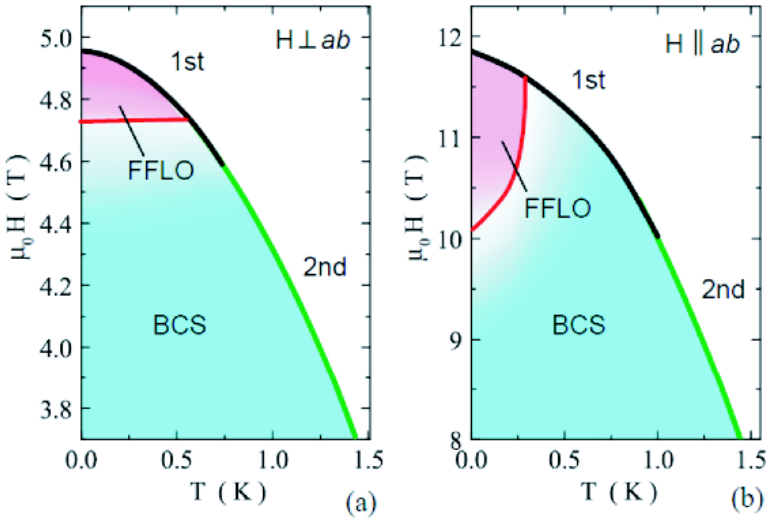
Condesate of Cooper pairs with finite total momentum

Candidates

(1) Strongly correlated electron systems

$CeCoIn_5$, $(TMTSF)_2X$ .....

Broken translational symmetry:
No experimental observation !!



(2) Cold fermion gases

No translational symmetry

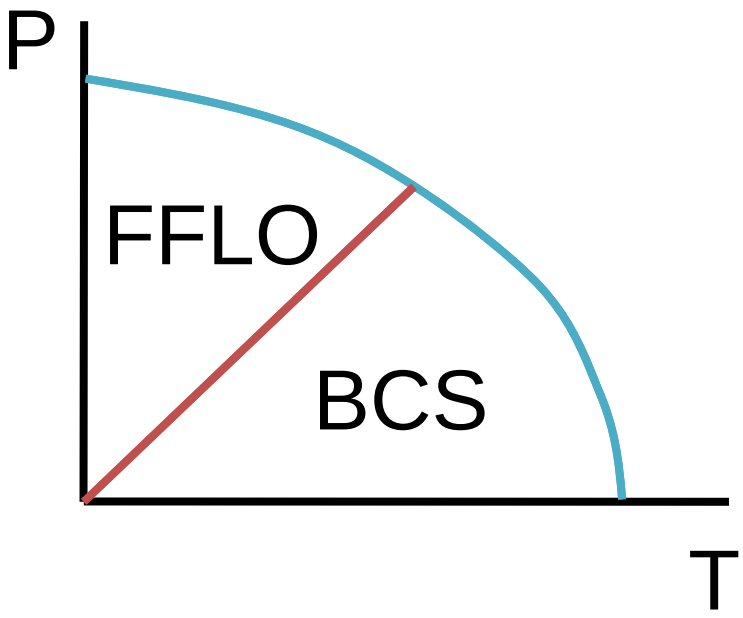
Rotational symmetry

(3) High density quark matter (Color superconductivity)

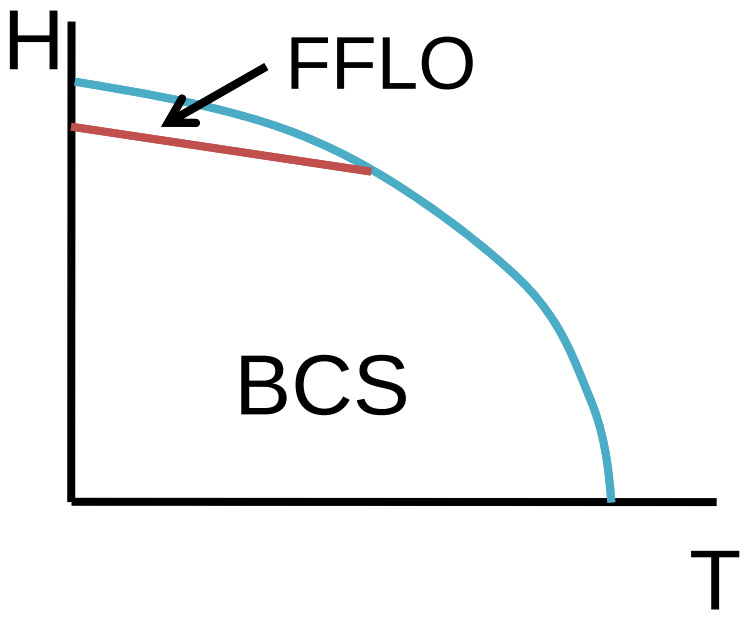
(4) Stripe phase in ^{3}He thin film

Superfluidity in imbalanced fermion gases

Cold fermion gases



Electron systems



Discussion with Machida and Mizushima

Fermi liquid correction: Attractive

→ Stabilize FFLO

Fermi liquid correction: Repulsive

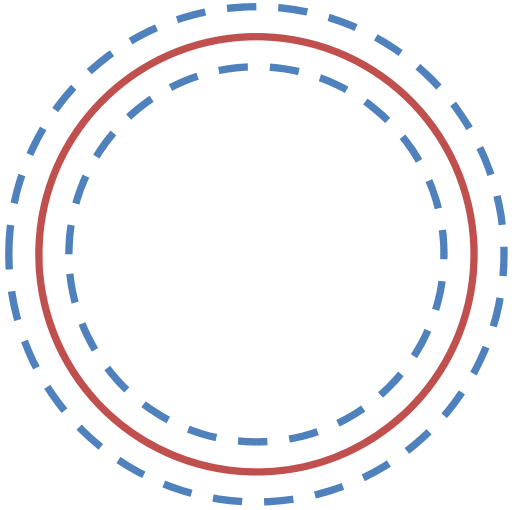
→ Suppress FFLO

BCS-BEC crossover

Eagles (1969)
Leggett (1980)
Nozieres, Schmitt-Rink (1984)

BCS

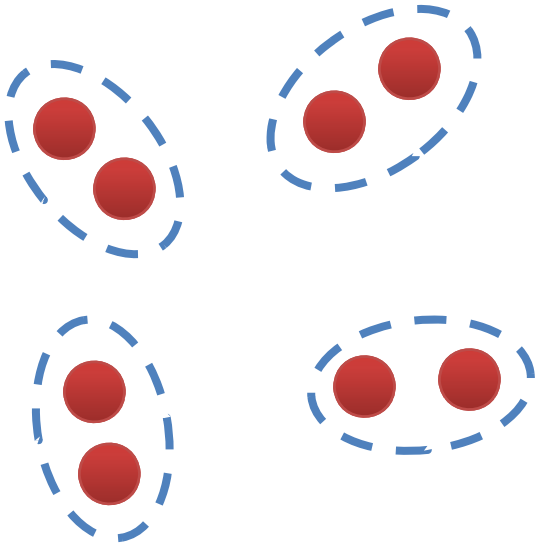
BEC



Attractive interaction

Weak Strong

Feshbach resonance



Pairing in momentum space

Pairing in real space

BCS-BEC crossover v.s. Resonance scattering

Resonance scattering — Negligible chemical potential shift

(1) Semiconductors

(2) High-Tc cuprates

"Effectively"
strong attractive interaction

$$T_c/E_F^* \sim 1/10$$

BCS-BEC crossover — Chemical potential shift

(3) Cold fermion gases

Strong attractive interaction

$$T_c/E_F \sim 1/10$$

? (4) Exciton gas — Nozieres, Schimitt-Rink

? (5) High density quark matter — Kitazawa

FFLO superfluidity in rotation symmetric system

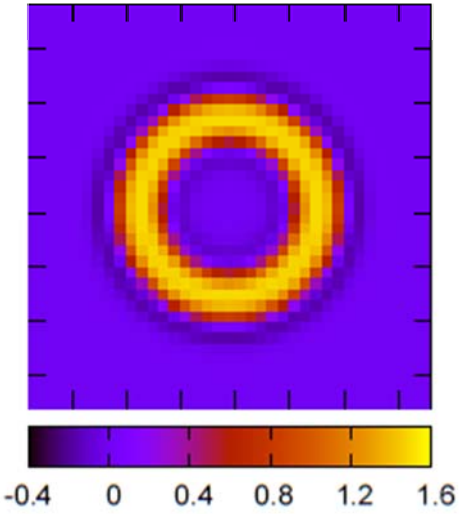
Radial-FFLO state — No symmetry breaking — Difficult to detect

Mizushima et al.
Randeria
Tezuka-Ueda

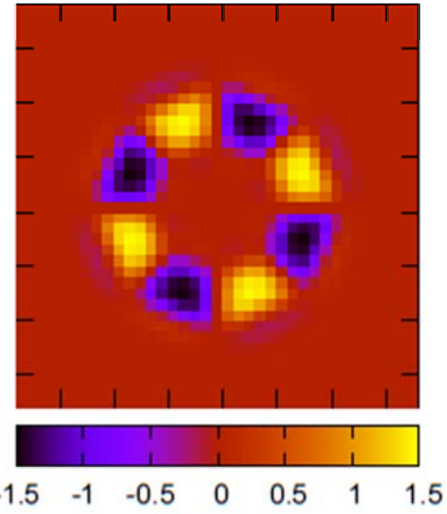
Angular-FFLO state — Broken rotation symmetry !!

→ Experimental test !!

Radial-FFLO



Angular-FFLO



FFLO superfluidity in rotation symmetric system

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Angular-FFLO state — Broken rotation symmetry !!

→ Experimental test !!

My interests

(1) Possibility of Angular FFLO state

Theory beyond LDA !!

(2) Stability near BCS-BEC crossover

Theory beyond mean field !!

"FFLO state is unstable aginst the fluctuation."

Life time effect, Directional order Shimahara, Ohashi

Our results

X Harmonic trap

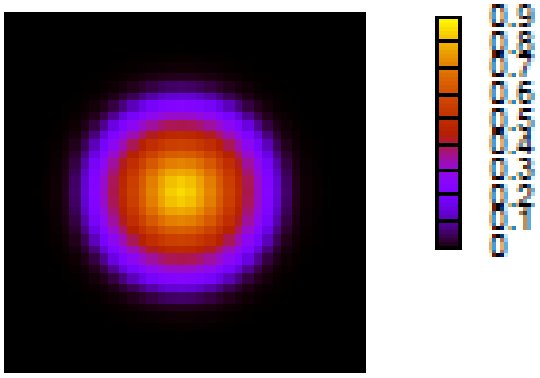
O Toroidal trap This presentation !!

Stable vortex in BEC: Ryu et al. PRL (2007)

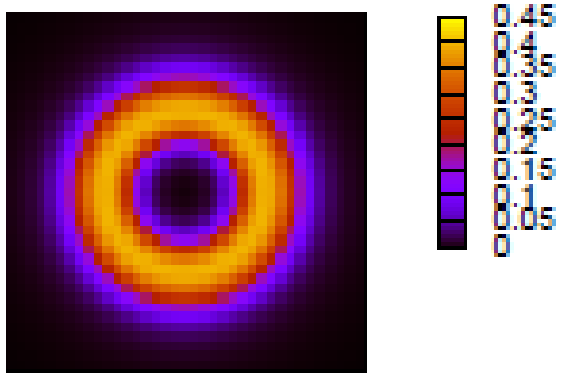
O Harmonic trap + Optical lattice

Number density

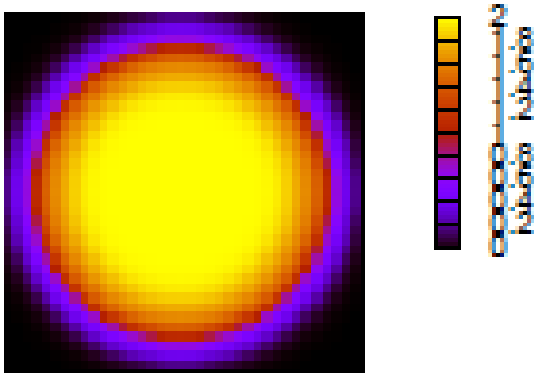
Harmonic trap



Toroidal trap



Harmonic trap + lattice



Model

Lattice model in a trap potential

$$H = t \sum_{<i,j>,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + \sum_i (W_i - \mu) n_i - 2H \sum_i S^z_i + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Low density limit ⟶ Without optical lattice

Trap potential

Harmonic potential $W(r) = \frac{1}{2}\omega_h (r/r_0)^2$

Toroidal potential $W(r) = \frac{1}{2}\omega_h (r/r_0)^2 + \omega_t \exp(-r/\xi)$

Method

BdG (M.F.A.) + RSTA (Self-consistent 1-loop)

What is RSTA ?

RSTA = Self-consistent T-matrix approximation formulated in real space

History

(1) Pseudogap phase in high-Tc SC (2006)

(2) Superconductor-Insulator transition (2008)

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RSTA = Self-consistent T-matrix approximation formulated in real space

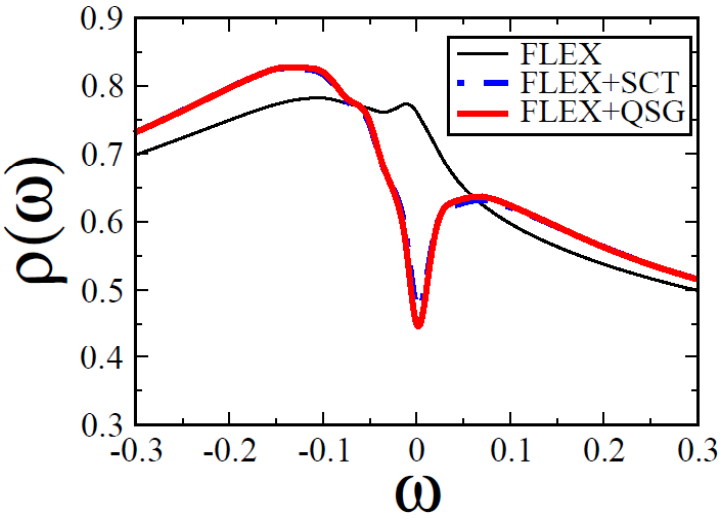
History (1) Pseudogap phase in high-Tc SC (2006)

(2) Superconductor-Insulator transition (2008)

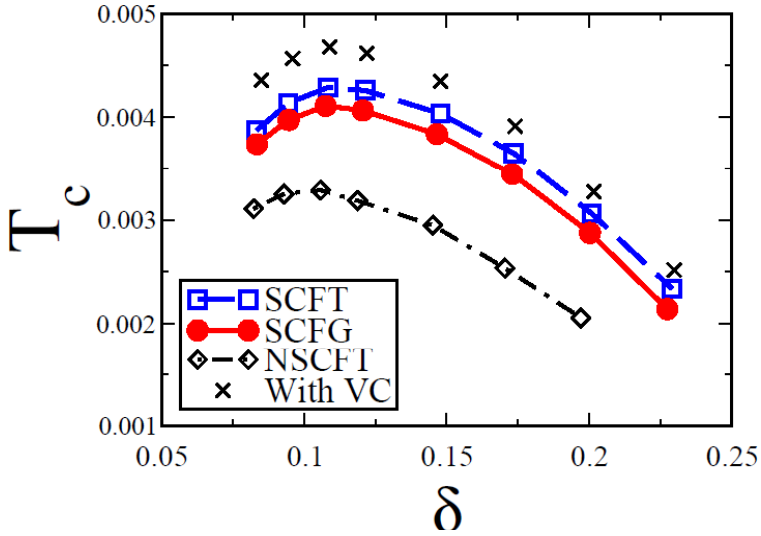
Infinite-loop order theory Sadovskii's method

Y. Y. (2004)

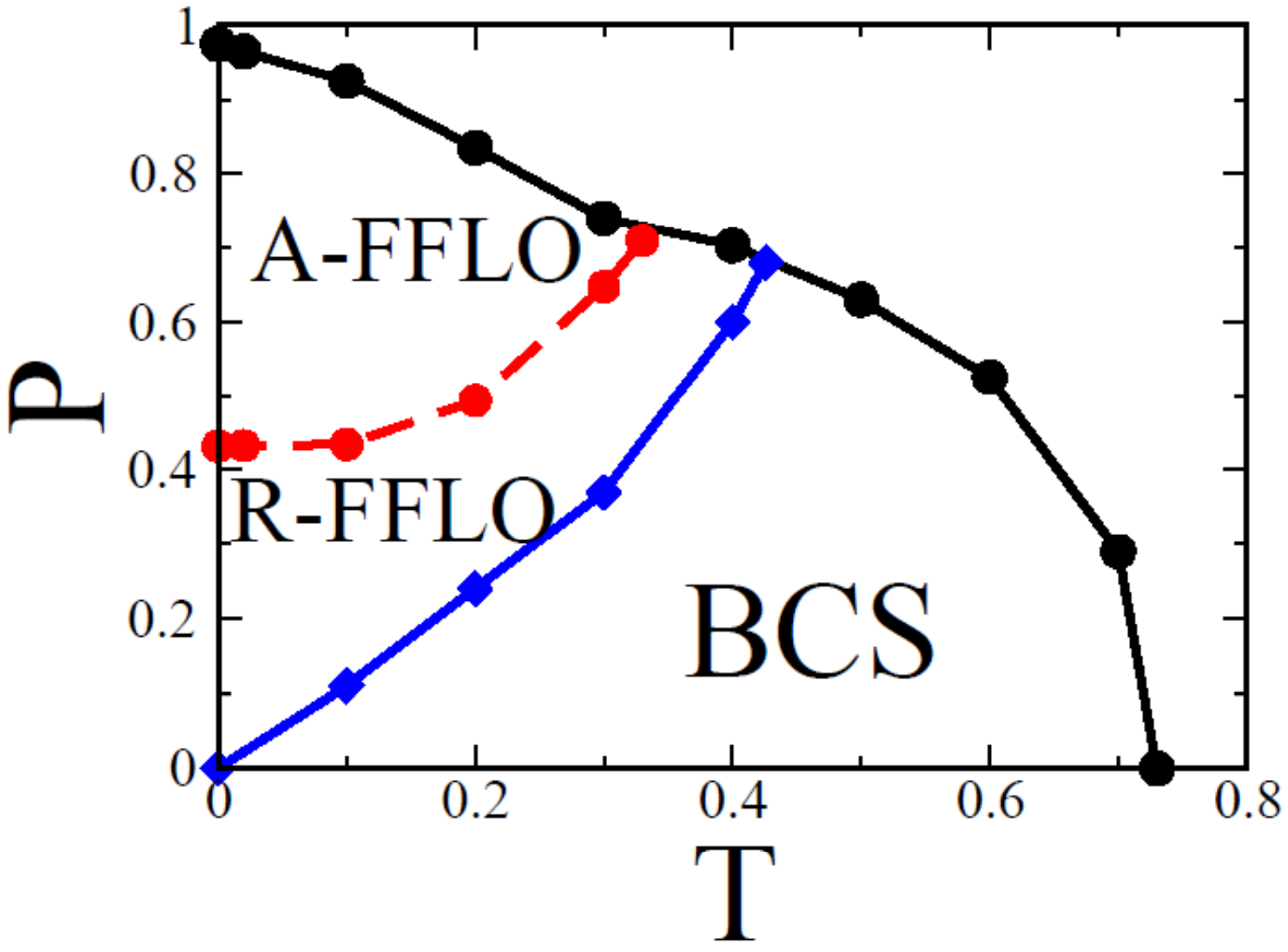
DOS



T_c



Mean field theory (BdG equation)



U=-5

ω_h=6

ω_t=8

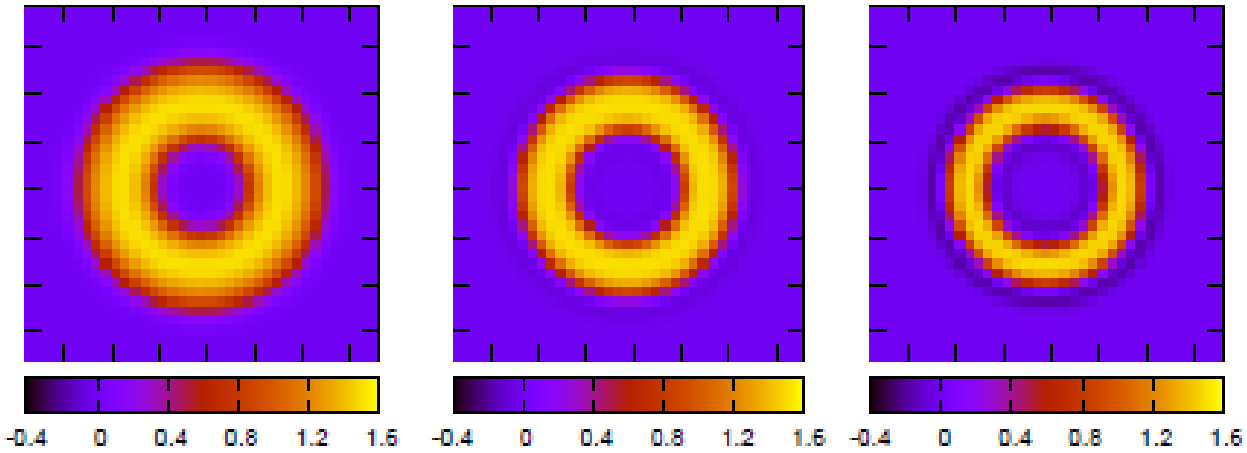
ξ=5

Spontaneous symmetry breaking in FFLO state

Order parameter

Imbalance: $P = (n_1 - n_2)/(n_1 + n_2)$

(a) P=0 (b) P=0.21 (c) P=0.39

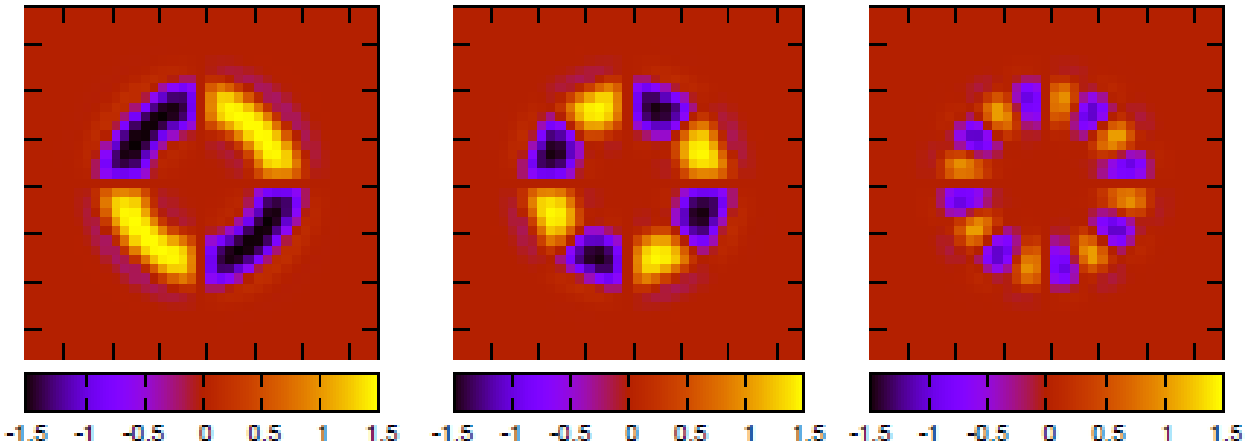


Radial-FFLO

✖ No symmetry breaking

Self-one-dimensionalization

(d) P=0.44 (e) P=0.49 (f) P=0.69

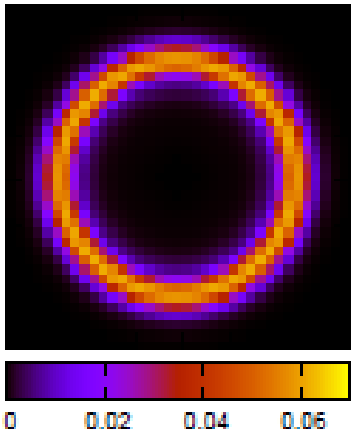


Angular-FFLO

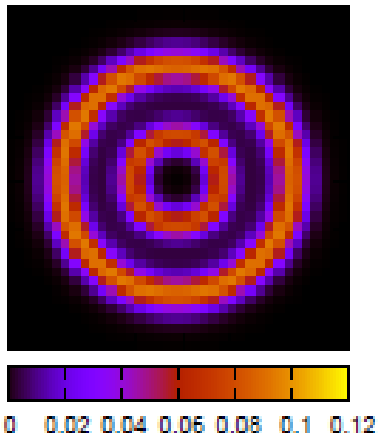
Rotation symmetry breaking !!

Local Population imbalance

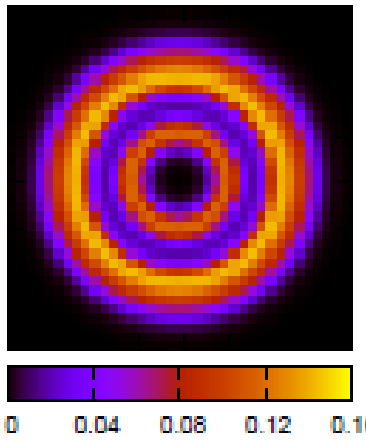
(a) P=0.1



(b) P=0.21



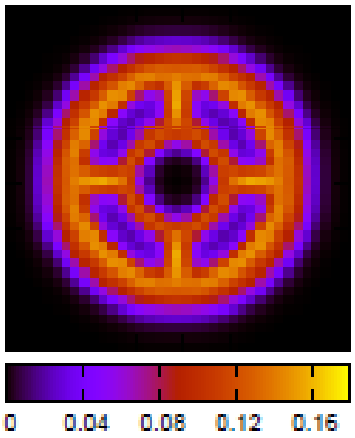
(c) P=0.39



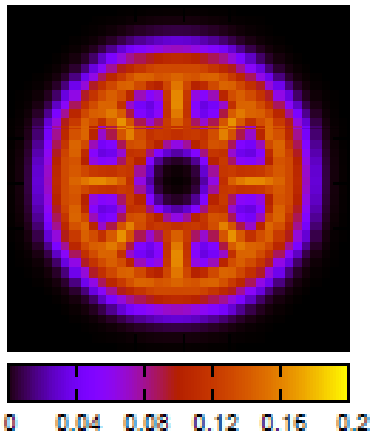
Radial-FFLO

✖ No symmetry breaking

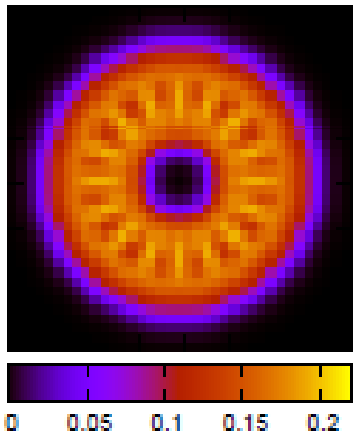
(d) P=0.44



(e) P=0.49



(f) P=0.69

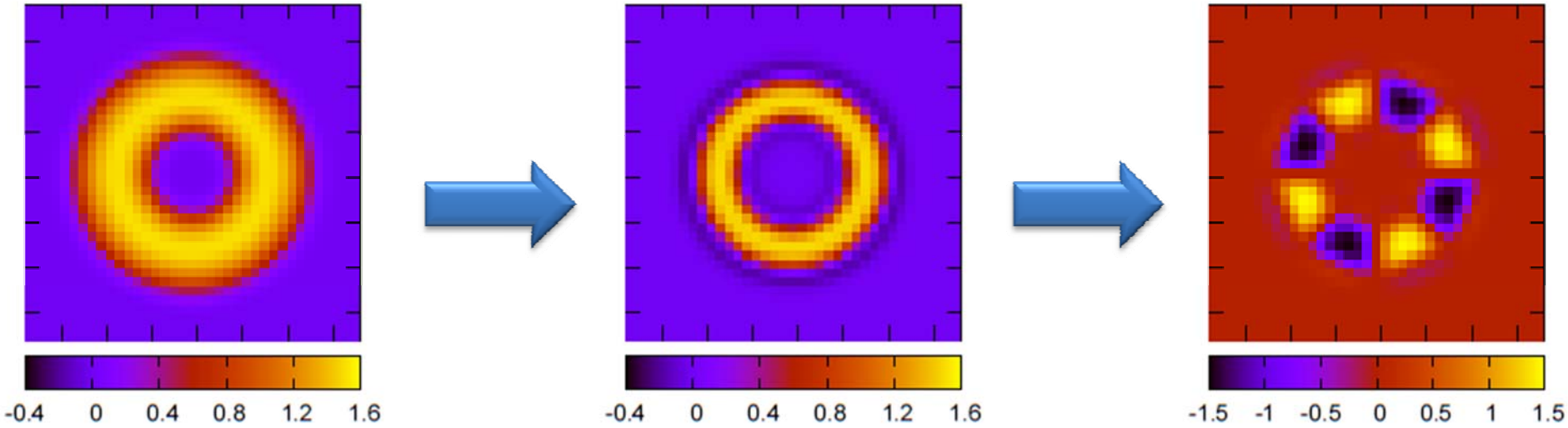


Angular-FFLO

Rotation symmetry breaking !!

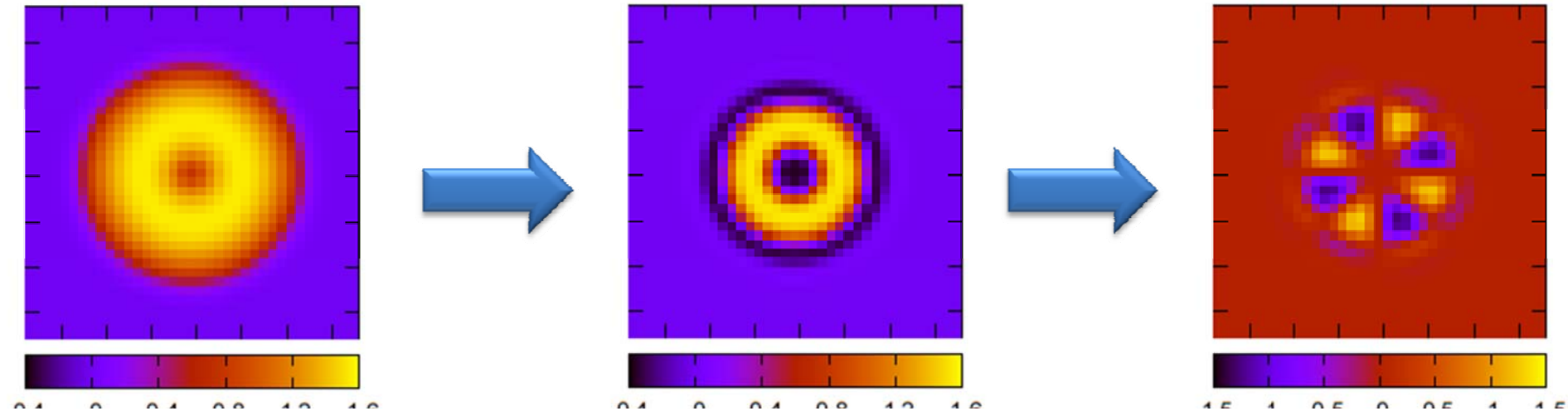
Self-one-dimensionalization

$\omega_t=8$

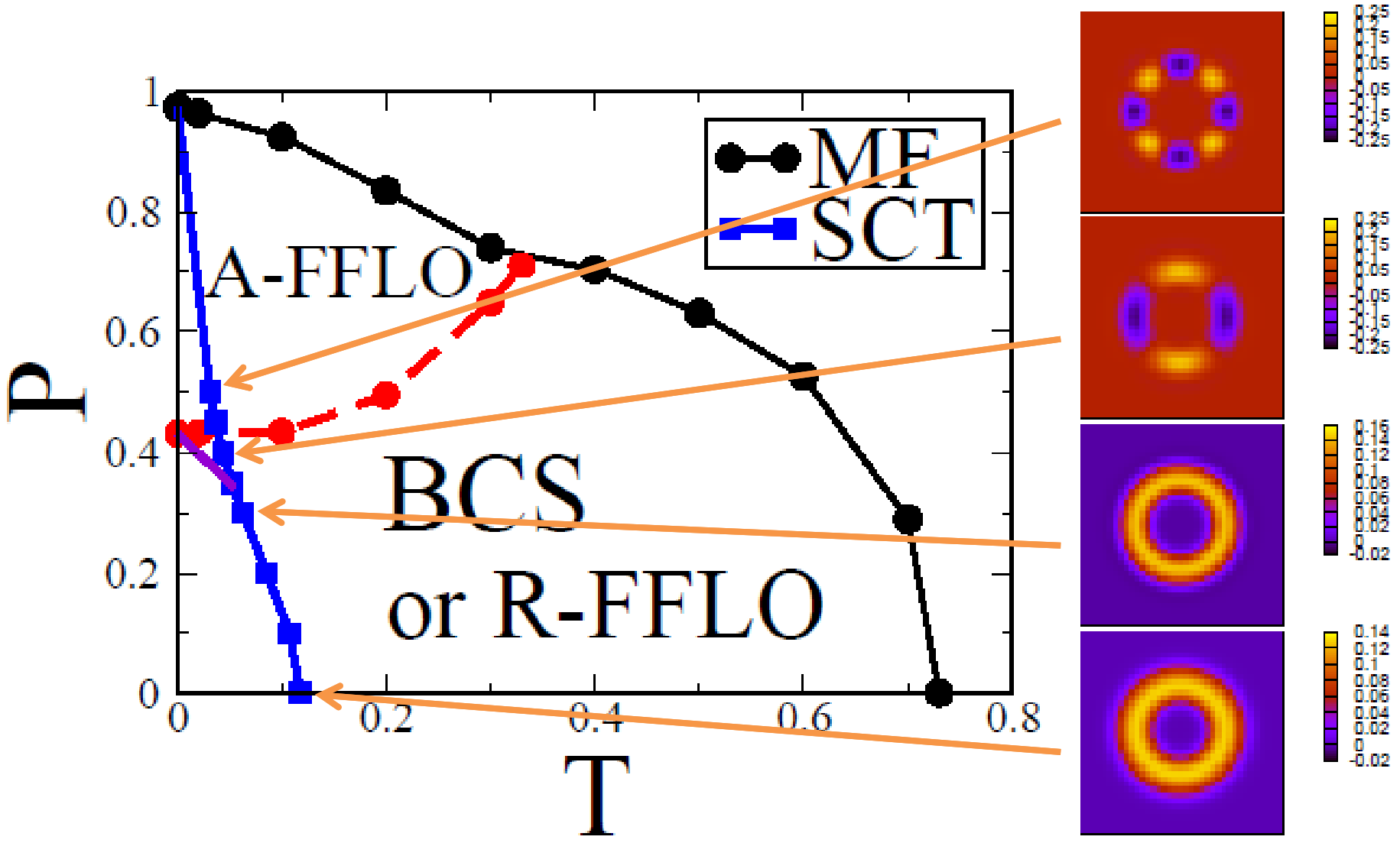


BCS R-FFLO A-FFLO

$\omega_t=2$



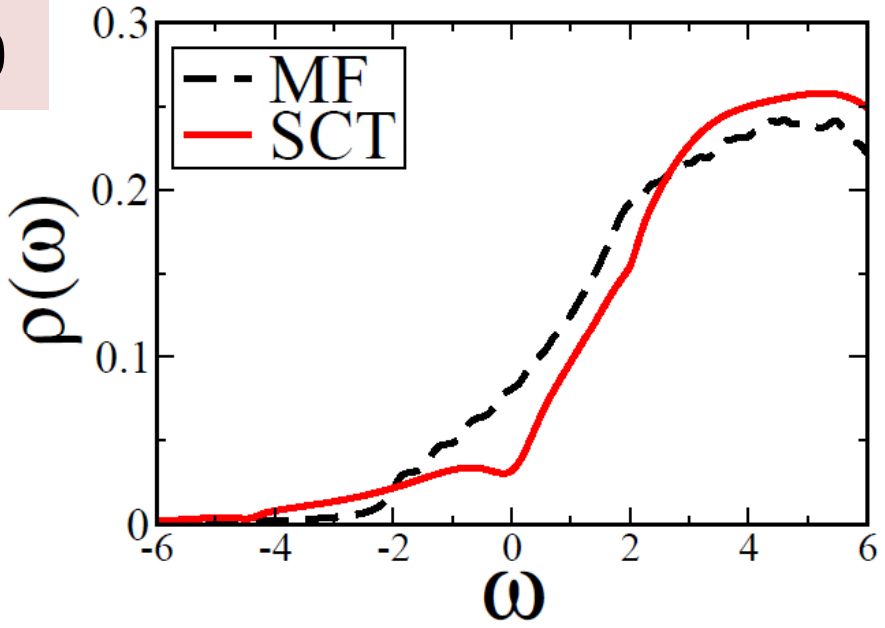
Beyond mean field theory (RSTA)



A-FFLO state is stable near BCS-BEC crossover !!

Pseudogap

P=0



$$P = \chi H$$

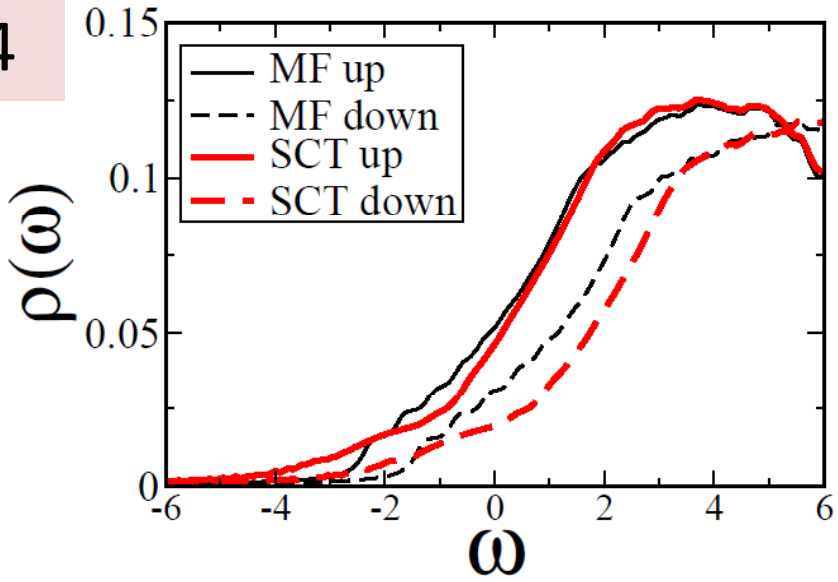
$\chi \propto \rho$: decreased by PG

Fixed polarization

➡ Large magnetic field

➡ FFLO state

P=0.4



Outlook

Internal degree of freedom ⇄ Symmetry breaking

(1) Relative angular momentum	S-wave, P-wave, D-wave ……
(2) Total spin	Spin triplet pairing : d-vector
(3) Total momentum	FFLO superfluidity
(4) Total angular momentum	Angular-FFLO state

Outlook

Internal degree of freedom ⇄ Symmetry breaking

(1) Relative angular momentum — S-wave, P-wave, D-wave ……

(2) Total spin — Spin triplet pairing : d-vector

(3) Total momentum — FFLO superfluidity

(4) Total angular momentum — Angular-FFLO state

→ Study of rotation systems !! — Giant response to rotation

Simulation of superconductivity without inversion symmetry