Unconventional Superfluid in quasi-one dimension

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Unconventional Superfluid in quasi-one dimension

- Parity-mixed superfluid controlled by spin-orbit coupling
- Realization in cold atoms

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Strongly-correlated system with cold atoms

・Change coupling constant

・Load on a lattice

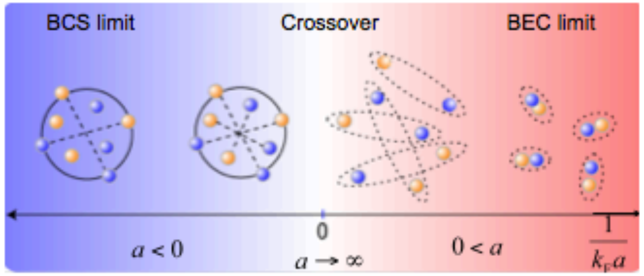
・Make low-dimensional system

Strongly-correlated system with cold atoms

- Change coupling constant

  Feshbach resonance

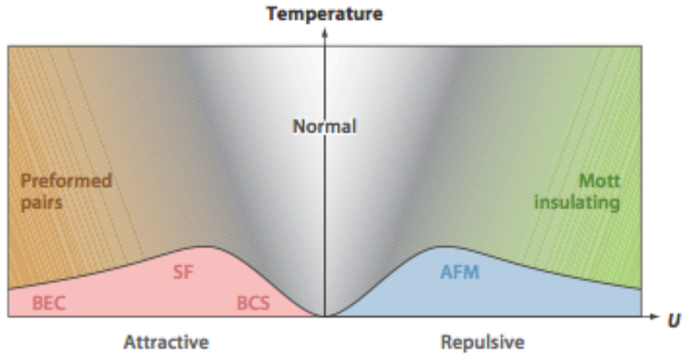
BCS-BEC crossover



- Load on a lattice

  Optical lattice

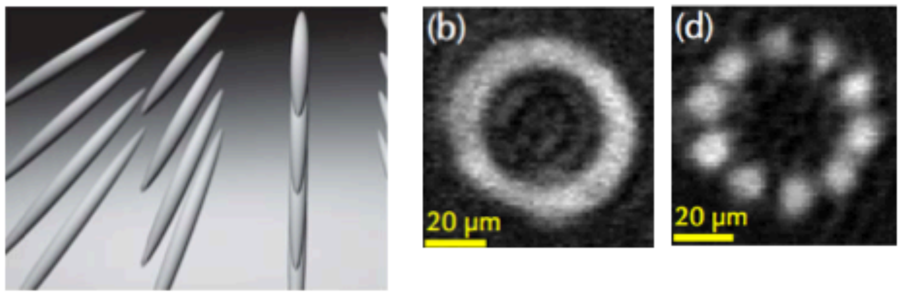
Fermi-Hubbard model



- Make low-dimensional system

  Tight confinement of atoms

Cold atoms in 1D



Strongly-correlated system with cold atoms

- Change coupling constant

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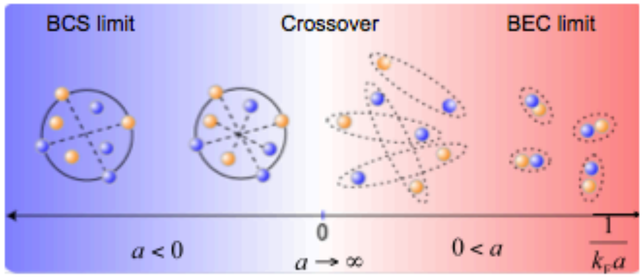

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  Optical lattice

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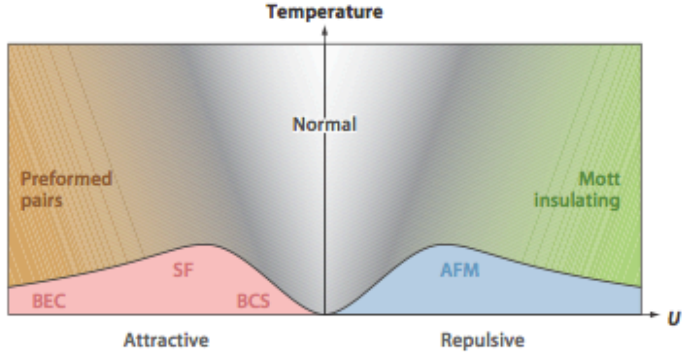

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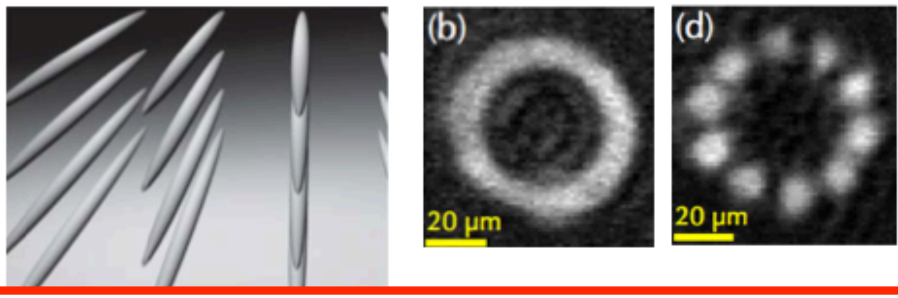
Cold atoms in 1D

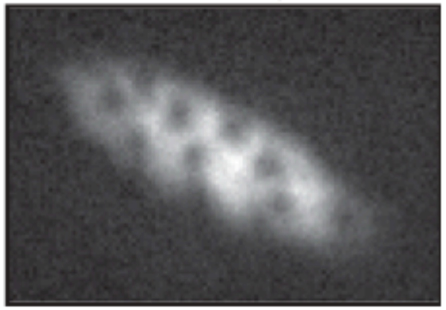


Synthetic gauge fields

$$H = \frac{(p - qA)^2}{2m}$$ A : Optically induced gauge field

- Spatial dependent gauge field

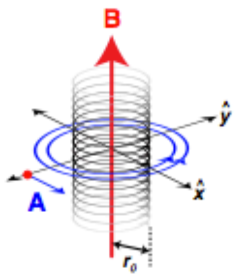
$$B = \nabla \times A$$: Magnetic field

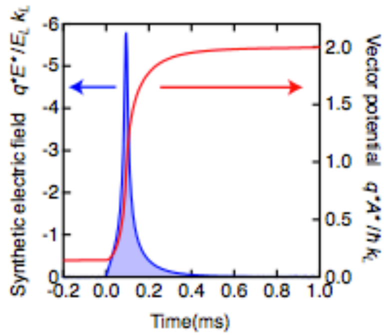


Y. Lin et al., Nature **462**, 628(2009)

- Time dependent gauge field

$$E = -\frac{\partial A}{\partial t}$$: Electric field

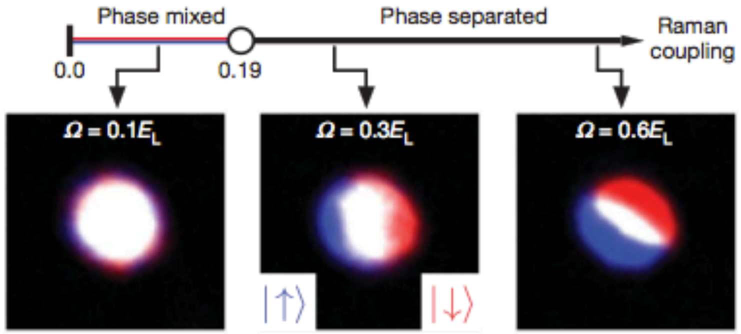




Y. Lin et al., Nat. Phys. **7**, 531 (2011).

- Gauge field with an internal degrees of freedom

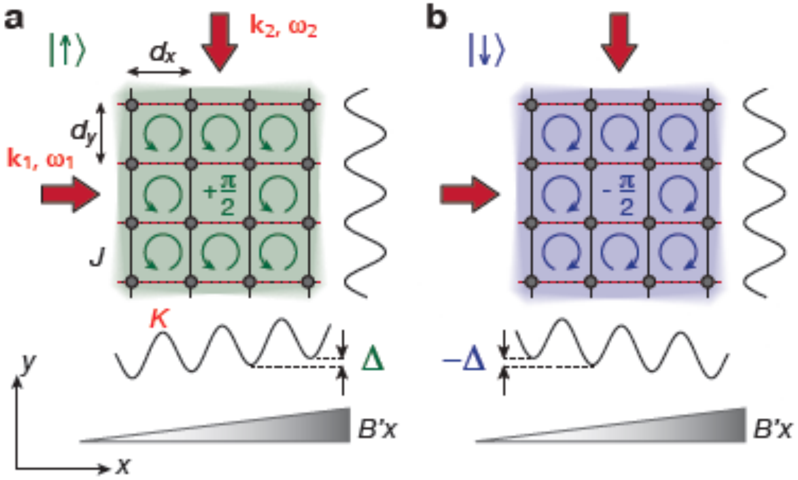
$$H = \frac{p^2}{2m} + b(p) \cdot \sigma$$: Spin-orbit coupling



Y. Lin et al., Nature **471**, 83(2011)

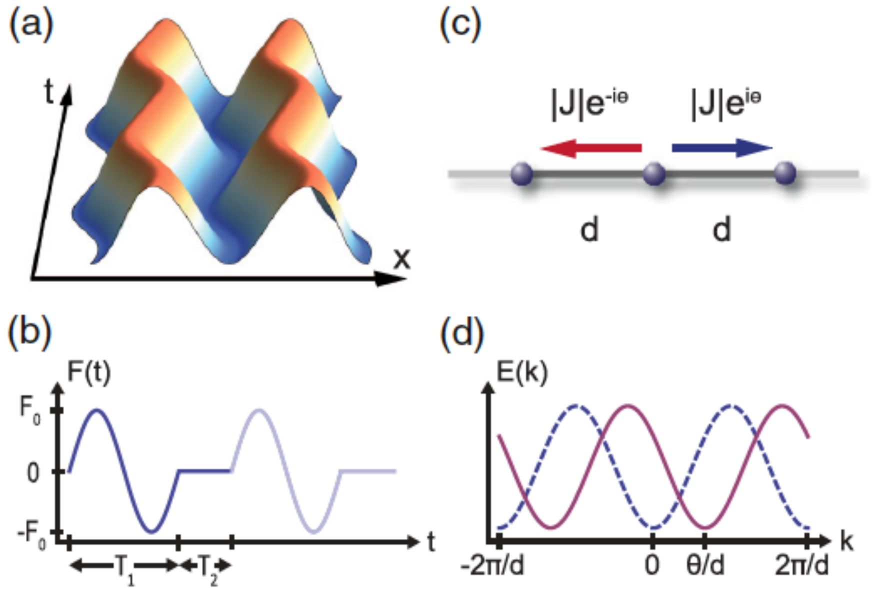
Gauge fields on optical lattices

- Raman laser on tilted lattice



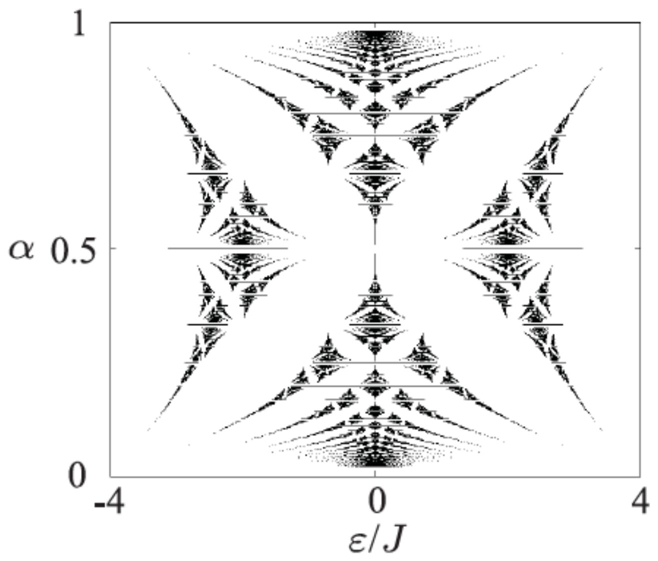
M. Aidelsburger et al., PRL **107**, 255301 (2011);
M. Aidelsburger et al., PRL **111**, 185301 (2013);
H. Miyake et al., PRL **111**, 185302 (2013).

- Lattice shaking



J. Struck et al., PRL **108**, 255304 (2012);
J. Struck et al., Nature Physics, **9**, 738 (2013).

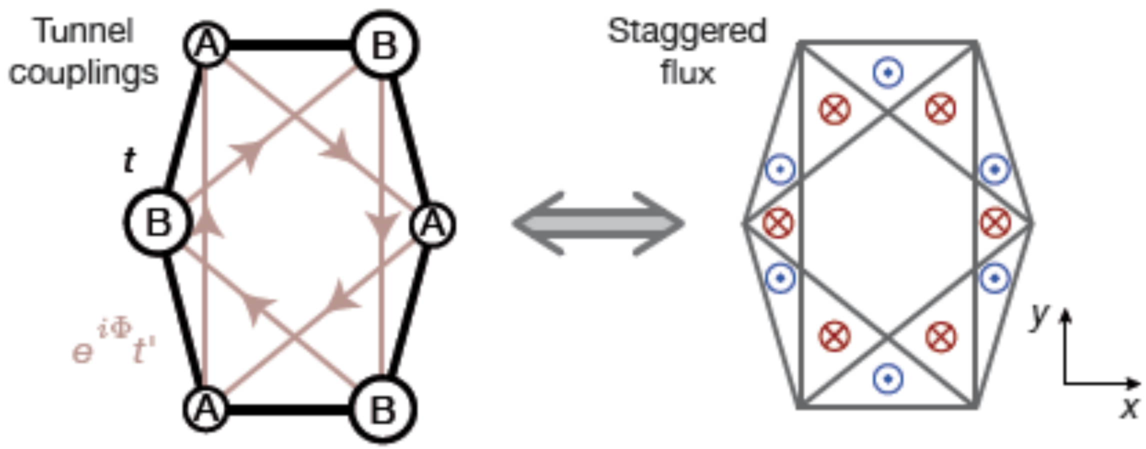
Gauge fields on optical lattices



Hofstadter butterfly

M. Aidelsburger et al., PRL **111**, 185301 (2013);
H. Miyake et al., PRL **111**, 185302 (2013);
M. Aidelsburger et al., arXiv:1407.4205

Haldane topological insulator



G. Jotzu, et al., arXiv:1406.7874

Gauge fields on optical lattices

- Spin-independent gauge field

$$-t\sum_j e^{i\Phi_j} c^+_{j,\sigma} c_{j+1,\sigma} + \text{h.c.}$$

Gauge field in charge sector
Artificial electromagnetic field

- Spin-dependent gauge field

$$-t\sum_j (e^{i\vec{\Phi}_j\cdot\vec{\sigma}})_{\sigma\sigma'} c^+_{j,\sigma} c_{j+1,\sigma'} + \text{h.c.}$$

Gauge field in spin sector
Artificial spin-orbit coupling

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Gauge field in spin sector
Artificial spin-orbit coupling

Why one dimensional system?

Limit of strong correlation

- (In most cases) no ordered phase

- There exist exactly solvable models

- Established analytical and numerical technique such as bosonization and DMRG

Tomonaga-Luttinger liquid

- Many 1d systems belong to this universality class

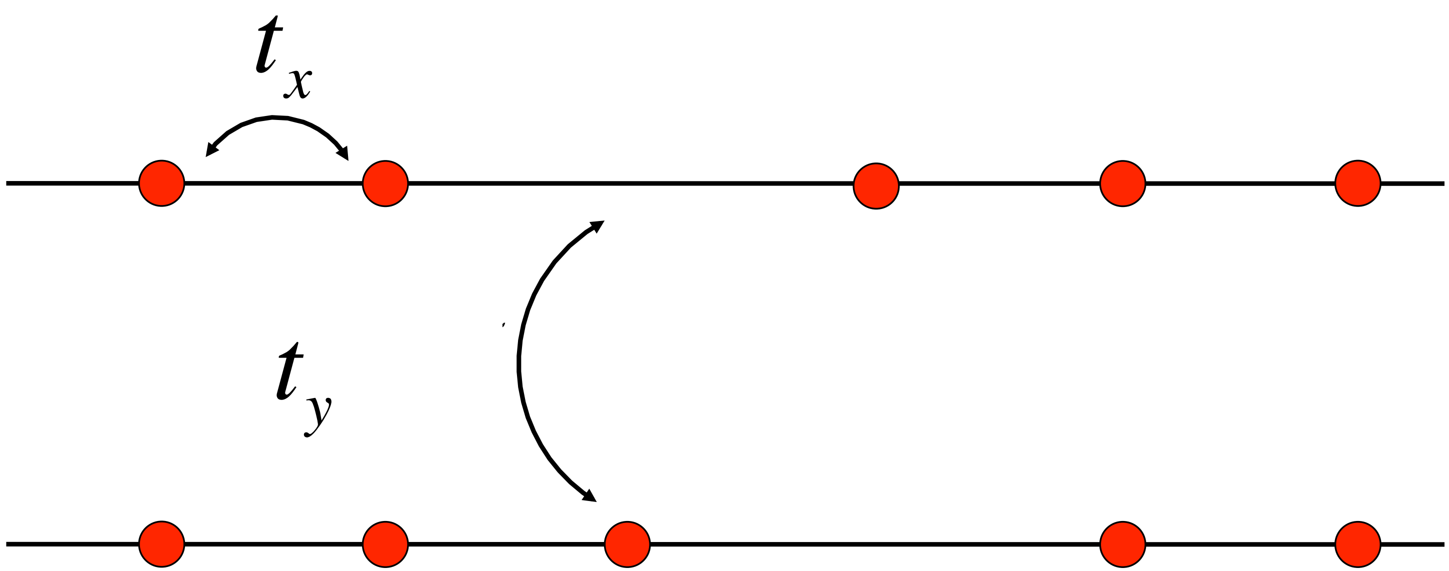
- c=1 CFT

- Quasi long-range order (due to massless)

⇨ Dominant quasi-long range order depends on a system

$$\left\langle O(r)O(0)\right\rangle \sim \left(\frac{1}{r}\right)^{K}$$

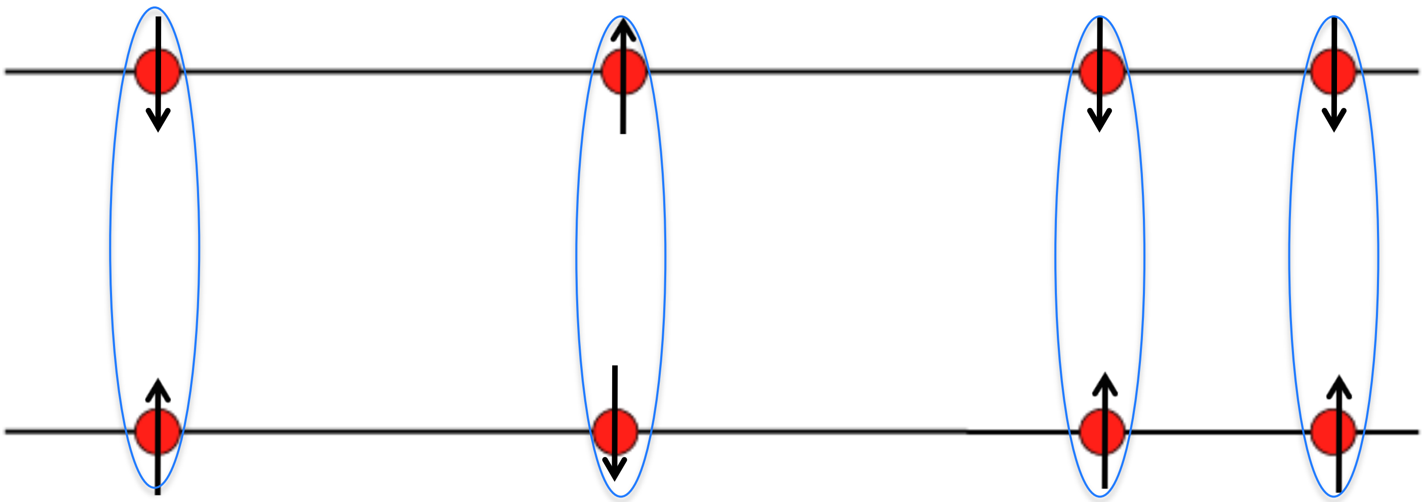
Two-leg fermionic Hubbard ladder



$$H = -t_x \sum_{j,p} c^{+}_{j,p,\sigma} c_{j+1,p,\sigma} - t_y \sum_{j} c^{+}_{j,1,\sigma} c_{j,2,\sigma}$$

$$+ U \sum_{j,p} n_{j,p,\uparrow} n_{j,p,\downarrow} + h.c.$$

Two-leg fermionic Hubbard ladder

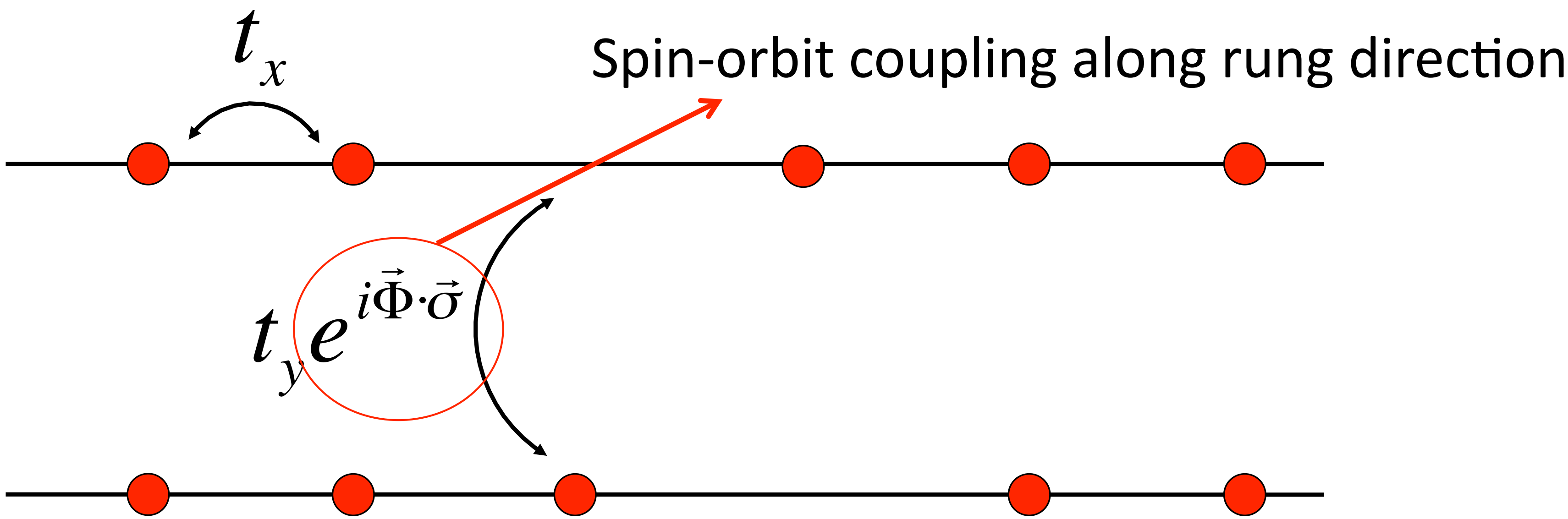


- For U>0, superfluidity with interchain spin-singlet pairing is dominant at incommensurate filling

Analogy with d-wave superfluid

See e.g., T. Giamarchi, Quantum physics in one dimension

System with spin-orbit coupling



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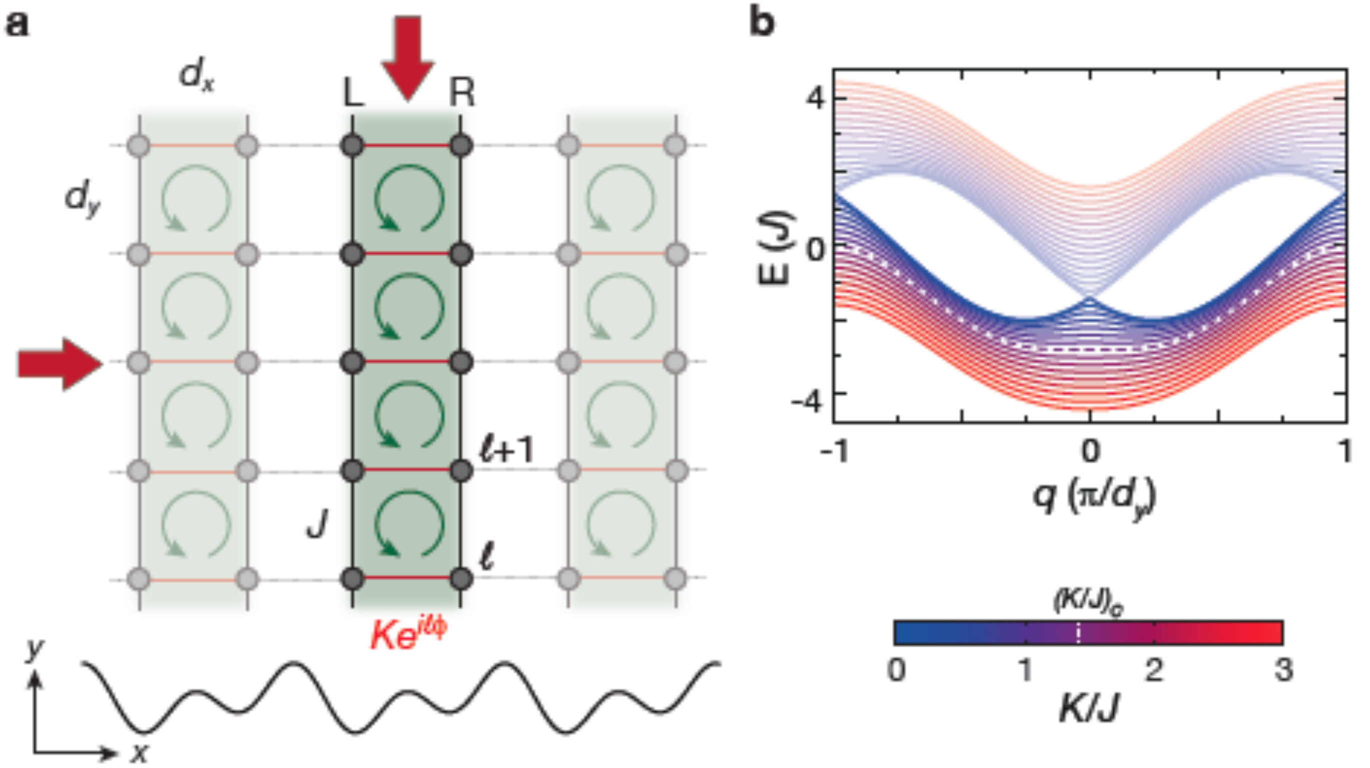
Gauge field in a two-leg ladder



M. Atala et al., Nature Physics **10**, 588 (2014).

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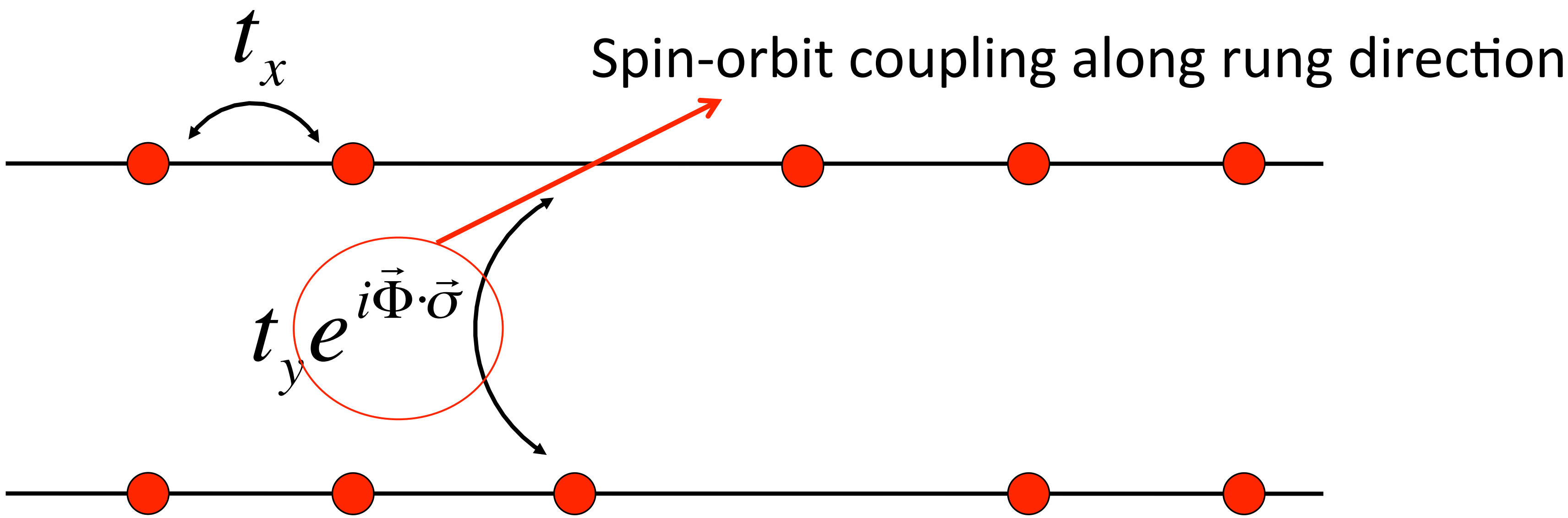

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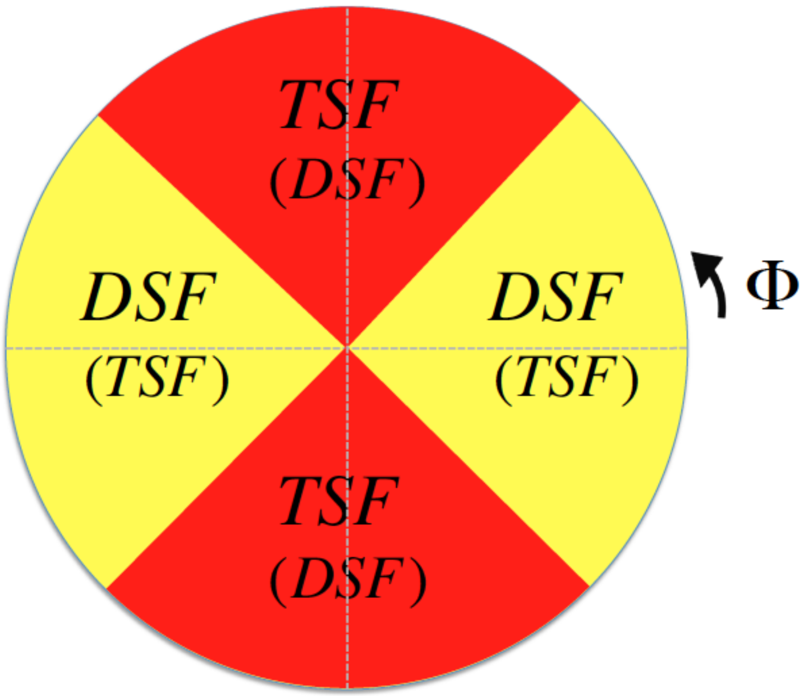
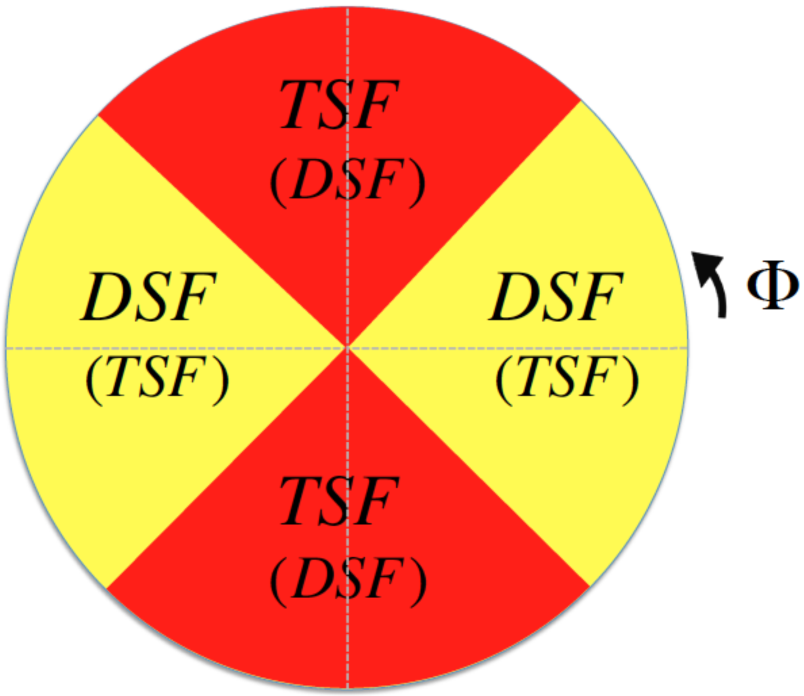
Phase diagram



DSF : d - wave superfluid

TSF : spin - triplet superfluid

Phase diagram

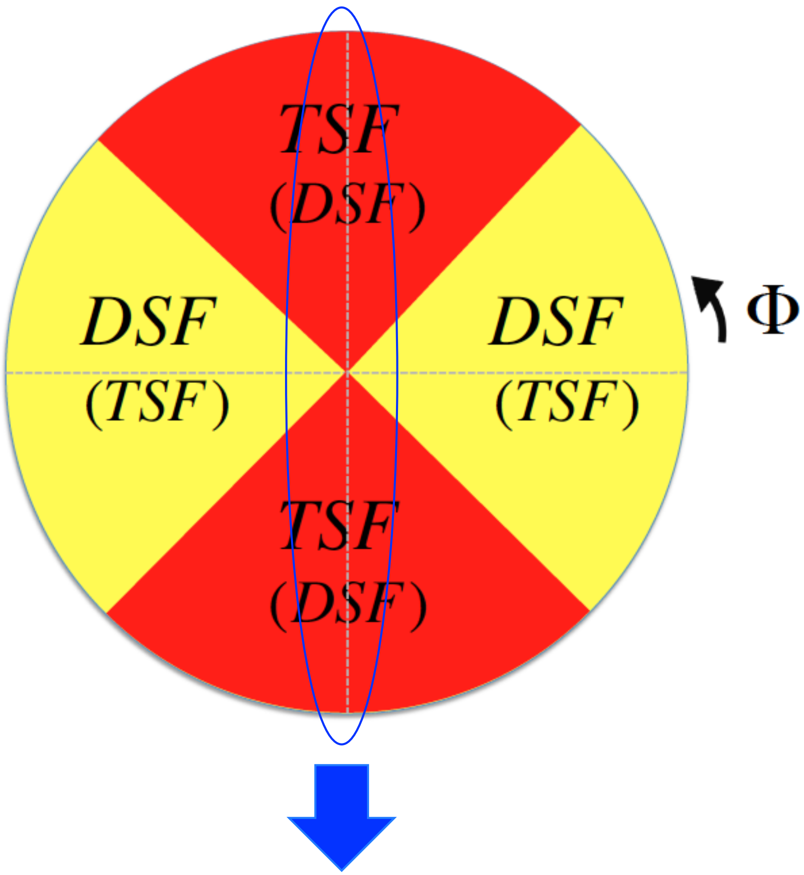


DSF : d - wave superfluid

TSF : spin - triplet superfluid

- In presence of spin-orbit coupling, admixture between spin singlet and triplet pairings occurs.
- Such an admixture is controllable with artificial gauge field.

Phase diagram



DSF : d - wave superfluid

TSF : spin - triplet superfluid

Pure spin - triplet superfluid emerges for $\Phi = \frac{\pi}{2}, \frac{3\pi}{2}$

Temperature for realization

$$T \leq t, U, \Delta$$

$$\Delta \sim t^2/U \quad \text{for } 4 < U/t < 10$$

C. Hayward and D. Poilblanc, PRB **53,** 11721 (1996)**;**
R. Noack, S. White, and D. Scalapino, Physica C **270**, 281(1996)**;**
S. White, I. Affleck, and D. J. Scalapino, PRB **65**,165122 (2002);
G. Roux et al., PRB **75**, 245119 (2007).

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↓

$$T \le 10^{-1} \varepsilon_F$$

Summary

- One dimensional analog of parity-mixed superfluid and spin triplet superfluid.
- Admixture of spin singlet and triplet pairing can be controlled by the synthetic gauge field.
- The superfluid discussed is promising in cold atoms.

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