Interacting fermions in flux lattices: Ferromagnetism and nematic ordering

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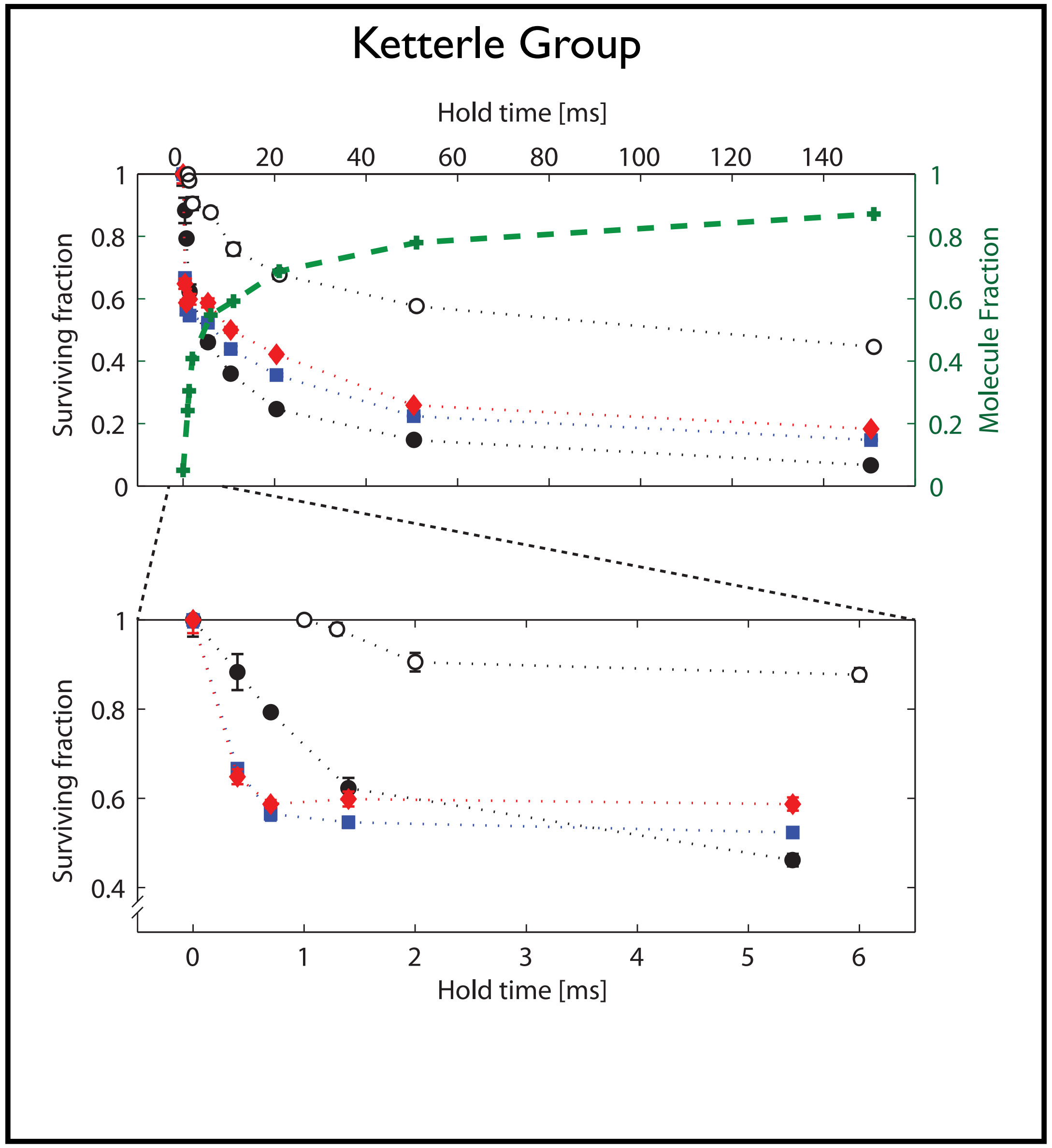
TCM Group, Cavendish Laboratory
University of Cambridge

see also Phys. Rev. Lett. 109, 265301 (2012)

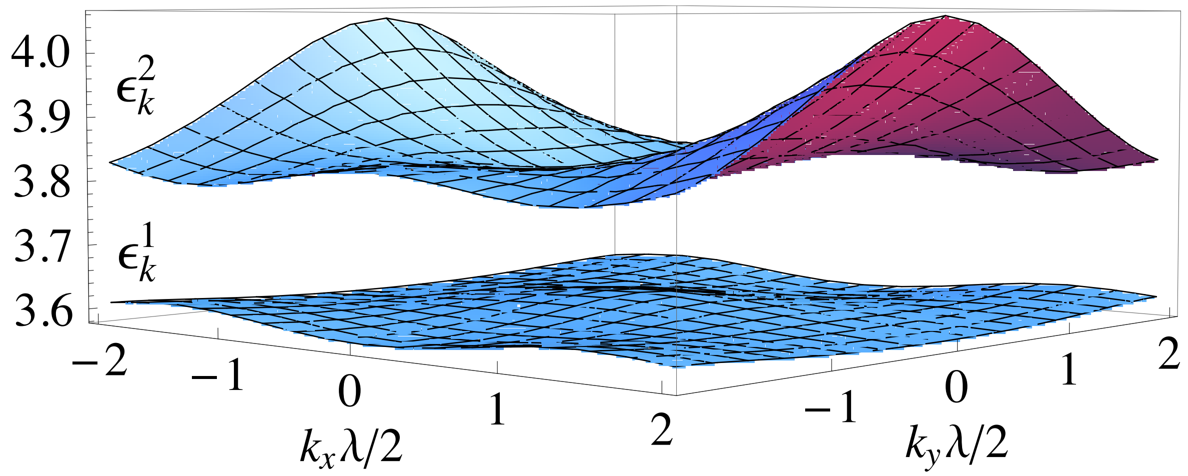
Motivation

Itinerant ferromagnetism with cold fermions is (so far) hampered by losses



Novel effects of interacting fermions in optical flux lattices

- Momentum dependent interactions
- Topological flat bands (2D)



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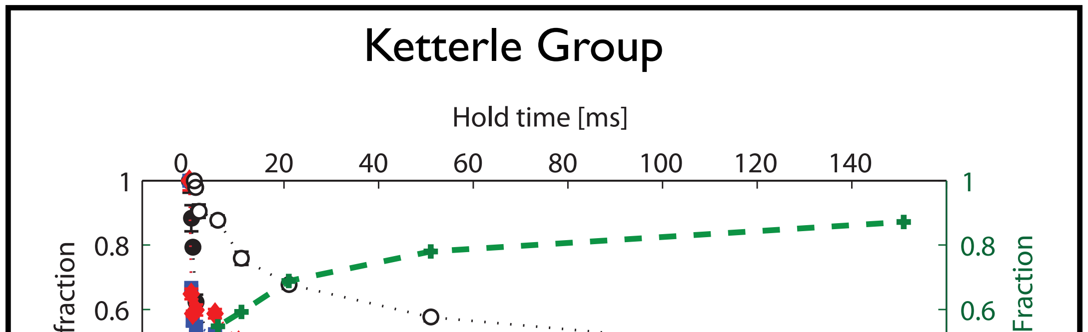

"Over a wide range of interaction strengths a rapid decay into bound pairs is observed over times on the order of 10 h/E_F, preventing the study of equilibrium phases of strongly repulsive fermions. Our work suggests that a Fermi gas with strong short-range repulsive interactions does not undergo a ferromagnetic phase transition."

Sanner et al, PRL 2012

Novel effects of interacting fermions in optical flux lattices

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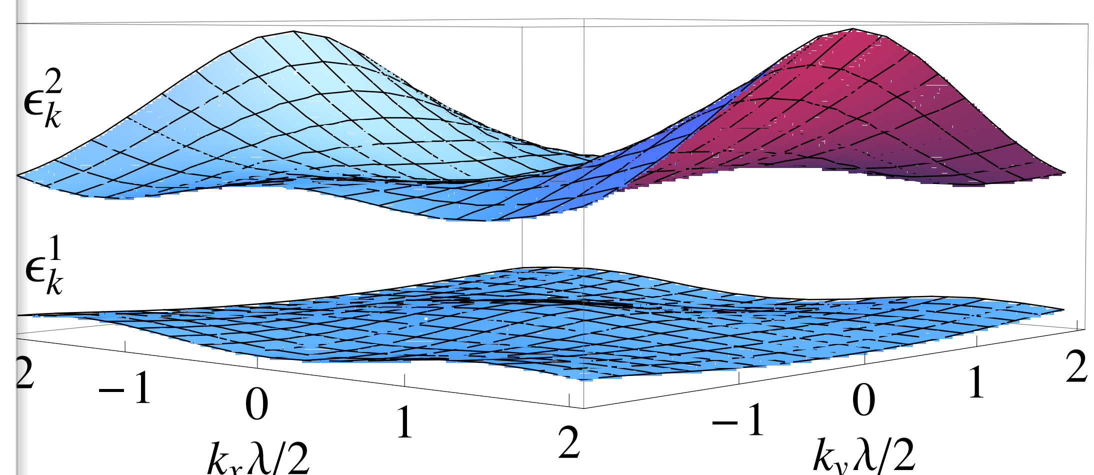
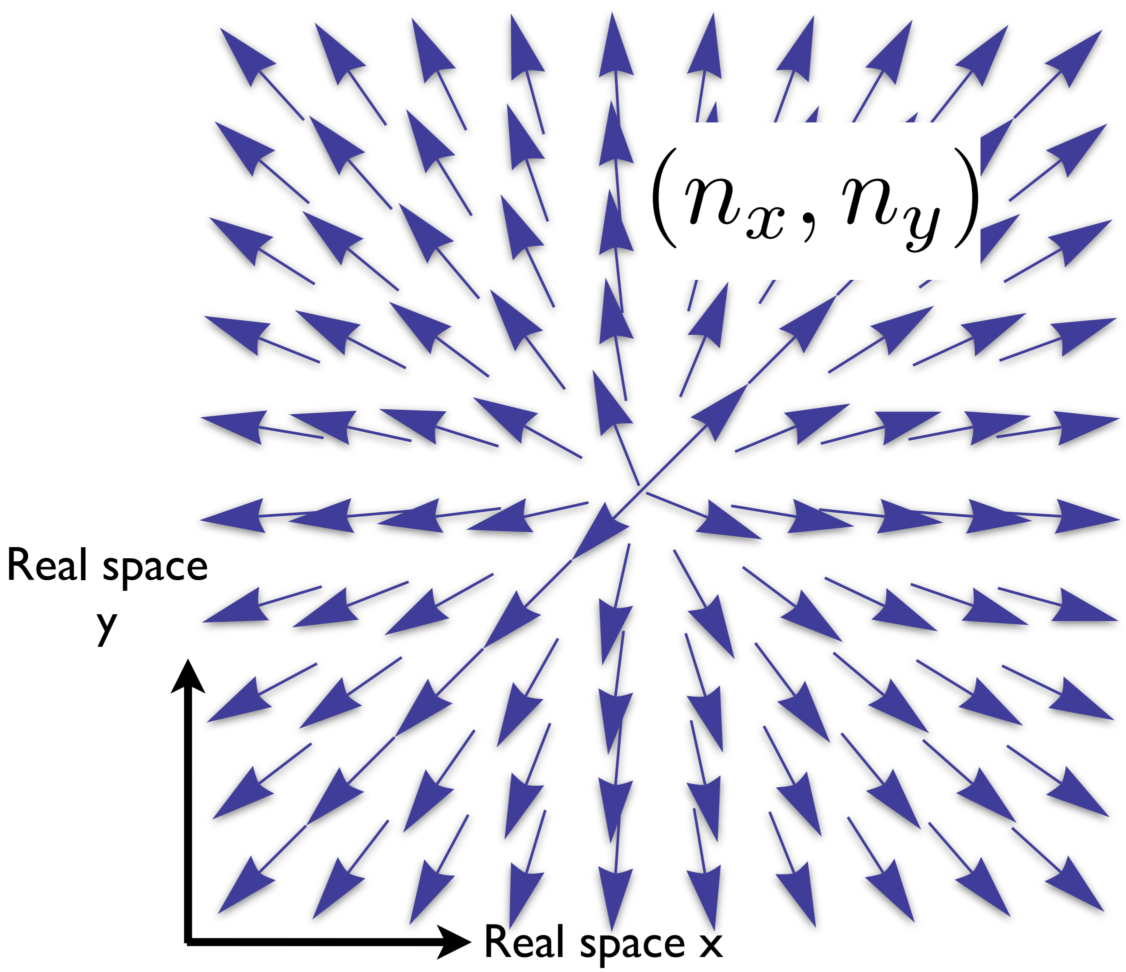
Topological flat bands (2D)

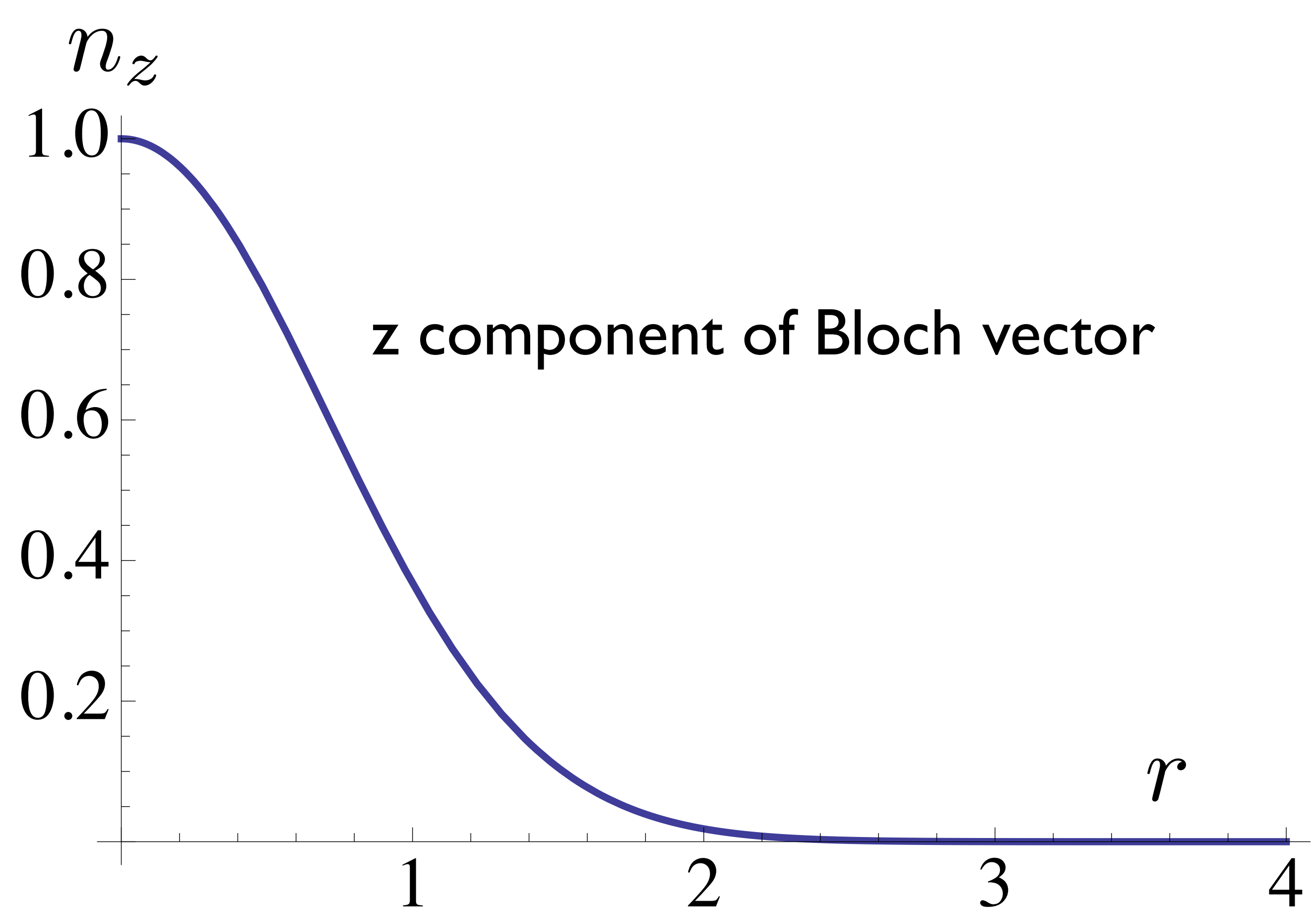


What is an optical flux lattice?

- Flux lattice: Example spin 1/2
- Toy model: Consider spin texture in 2D

x-y components of Bloch vector





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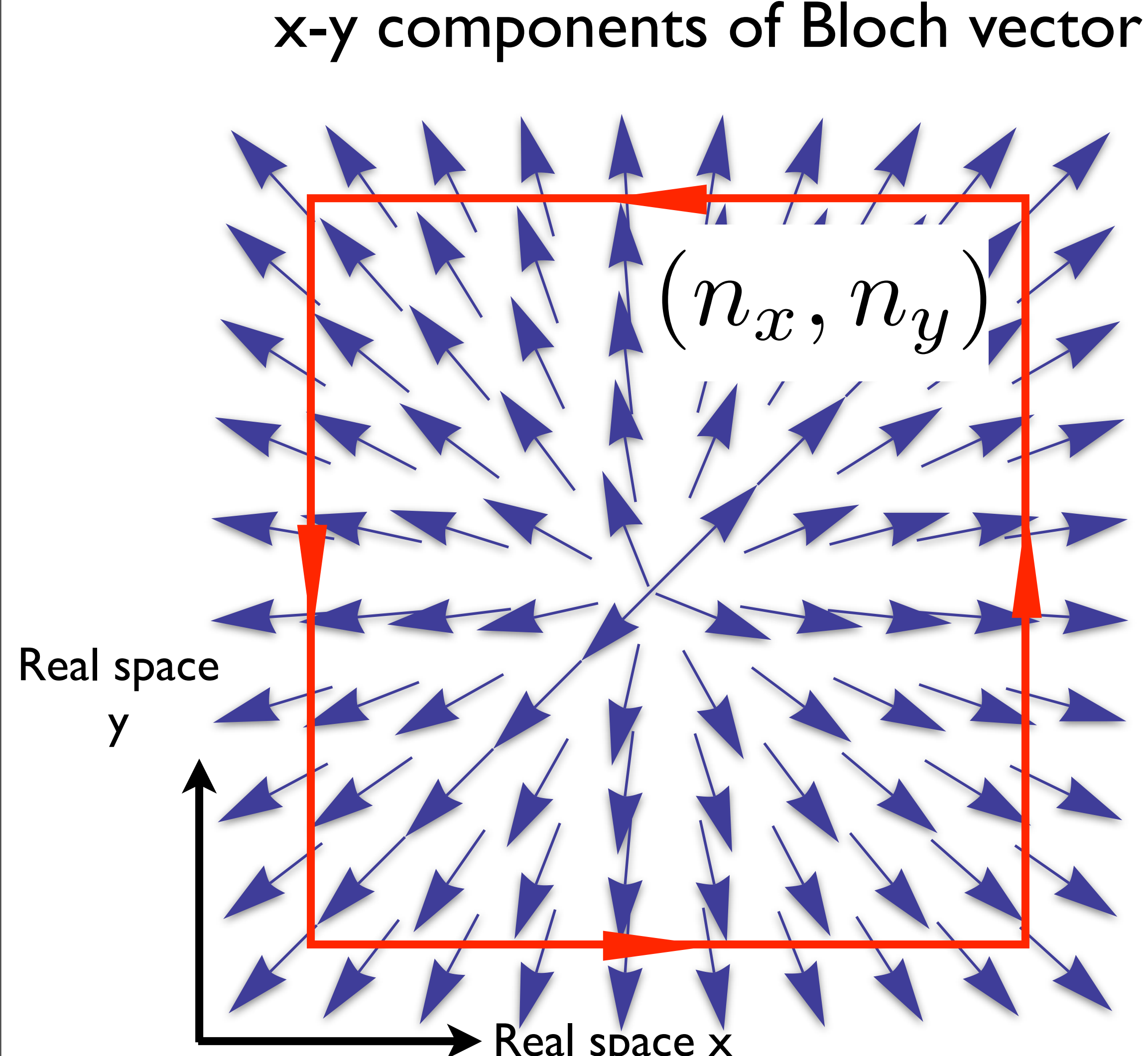
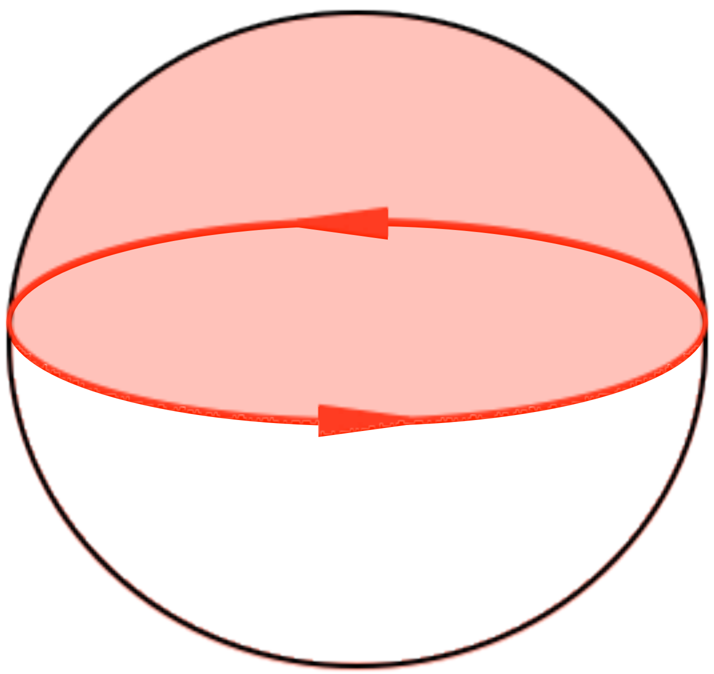


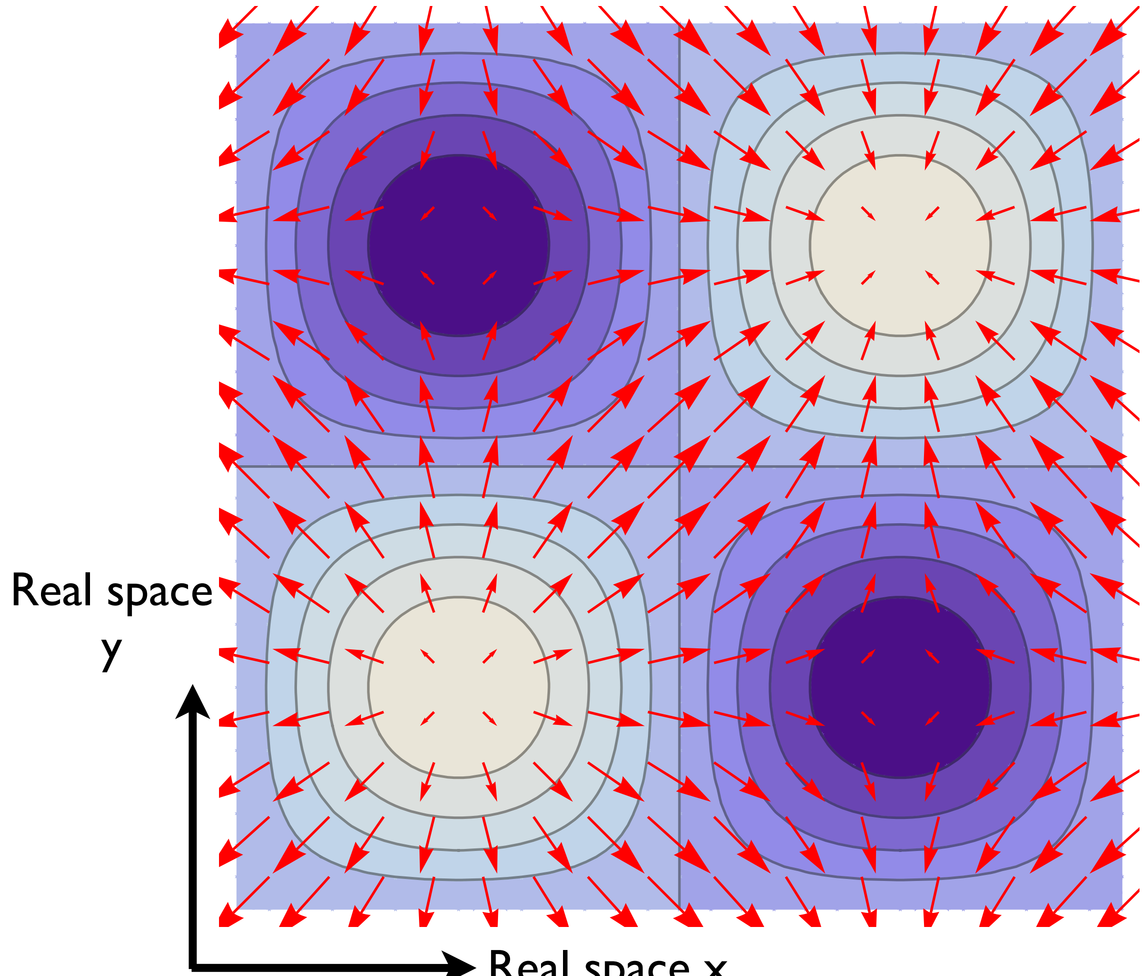


Wraps 1/2 of Bloch sphere

What is an optical flux lattice?

- Flux lattice: Lattice potential with periodic texture with net positive flux

Example: square



Cooper, PRL (2011); Juzeliūnas, Spielman, NJP (2012)

Gauge potential

$$\mathbf{A} = i\langle\psi|\nabla_{\mathbf{r}}\psi\rangle$$

Flux density

$$n_\phi = (\nabla \times \mathbf{A})/(2\pi)$$

$$n_\phi = \frac{-1}{4\pi}\mathbf{n}\cdot(\partial_x\mathbf{n}\times\partial_y\mathbf{n})$$

$4\times(1/2) = 2$ Flux quanta per unit cell

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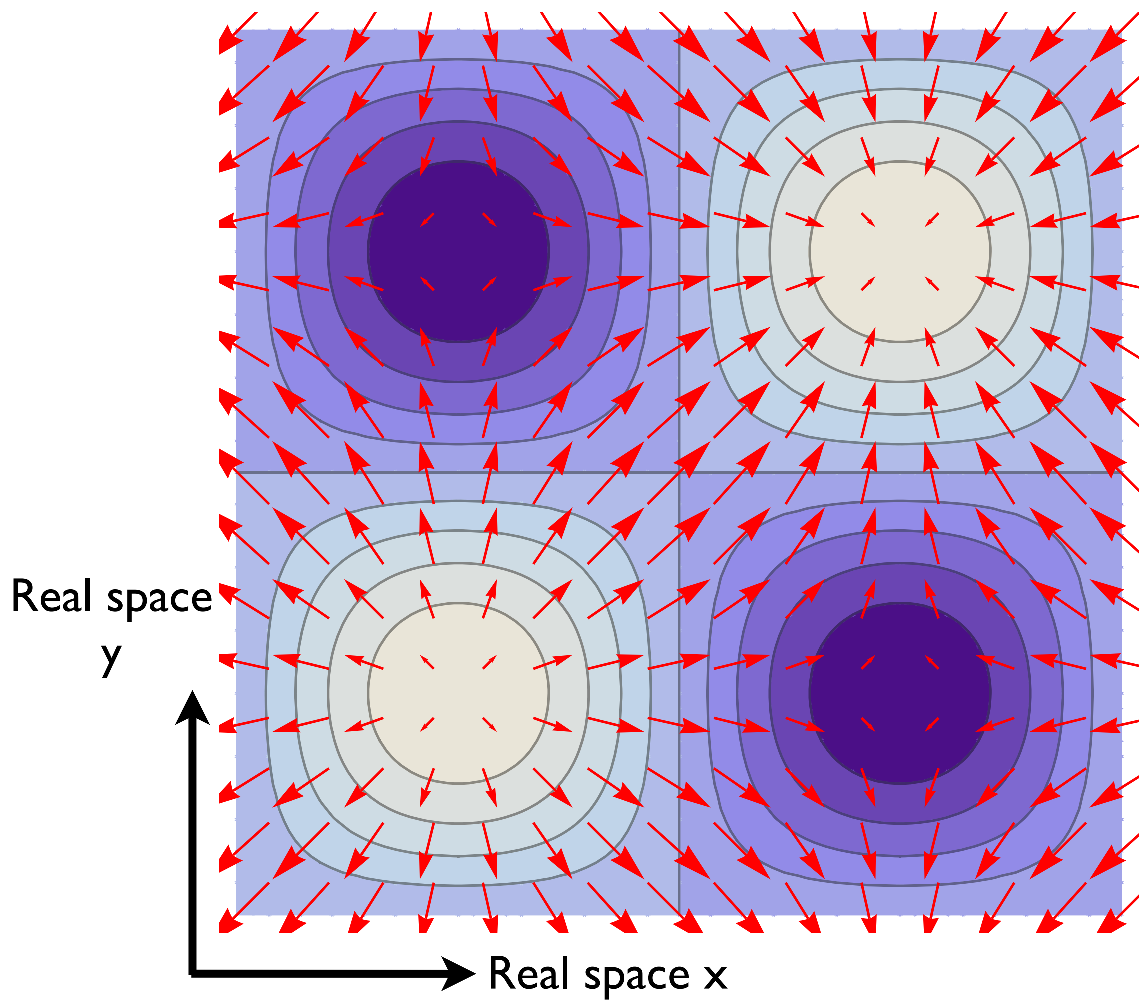

Cooper, PRL (2011); Juzeliūnas, Spielman, NJP (2012)

Spin dep. potential

$$H = \cancel{\frac{p^2}{2m}} + \sigma \cdot \mathbf{B}(\mathbf{r})/2$$

Adiabatic approx.

$$\psi(\mathbf{r}) = \begin{pmatrix} e^{-i\phi}\cos(\theta/2) \\ \sin(\theta/2) \end{pmatrix}$$

$$\mathbf{n}(\mathbf{r}) = \psi^\dagger(\mathbf{r})\sigma\psi(\mathbf{r}) \quad \mathbf{n} \parallel -\mathbf{B}$$

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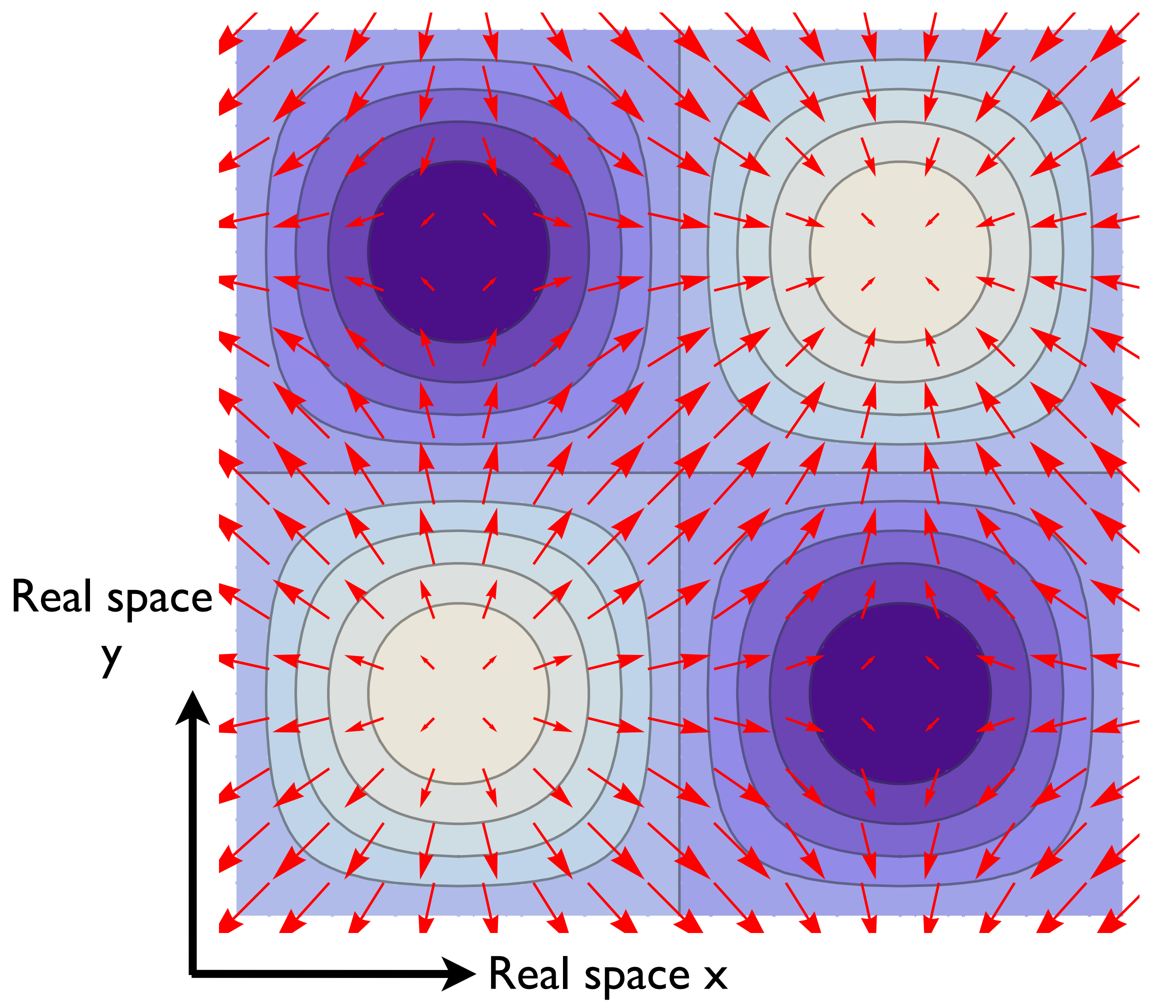

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Spin dep. potential

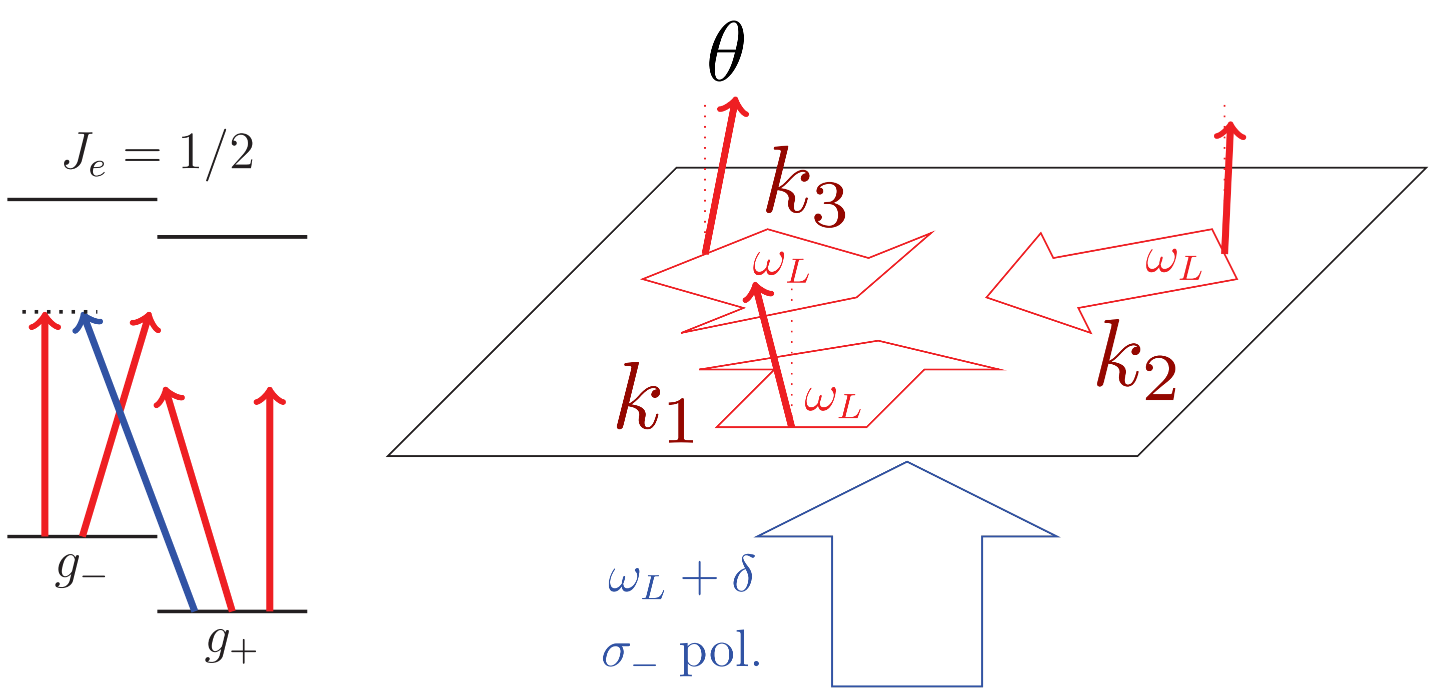
$$H = \frac{p^2}{2m} + \sigma \cdot \mathbf{B}(\mathbf{r})/2$$

state dep. light shift

$$\sigma \cdot \mathbf{B}(\mathbf{r}) = \begin{pmatrix} B_z & B_x + iB_y \\ B_x - iB_y & -B_z \end{pmatrix}$$

Raman dressing

Proposal by Cooper and Dalibard



3 Parameters to play with:

1) Lattice depth V_0/E_R
2) Polarization angle θ
3) Raman coupling ϵ

Cooper and Dalibard, EPL 95, 66004 (2011)

Two photon Raman-scheme for e.g. ^{171}Yb with J=1/2

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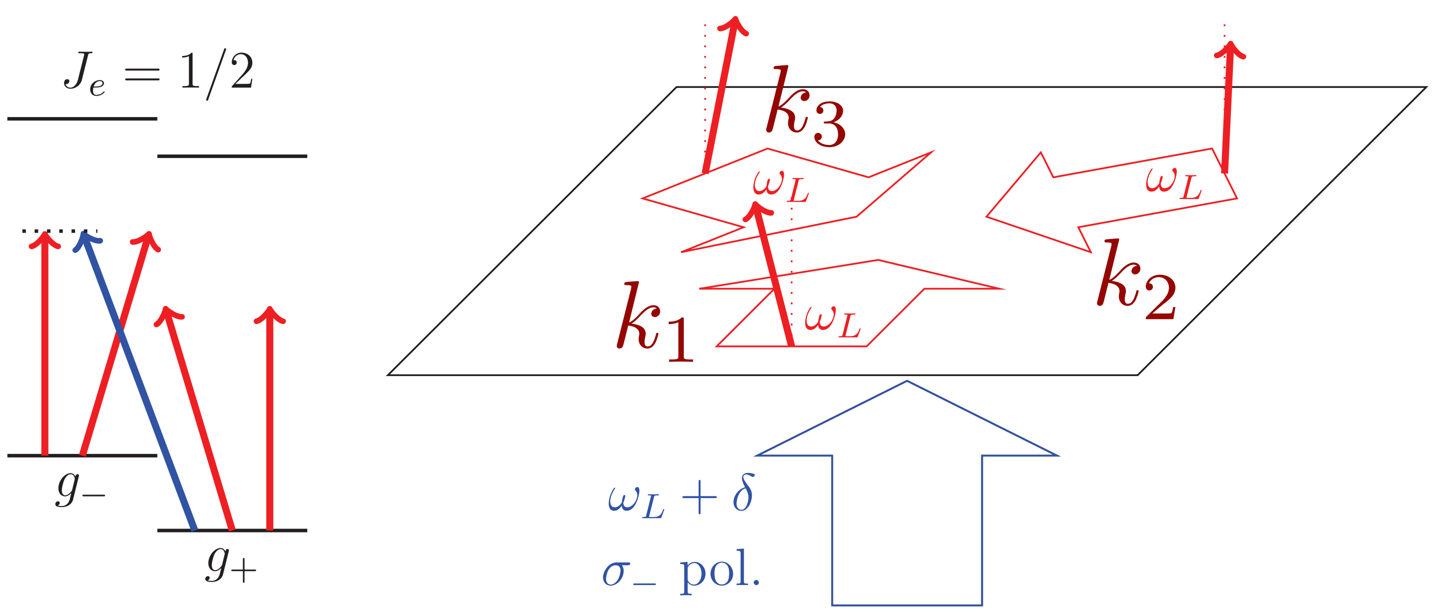
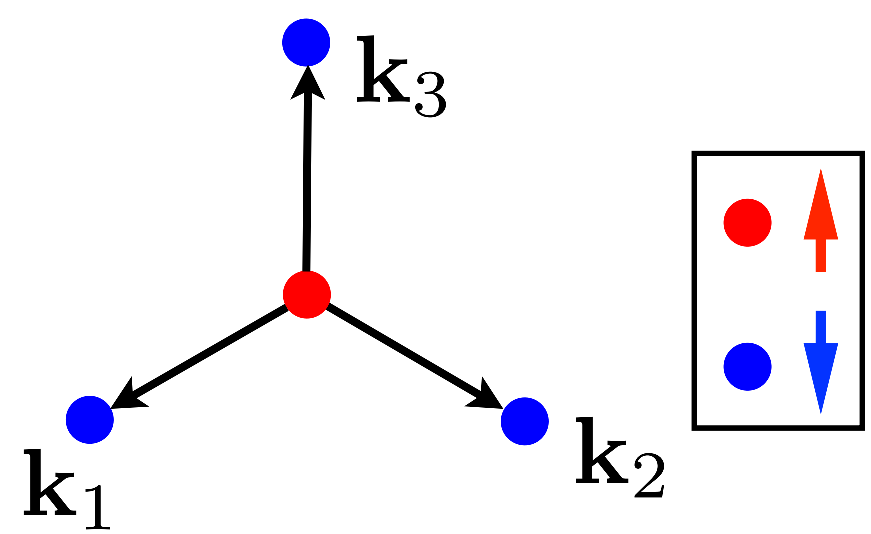


Cooper and Dalibard, EPL 95, 66004 (2011)

Momentum transfers



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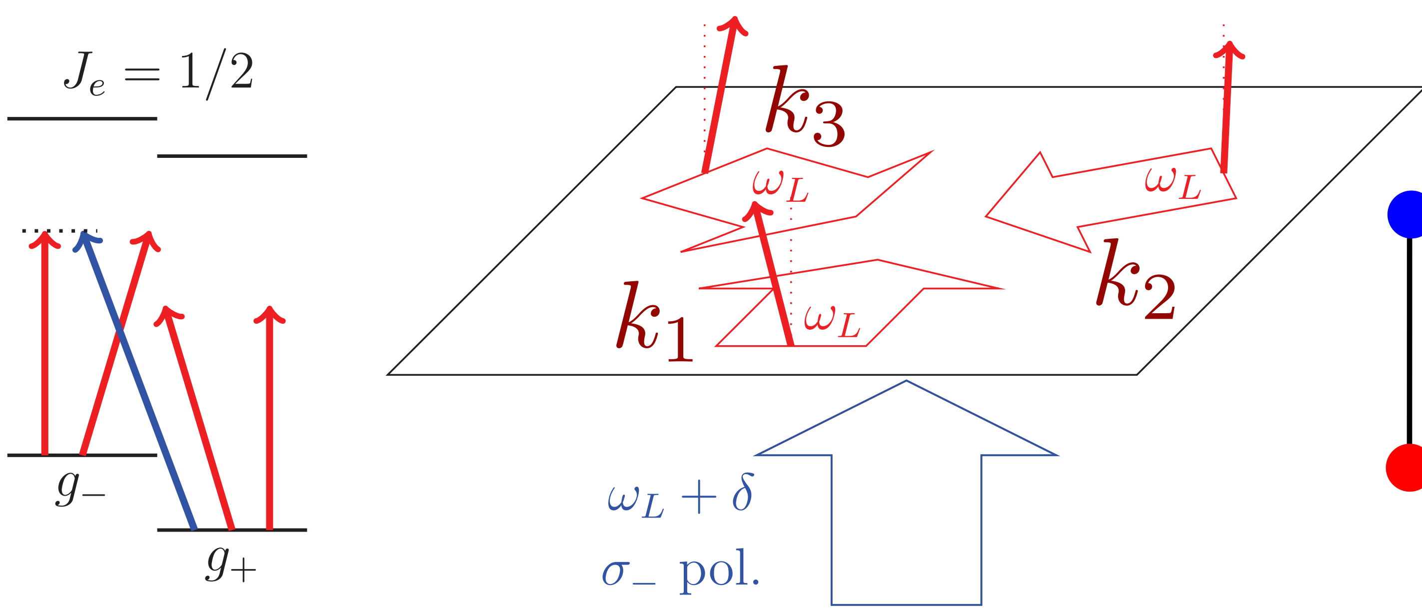
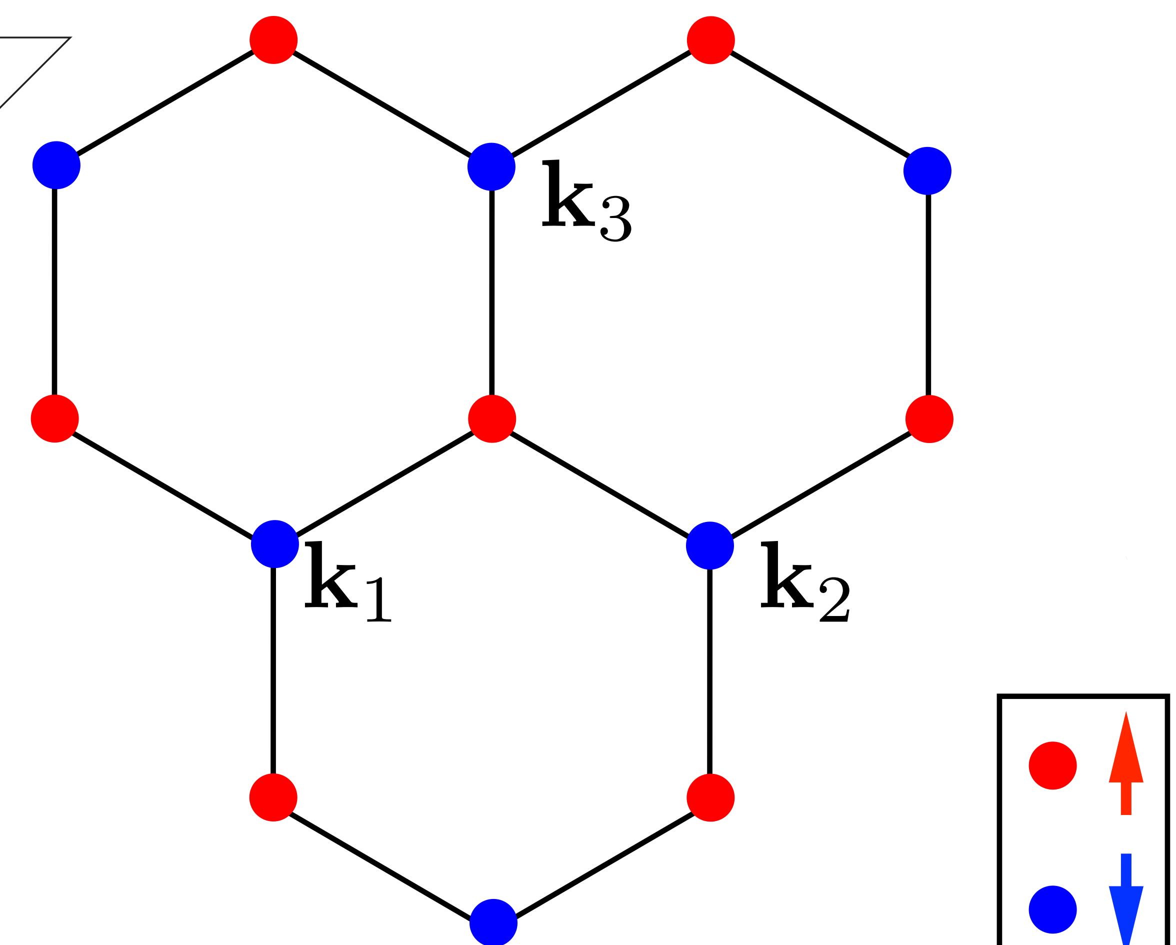


Momentum space



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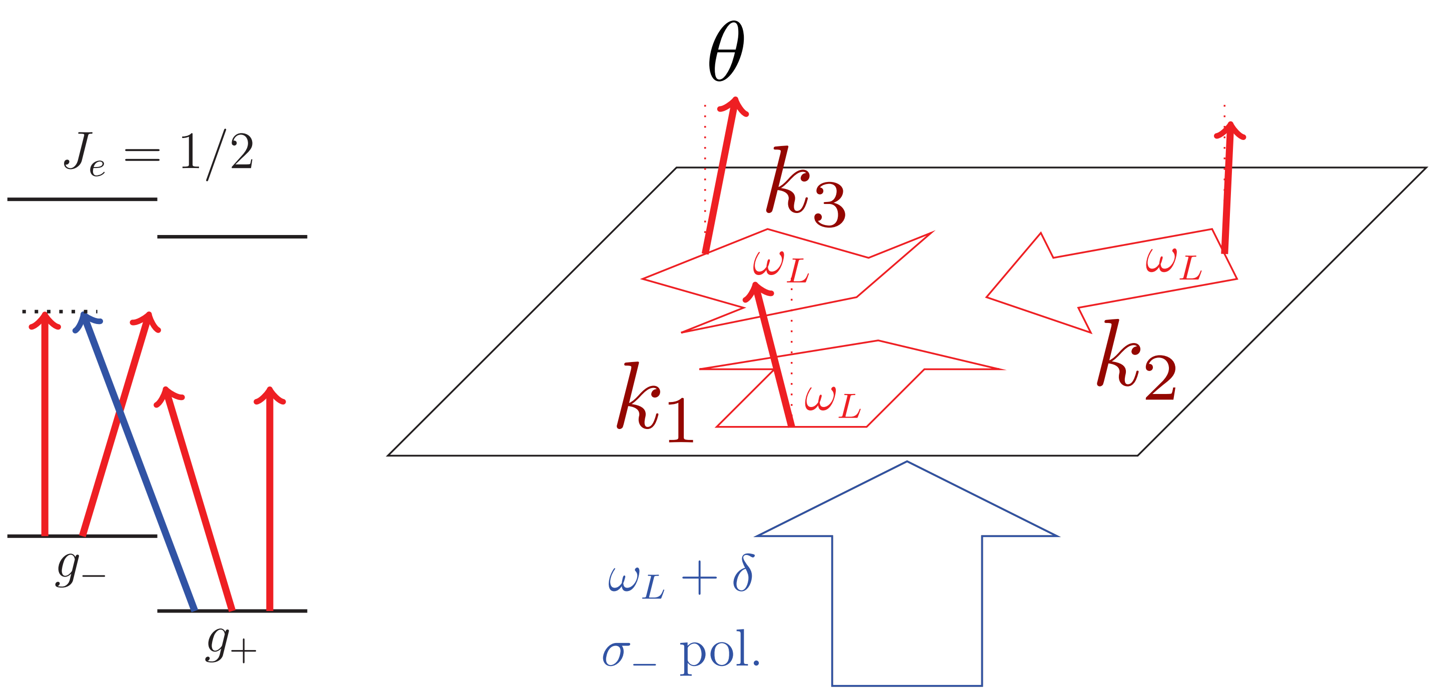
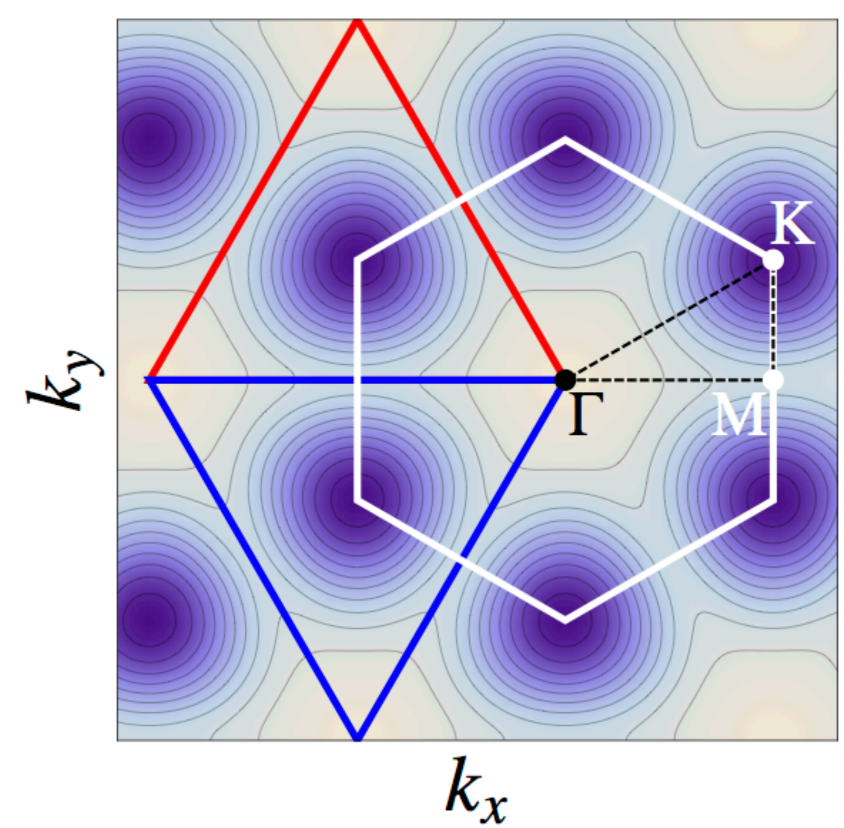
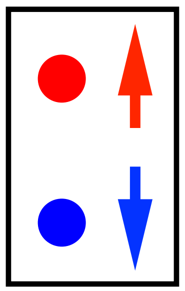


Cooper and Dalibard, EPL 95, 66004 (2011)

Band-structure (2D)



$V_0/E_R = 1.8$
$\epsilon = 0.4;\ \theta = 0.3$



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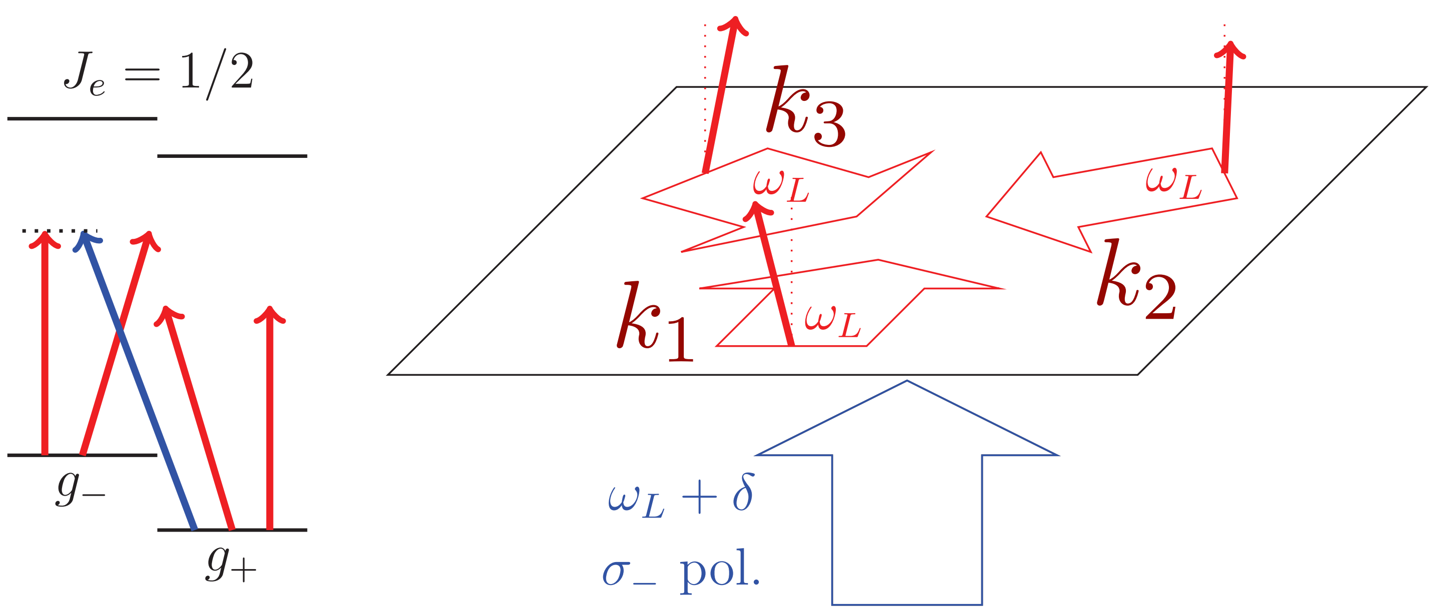

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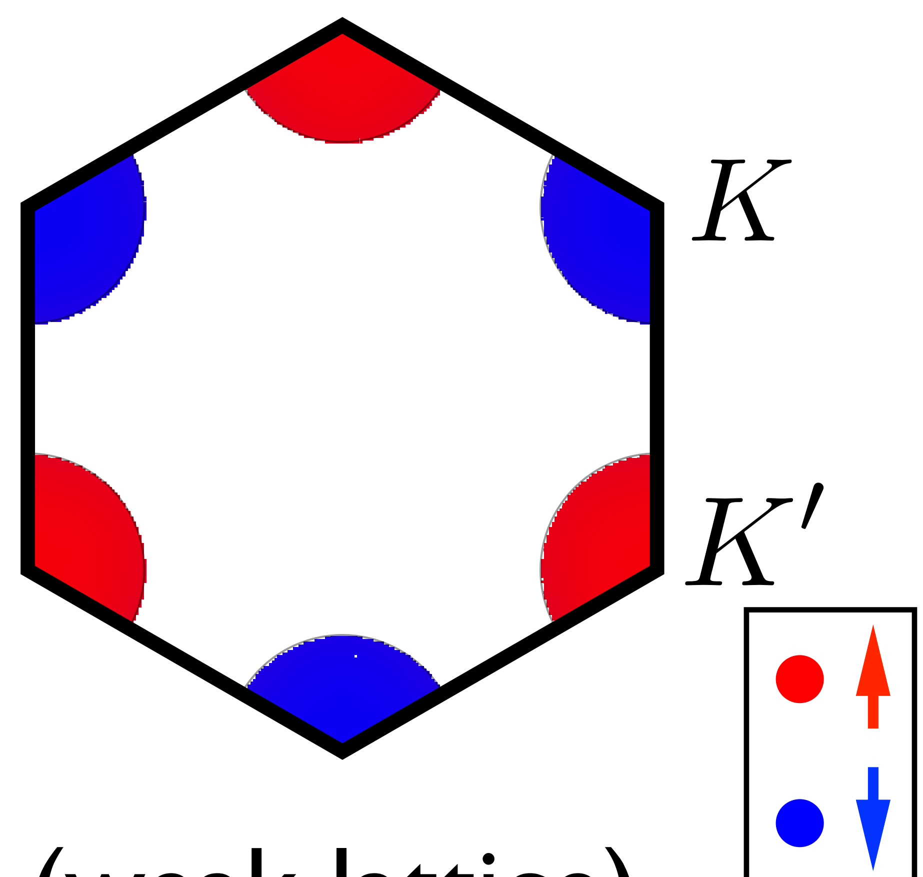
Two photon Raman-scheme for e.g. ^{171}Yb with J=1/2

Fermi surface

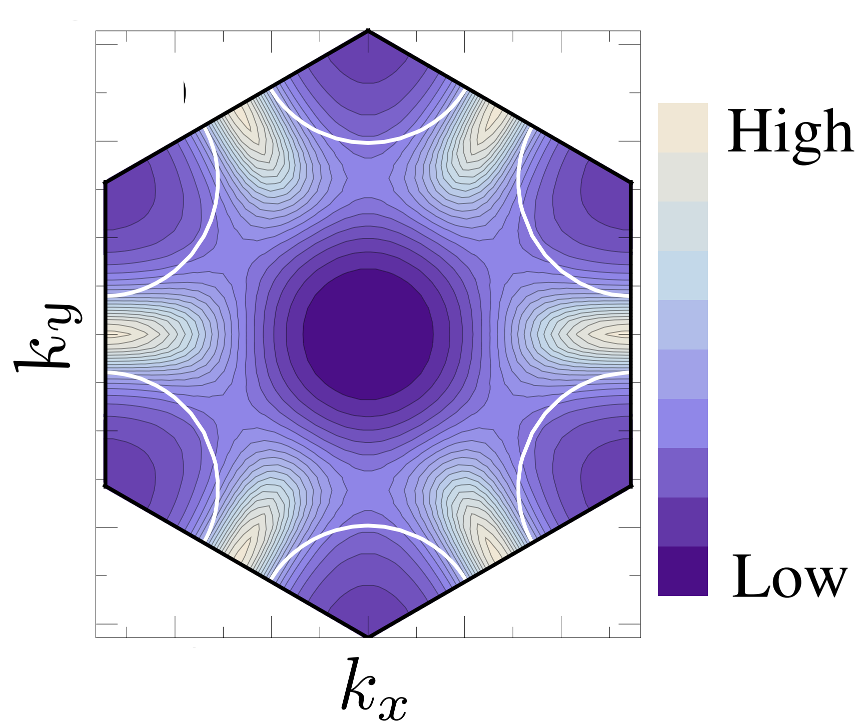


(weak lattice)

Summary of single particle properties

- Lowest band ~ similar to lowest Landau level

<table>
<tr><th>Topology</th><th>Band flatness</th></tr>
<tr><td>
Berry curvature



Chern # of lowest band is 1
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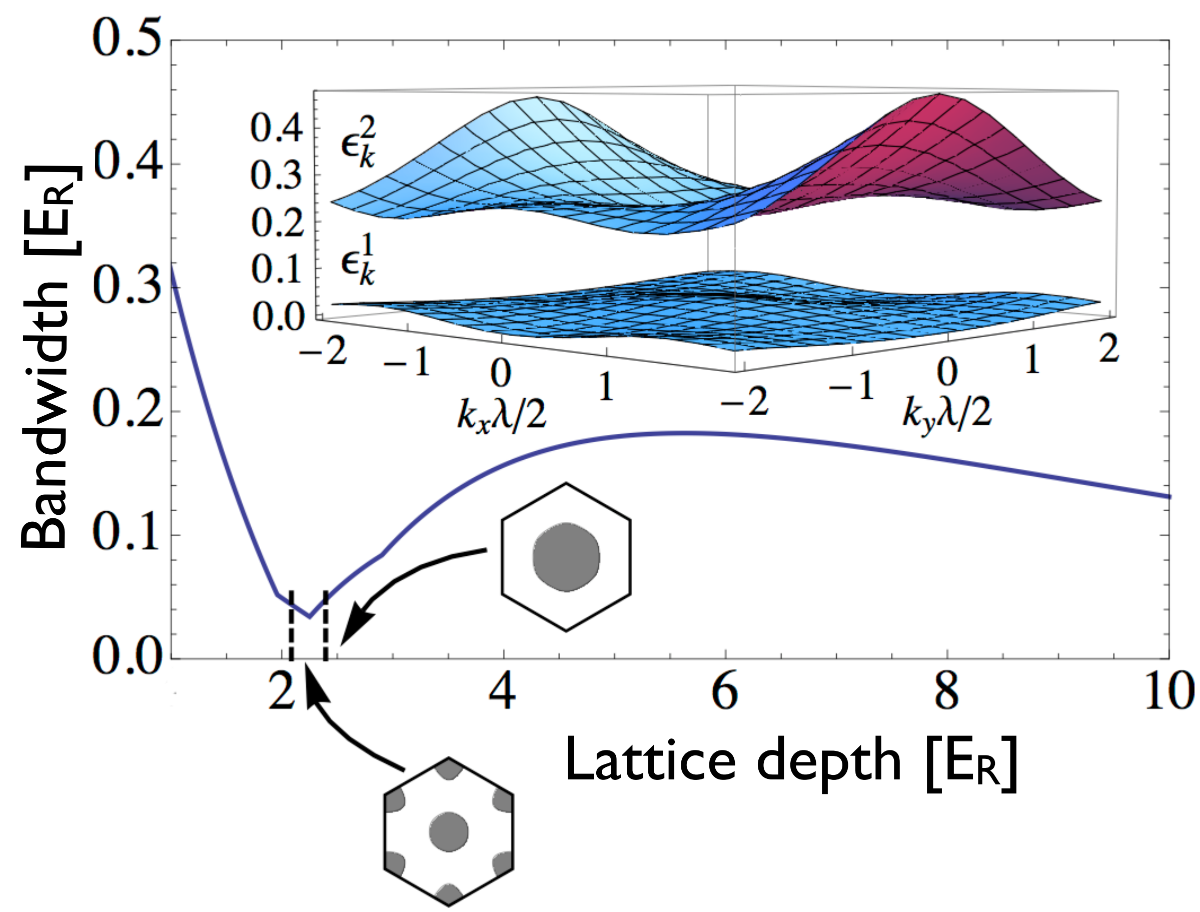

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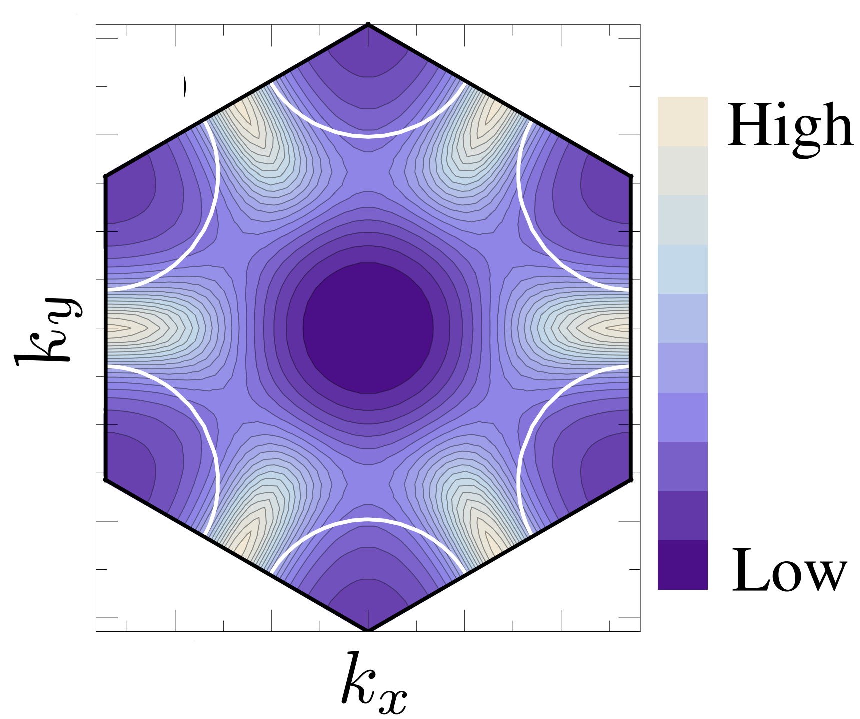
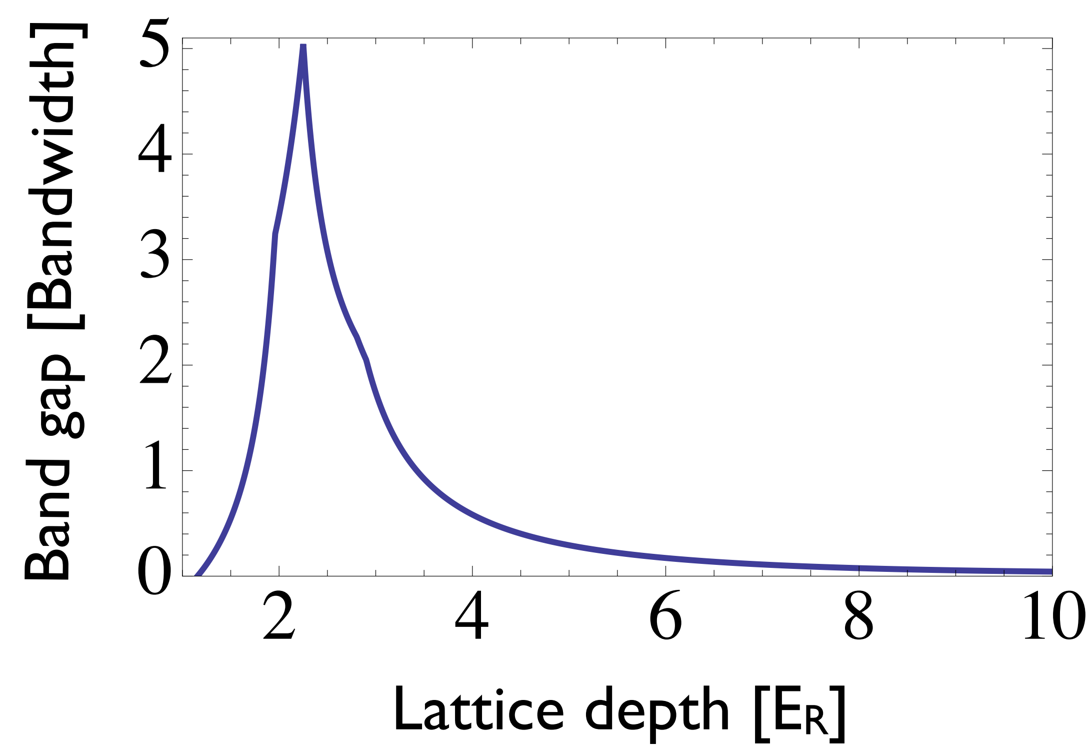
Berry curvature  Chern # of lowest band is 1	

Interactions

- Project interactions onto lowest band

$$H = \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}} c_{\mathbf{k}} \epsilon_{\mathbf{k}} + \sum_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3\mathbf{k}_4} V_{\mathbf{k}_1\mathbf{k}_1\mathbf{k}_3\mathbf{k}_4} c^\dagger_{\mathbf{k}_1} c^\dagger_{\mathbf{k}_2} c_{\mathbf{k}_3} c_{\mathbf{k}_4}$$

$$V_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3\mathbf{k}_4} = g_{2\mathrm{D}} \int d^2\mathbf{r} \sum_{\sigma} \phi^*_{\mathbf{k}_1\sigma}(\mathbf{r}) \phi^*_{\mathbf{k}_2\bar{\sigma}}(\mathbf{r}) \phi_{\mathbf{k}_3\bar{\sigma}}(\mathbf{r}) \phi_{\mathbf{k}_4\sigma}(\mathbf{r})$$

Interacting spinless fermions!
(starting from contact s-wave int.)

Cooper, Dalibard EPL (2011); Williams et al., Science (2012);
Cui PRA (2012) ...

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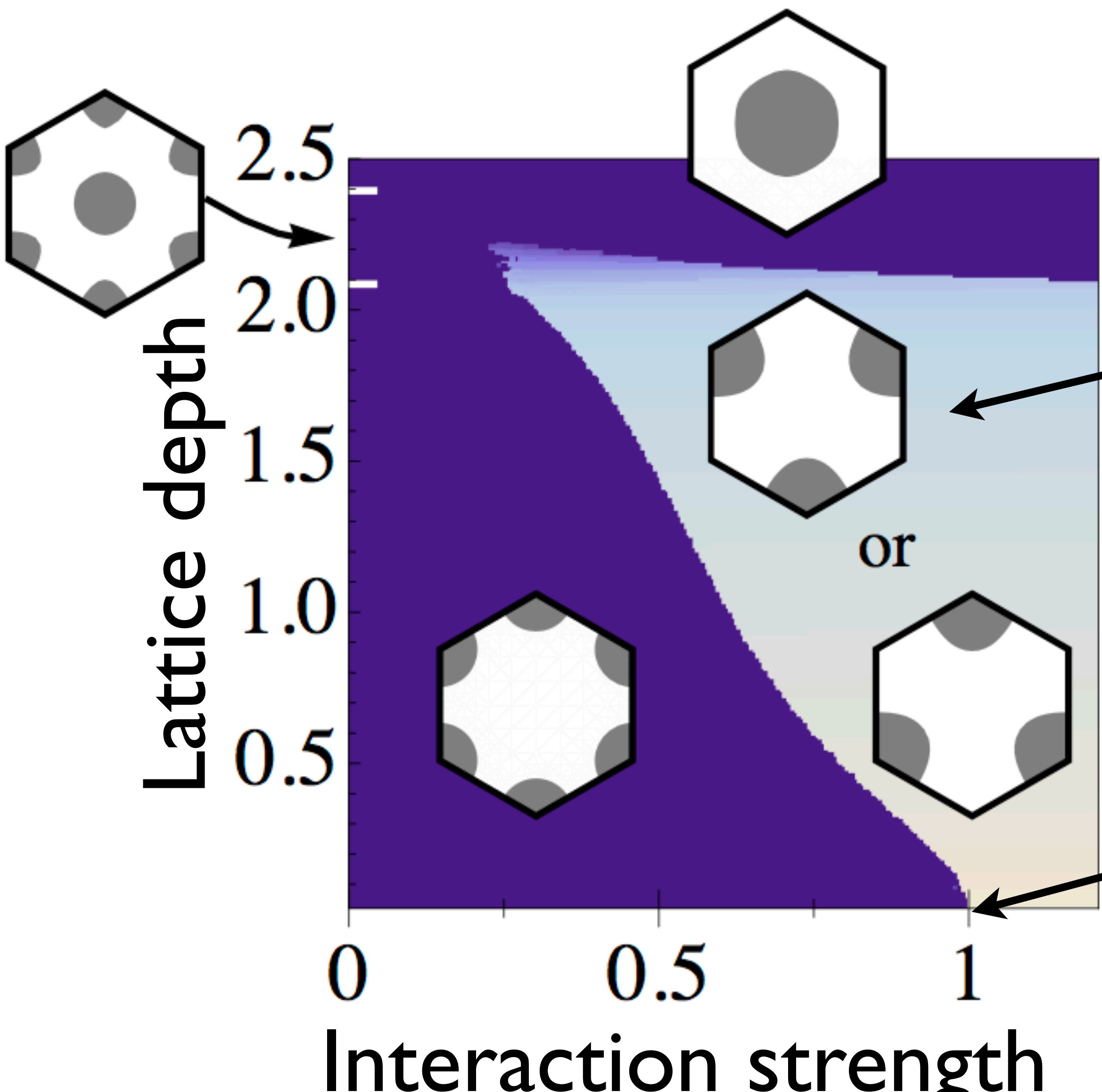
- Hartree-Fock decoupling

$$E[\{n_{\mathbf{k}}\}] = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} n_{\mathbf{k}} + \frac{1}{2} \sum_{\mathbf{k}\mathbf{k}'} V_{\mathbf{k}\mathbf{k}'} n_{\mathbf{k}} n_{\mathbf{k}'}$$

$$V_{\mathbf{k}\mathbf{k}'} = \underbrace{V_{\mathbf{k}\mathbf{k}'\mathbf{k}'\mathbf{k}}}_{\text{Hartree}} - \underbrace{V_{\mathbf{k}\mathbf{k}'\mathbf{k}\mathbf{k}'}}_{\text{Fock}}$$

Hartree-Fock phase diagram

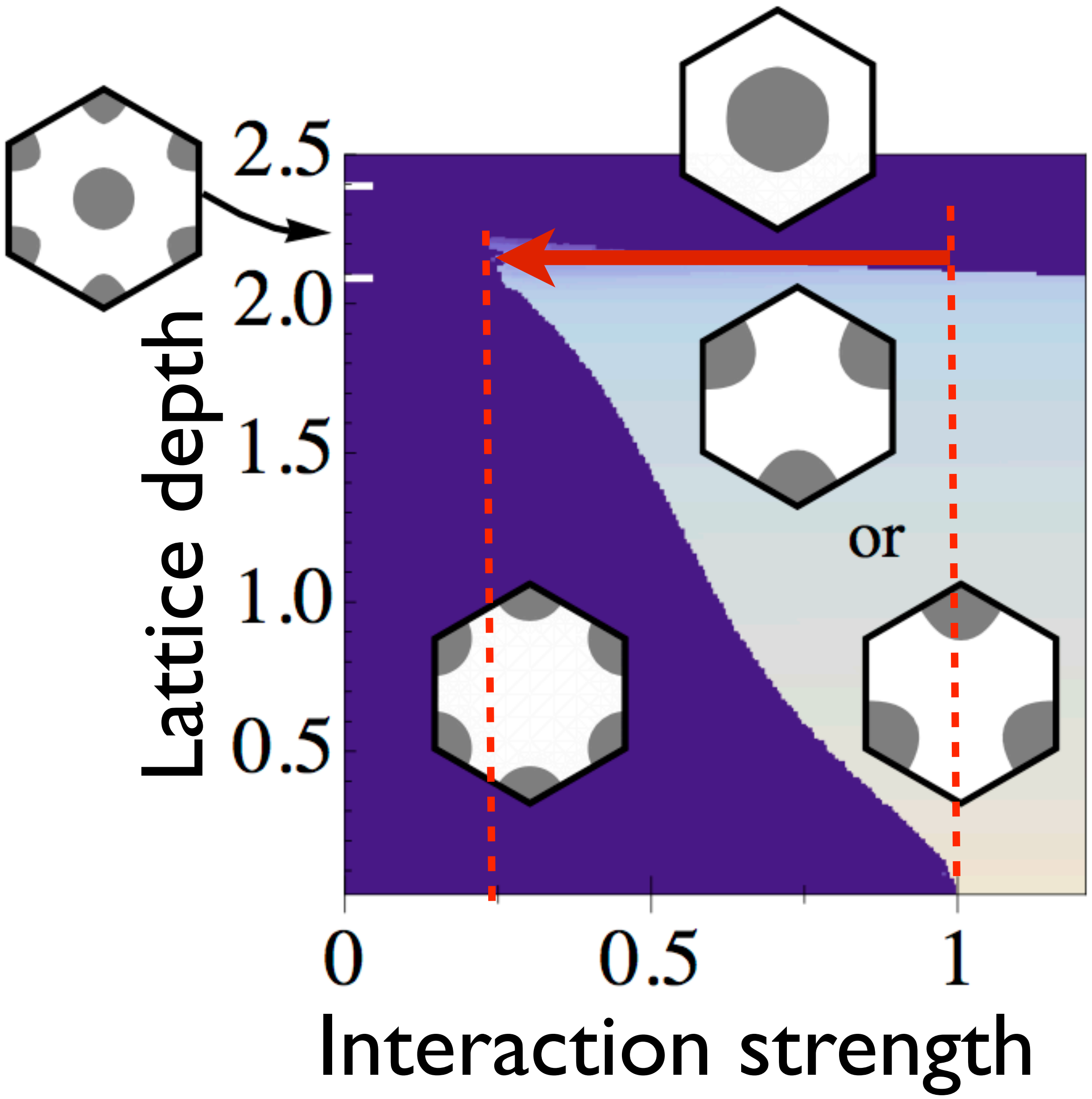


Ordered phase:
Ising nematic/
Stoner FM
Breaks C_6 to C_3

2D Mean-field Stoner
without lattice

Filling: $\nu = 1/4$

Hartree-Fock phase diagram

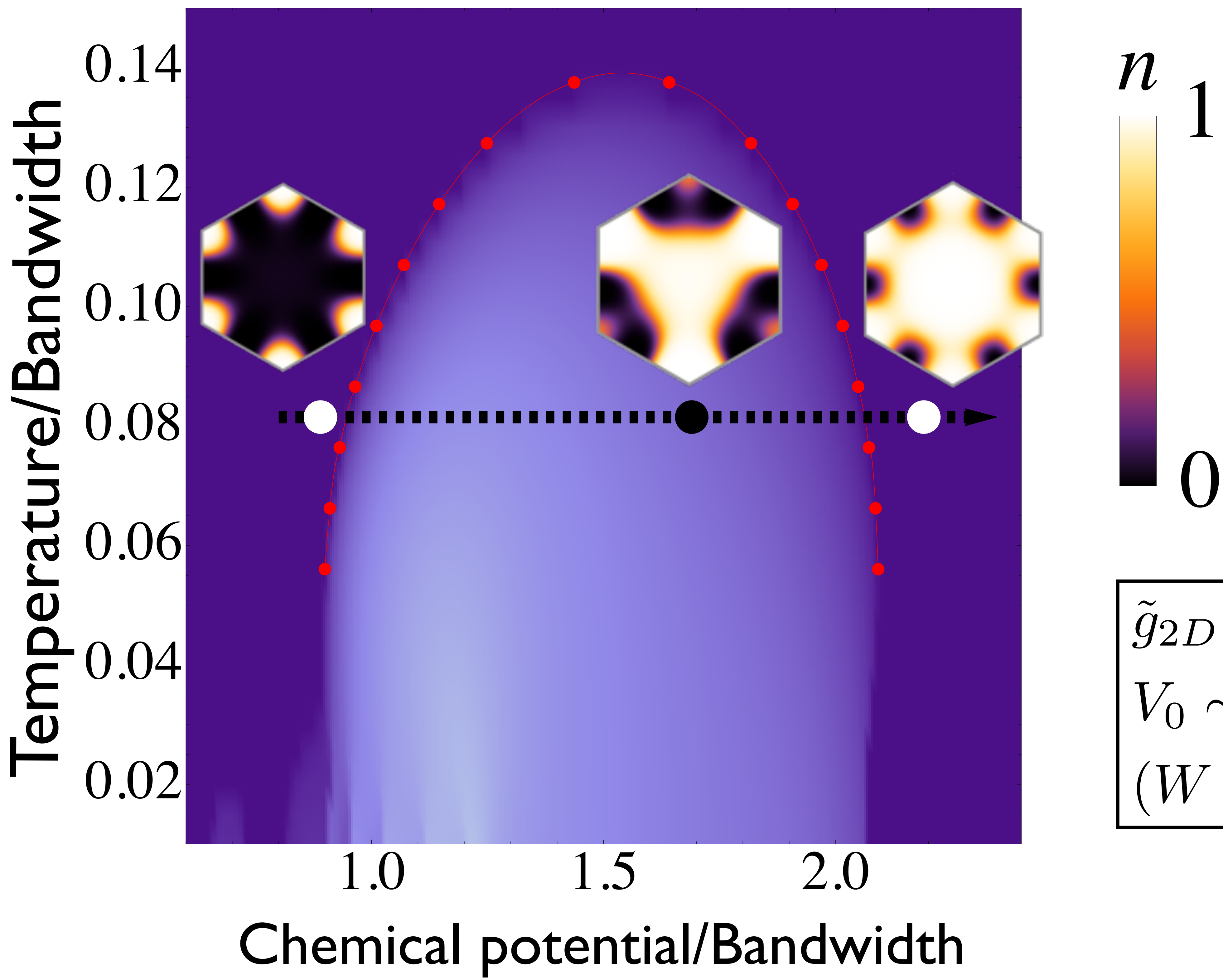


Filling: $\nu = 1/4$

Up to 4 times weaker bare interaction needed for Stoner.

Huge increase in lifetime at Stoner transition (~100)

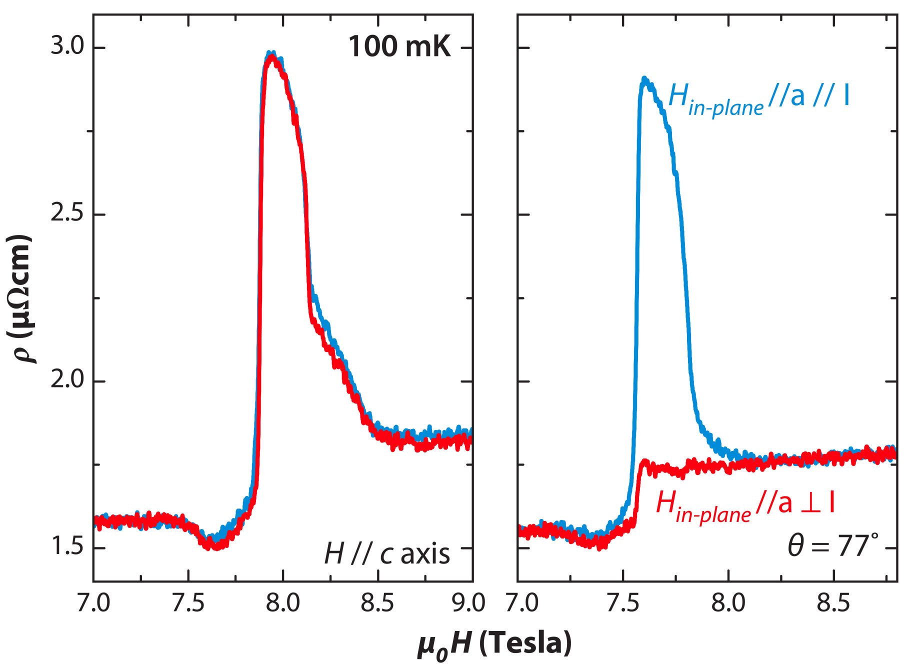
Phasediagram: finite T



$\tilde{g}_{2D} \sim 1.9$
$V_0 \sim 2E_R$
$(W + \Delta)/W \sim 4$

Nematic order of fermions: Ubiquitous in correlated fermion systems

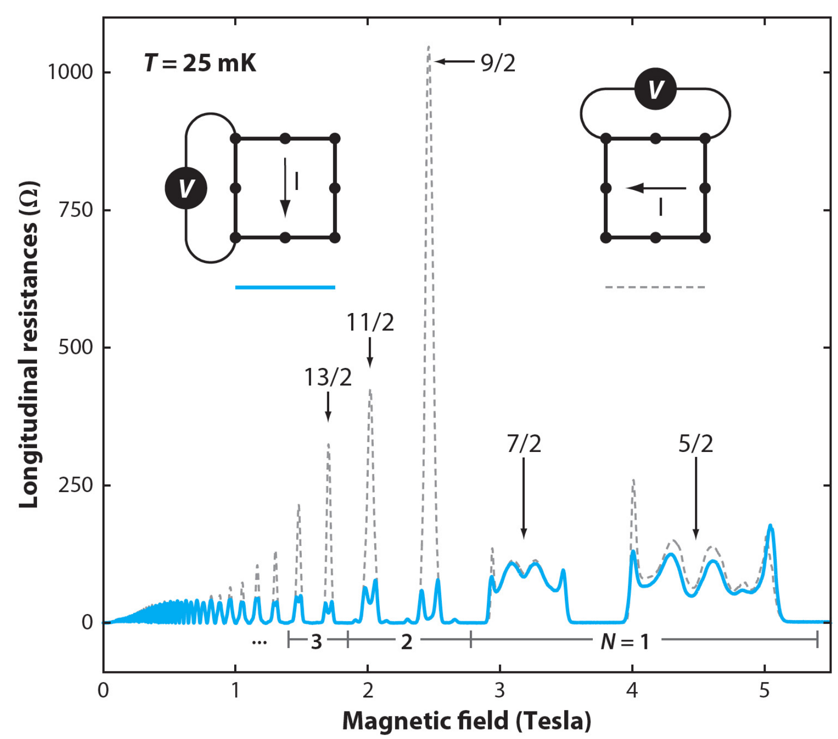
Ruthenates: $Sr_3Ru_2O_7$



Resistivity anisotropy

Borzi et al, Science 2007

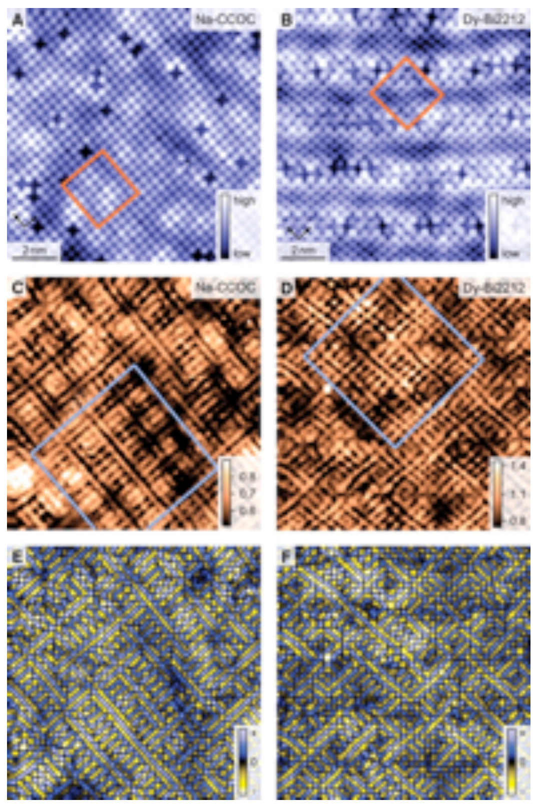
2DES, magnetic field



Resistivity anisotropy

Lilly et al, PRL 1999

Cuprates

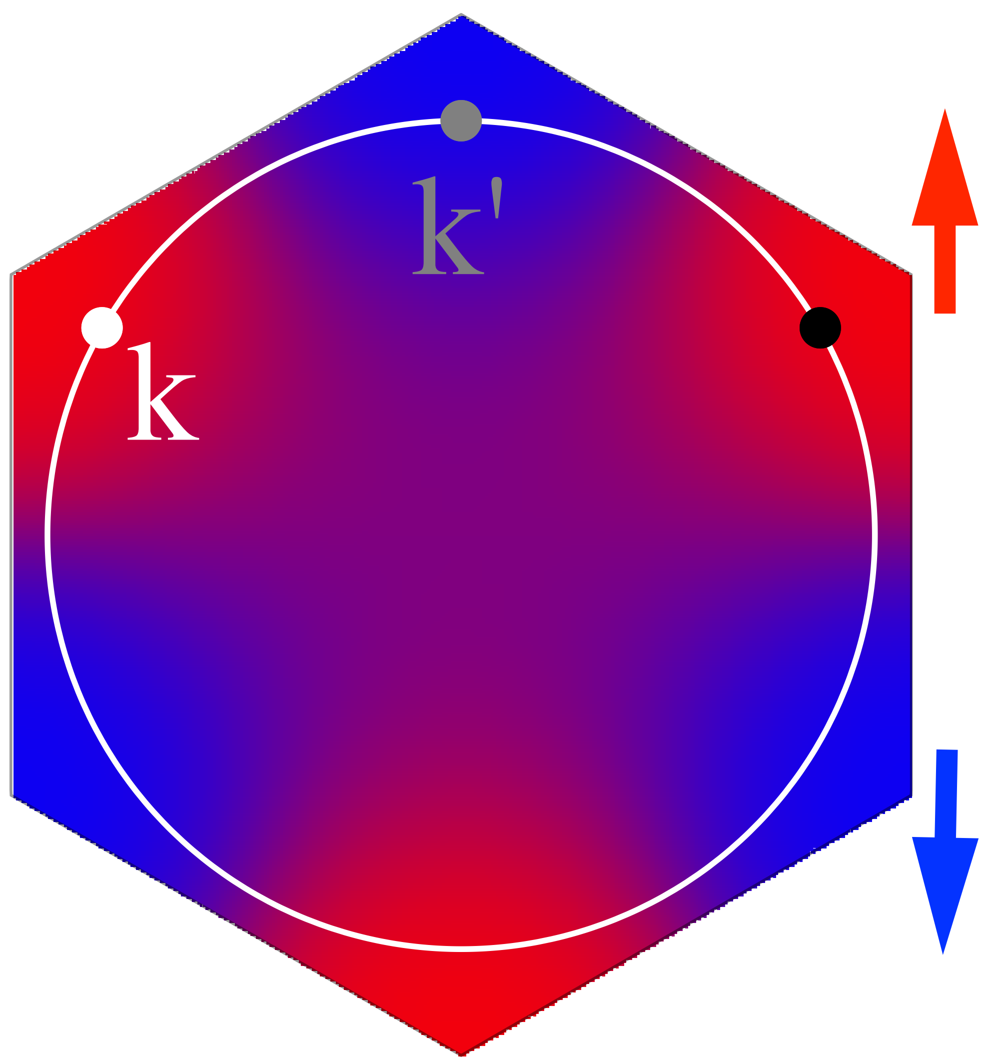


STM

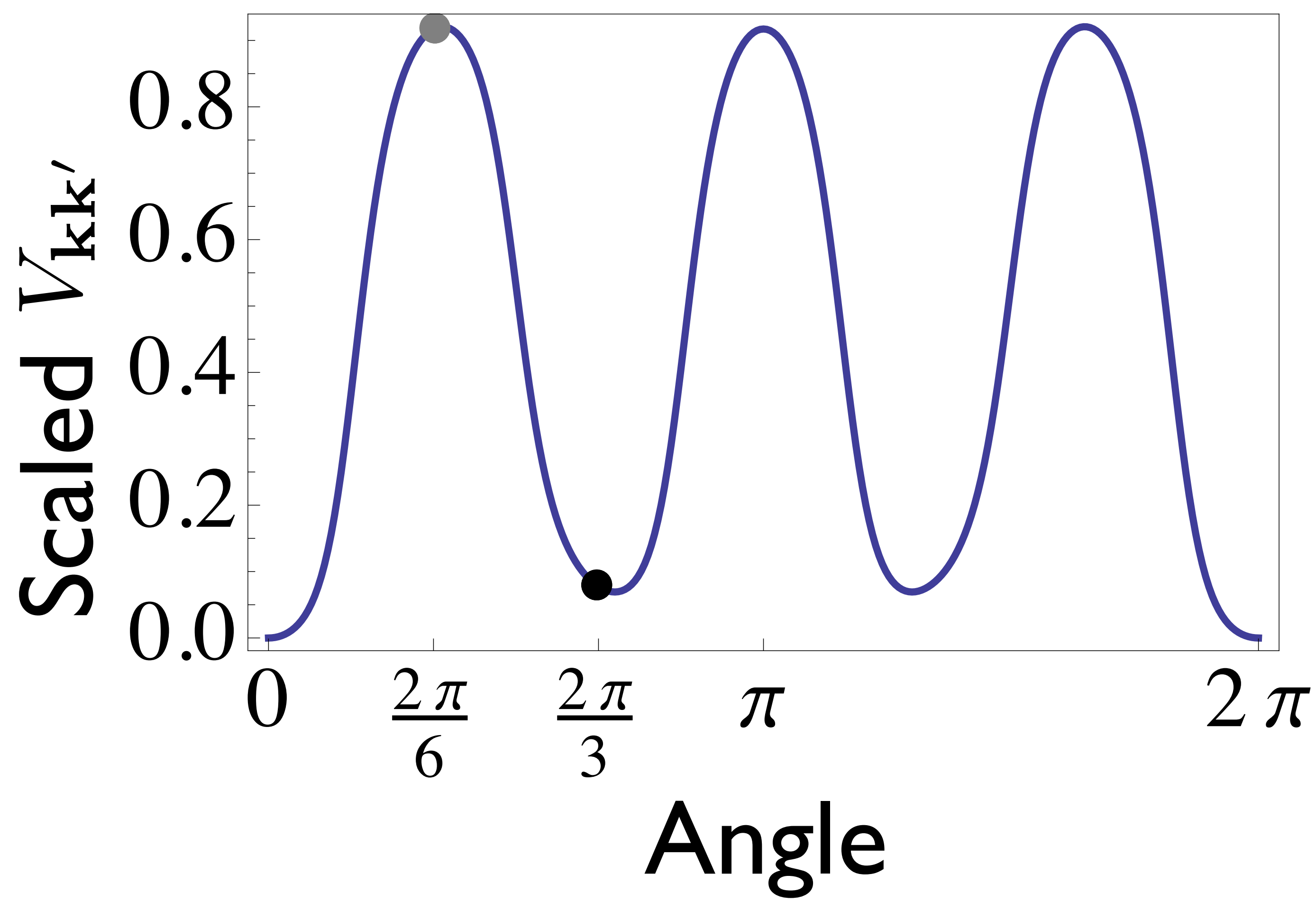
Kohsaka et al, Science 2007

See review by Fradkin, Kivelson, Lawler, Eisenstein, McKenzie, Ann. Rev. Cond. Mat. 1, 153 (2010)

Origin of nematic order: Anisotropic interaction between identical fermions



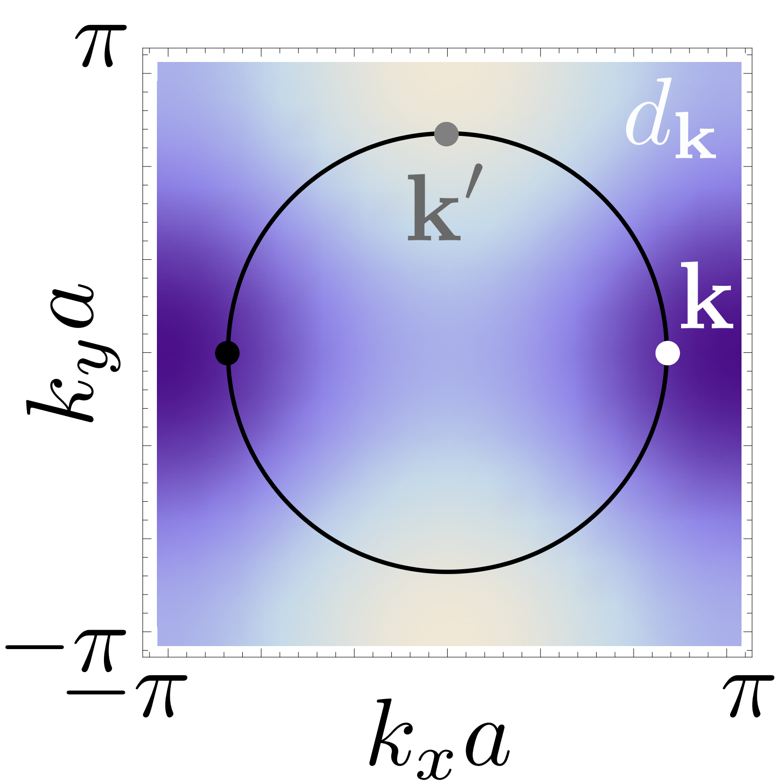
Spin-structure in Brillouin zone

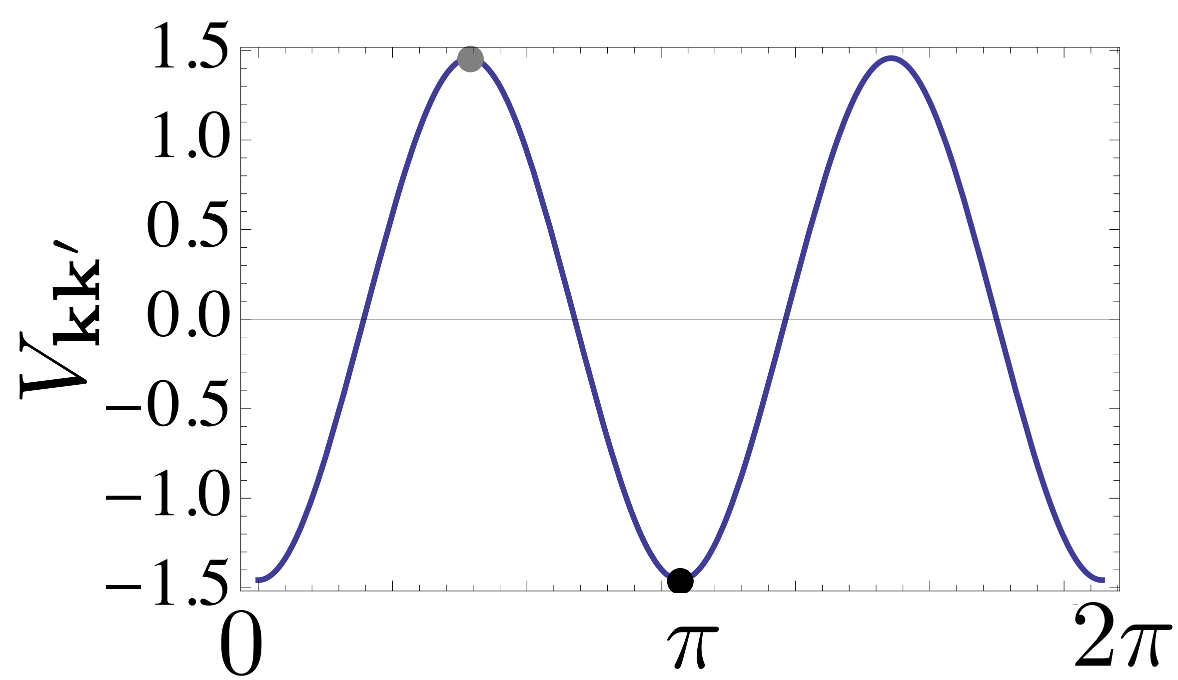


Connection to models with Ising nematic order

- Mean-field model for Ising nematic (2D square)

$$\boxed{V_{\mathbf{k}\mathbf{k}'} = u - g d_{\mathbf{k}} d_{\mathbf{k}'} \quad d_{\mathbf{k}} = \cos(k_x) - \cos(k_y)}$$





Yamase, Oganesyan, Metzner, PRB 72, 35114 (2005)

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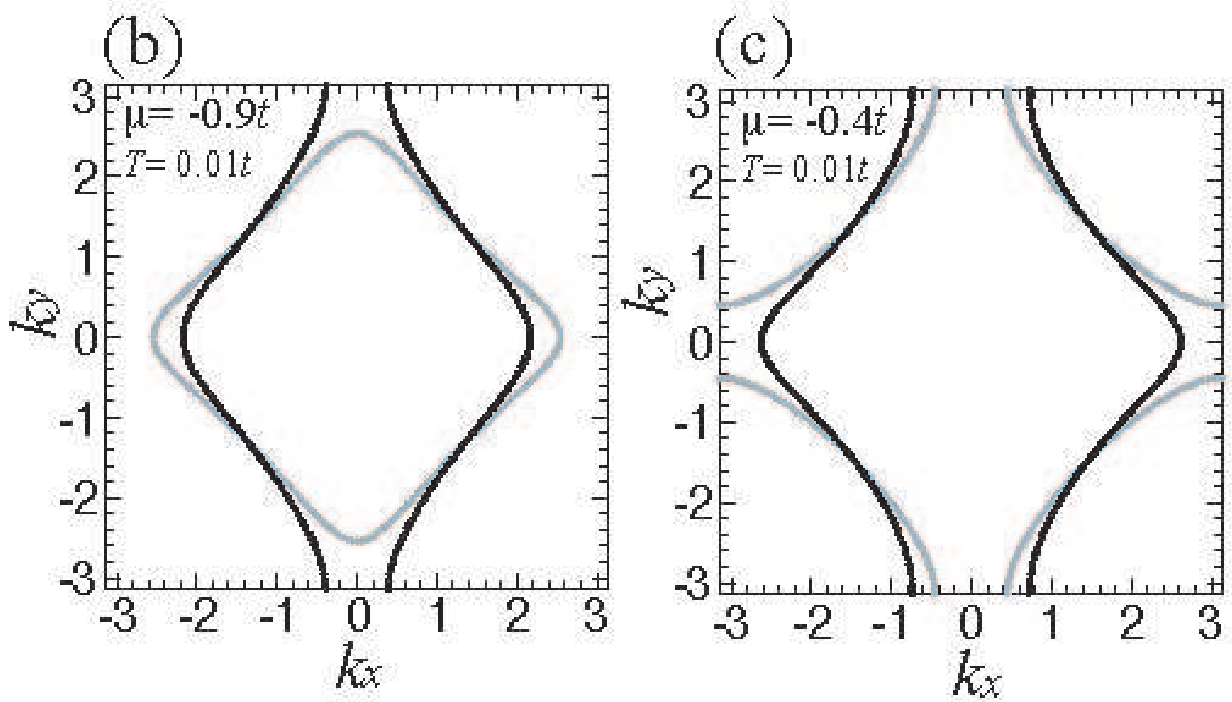
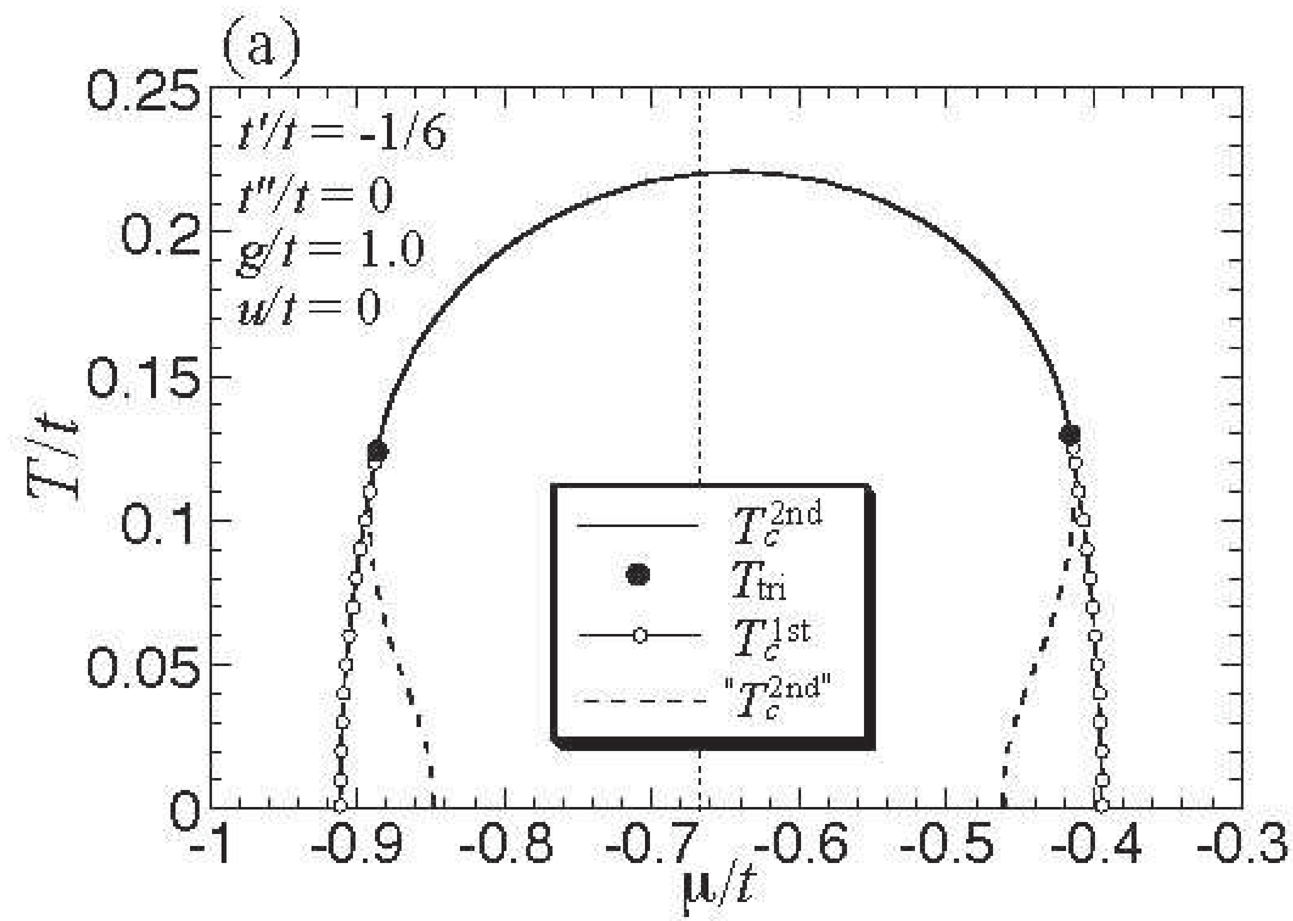


d-wave Pomeranchuk instability near van Hove singularity



Yamase, Oganesyan, Metzner, PRB 72, 35114 (2005)

Conclusion

- Optical flux lattices offer route to itinerant ferromagnetism at weaker bare interaction strength
- Coupling between (pseudo) spin and lattice gives rise to Ising-nematic symmetry breaking
- Open questions: Competition of nematic order/magnetism with other correlated states (FQH)