Physics Seminar, IAS of Tsinghua Univ, Sep 12, 2012

Two examples of one-dimensional cold gases in new many-body regimes

W. Vincent Liu (刘文胜)
University of Pittsburgh, Pennsylvania, USA

[View of Pittsburgh---source: PittsburghSkyline.com]

Advertisement

One to Two postdoc openings in Pittsburgh

Area: Theoretical Condensed Matter and Cold Atom Physics

More information:
http://liu.phyast.pitt.edu/

New many-body regimes: unique to cold atoms

Features of interest, no prior analogue from solids:

A. Strong interaction. “High temperature physics” for ultracold atoms.

B. Large spin population and mass imbalance. Effective Zeeman splitting comparable with Fermi energy E_F

C. Quantum particles (especially bosons) in the excited “higher orbital” bands of optical lattices. Beyond the s: p, d, …

D. “Slow” quantum dynamics – learn the details from a slow motion of the physical process

E. …

- This Talk

Outline – two examples

1. Spin imbalanced Fermi gases
   A. Heuristic introduction to exotic pairing (FFLO, breached pair)
   B. The 1D problem – A heuristic model. Exact thermodynamic Bethe ansatz. Effective field theory and Phase diagram of FFLO. Effect of polarization: spin-charge mixing. Experimental progress.

2. Topological orbital ladder in optical lattices
   A. The p-band, Hamburg experimental system, etc.
   B. The sp-orbital ladder from Hamburg = Topological Insulator (indexing group Z class) -- Due to hybridization of opposite parity s and p orbitals. Fermion zero modes (edge states). Staggered sp tunneling → equivalent of Rashba-like spin-orbit coupling. Topological phase transition to Mott insulator.

Summary of Our Main Results – 1D Fermi gas part

A. A new effective field theory of 1D crystalline superfluid (FFLO) phase [Zhao, WVL, PRA 2008]

1) Baned on both Bethe ansatz and conformal field theory
2) Constructed to match the exact Bethe ansatz spectrum (low energy part)

B. Zero Temperature (T=0) phase diagram for a system of weakly coupled tubes by Renormalization Group (RG) analysis

1) Based on our effective field theory (EFT)
2) New unpublished results: Finite T phase diagram derived by applying RPA to the above EFT

C. Breakthrough in exact solvable models: Analytic, exact thermodynamic Bethe ansatz (TBA) solution of 1D imbalanced fermions at finite T and strong interaction by a simple set of 4 algebraic equations (pressures and chemical potentials). [Zhao, Guan, WVL, et al, PRL 2009]

D. Proof of a new two-component Tomonaga-Luttinger liquid (TLL) with spin-charge mixing, outside the paradigm of standard spin-charge separation. *[This is for understanding crystalline superfluidity-FFLO.]*

1) By both EFT and analytical solution of TBA

E. Application: two-stage scheme to achieve accurate thermometry

Topic 2:
Topological orbital ladder in optical lattices

Work done (in collaboration) with:

Sankar Das Sarma, Andreas Hemmerich, Xiaopeng Li, Kai Sun, Erhai Zhao.

References:

- **Background and perspective (news & views):**
  Nature Physics 7, 101 (2011) [with M. Lewenstein]

- **Nature Physics 8, 67 (2012)**
- ***arXiv:*****1205.0254**

Outline – two examples

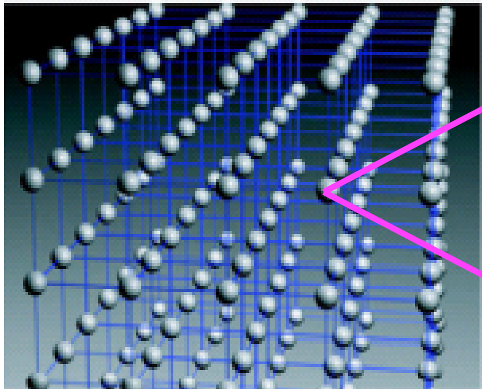
1. Spin imbalanced Fermi gases
   A. Heuristic introduction to exotic pairing (FFLO, breached pair)

   B. The 1D problem – A heuristic model. Exact thermodynamic Bethe ansatz. Effective field theory and Phase diagram of FFLO. Effect of polarization: spin-charge mixing. Experimental progress.

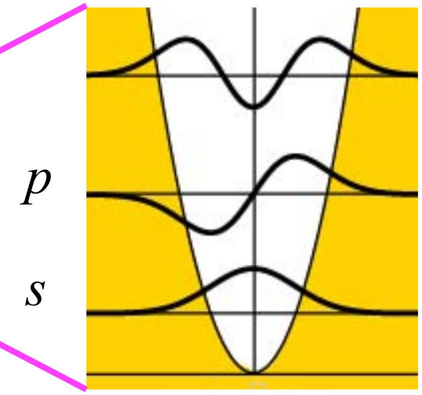
2. Topological orbital ladder in optical lattices
   A. The p-band, Hamburg experimental system, etc.

   B. The sp-orbital ladder from Hamburg = Topological Insulator (group Z class) -- Due to hybridization of opposite parity s and p orbitals. Fermion zero modes (edge states). Staggered sp tunneling → equivalent of Rashba-like spin-orbit coupling. Topological phase transition to Mott insulator.

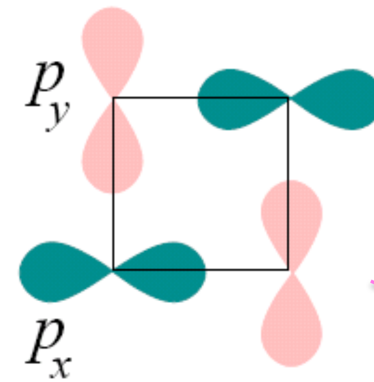
p-band of an optical lattice (illustration)



[optical lattice picture]

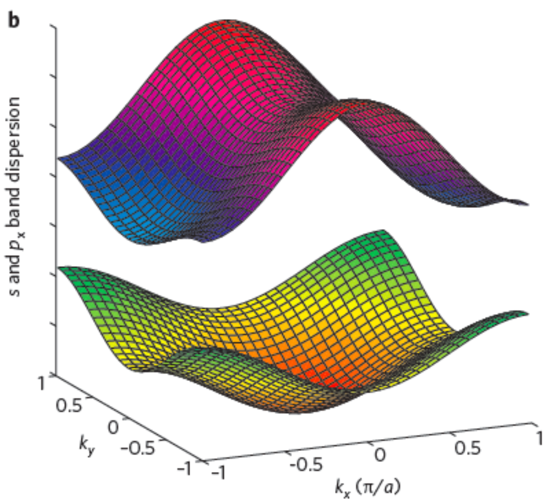


Top view



Lattice spacing $\lambda_L \sim 400$nm
Level spacing $\sim$ 1MHz$\sim$ 50μK

With tunneling, discrete levels become Bloch bands.



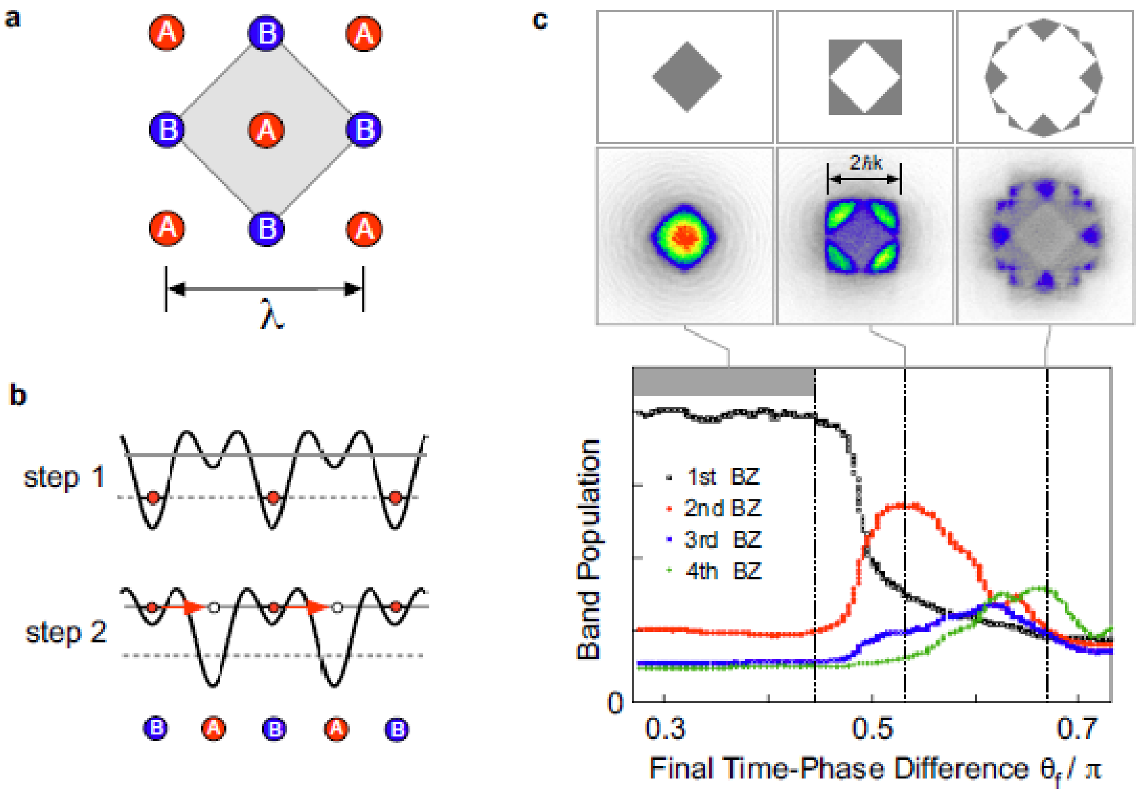
p-band

s-band

- This talk
- Compared with s: orbital degeneracy → emergent symmetry

[M. Lewenstein & WVL, Nature Phys. 7, 101 (2011)]

New p- and f-band experiments – double well lattices



Hamburg/
A. Hemmerich group

- "P-band superfluidity+orbital order in chequerboard (double well) lattice", long life time [G. Wirth. M. Olschlager, A. Hemmerich, *Nature Physics* 2011]

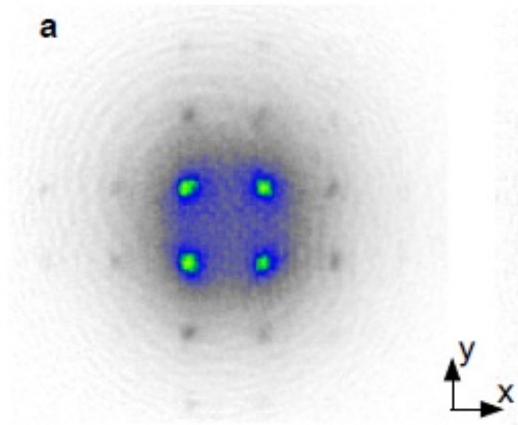
- "F-band" [M. Olschlager, G. Wirth, A. Hemmerich, PRL 2011]

Observation- Boson : complex p-orbital superfluids

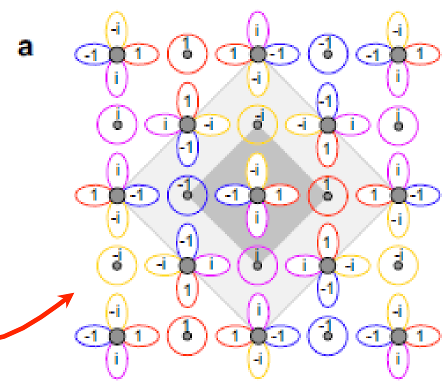
G. Wirth, M. Olschlager, A. Hemmerich, Nature Phys. 2011

Isotropic lattice

Observed momentum distribution

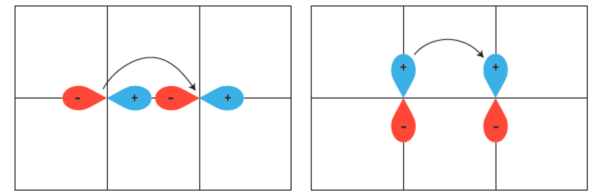


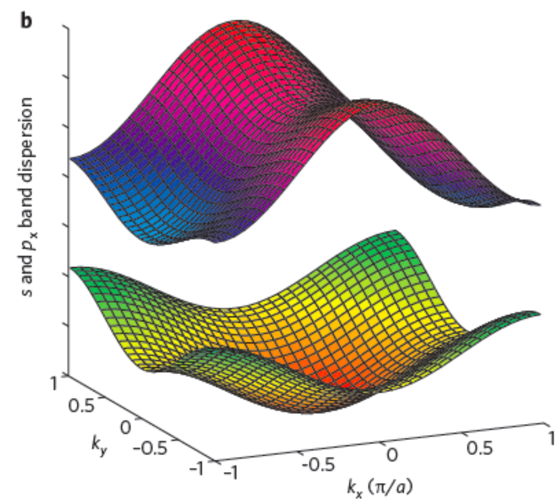
Interpretation:
Nature of orbital order



complex $p_x \pm ip_y$

Theoretical understanding

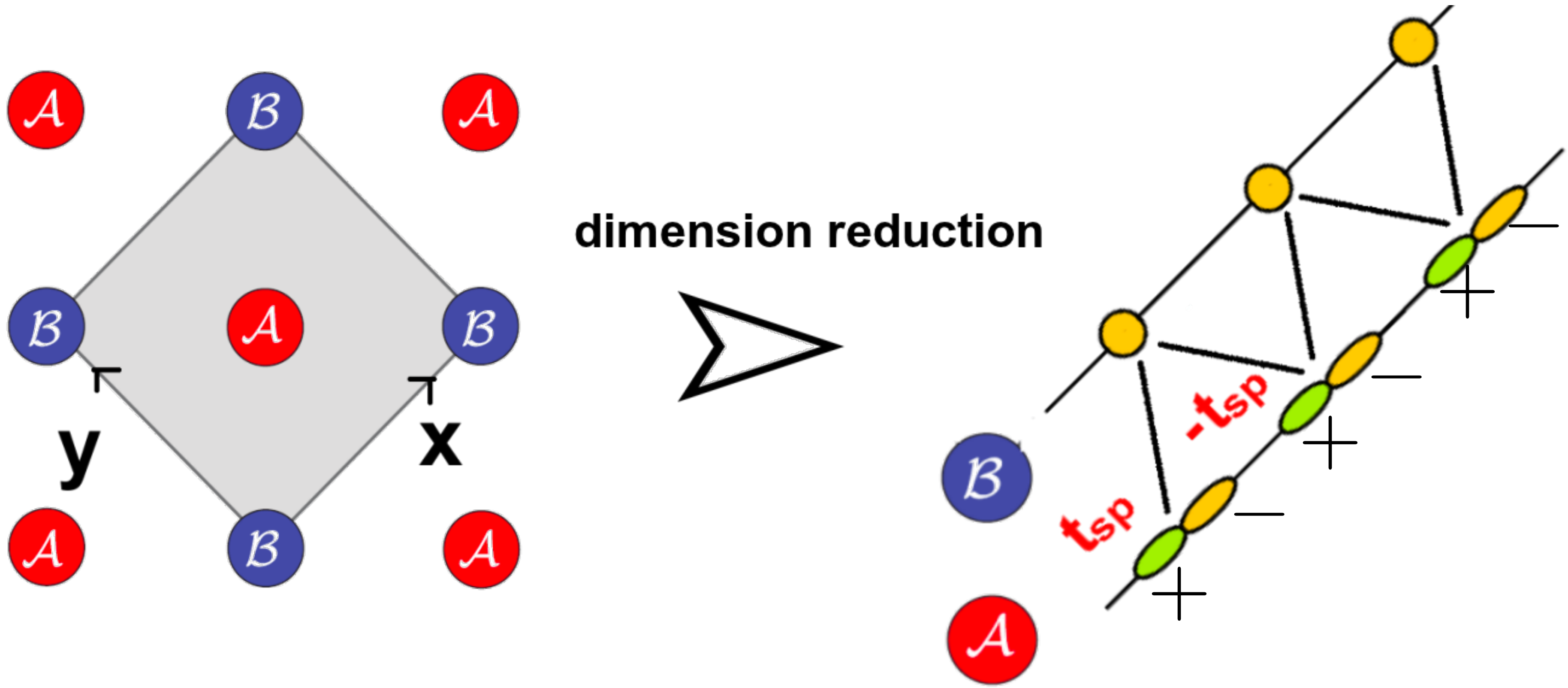




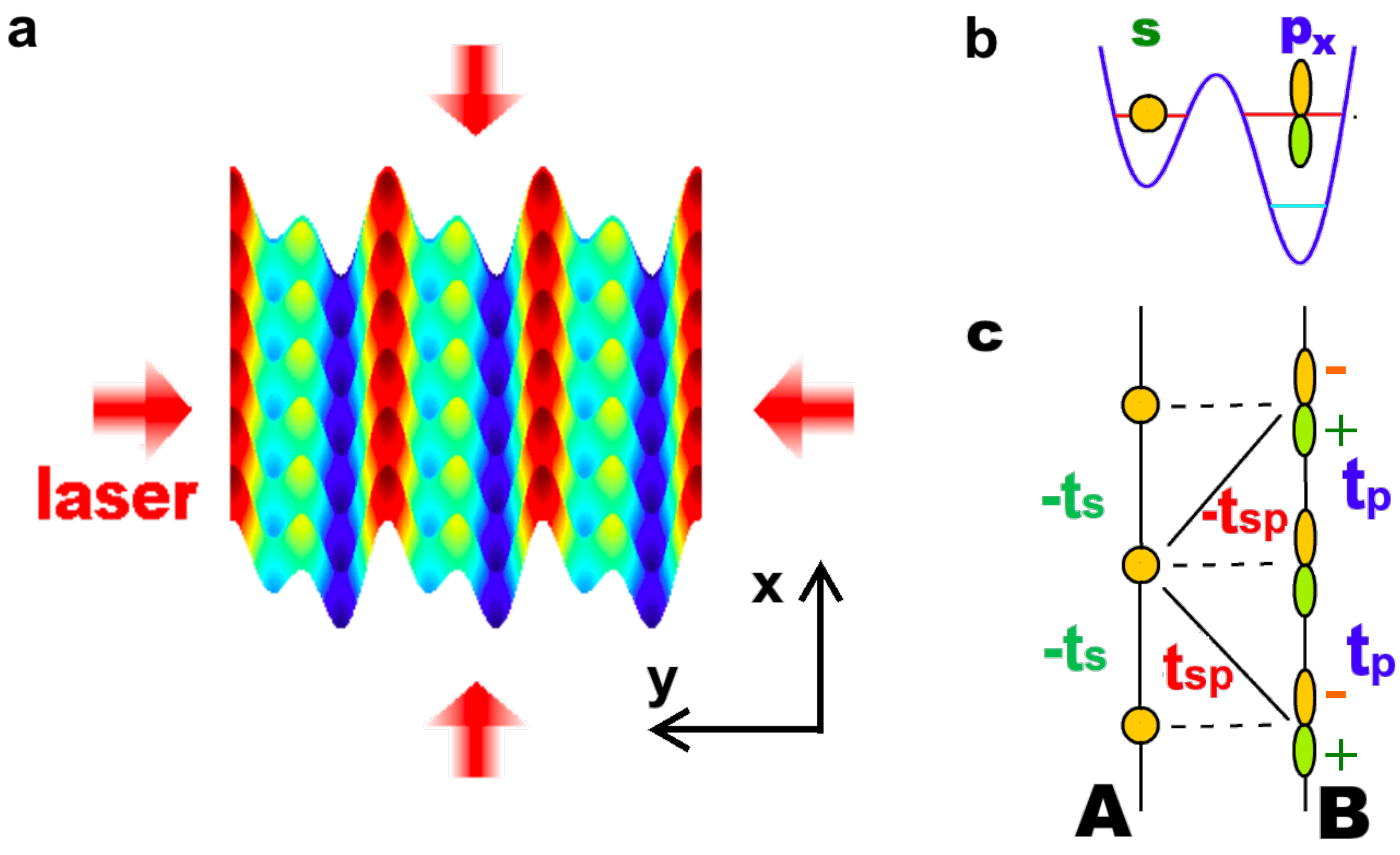
[M. Lewenstein & WVL, Nature Phys. 7, 101 (2011)]

Experimental finding consistent with prediction by [WVL, C. Wu, PRA 2006]

Hamburg 2D double-well lattice → sp-orbital Ladder



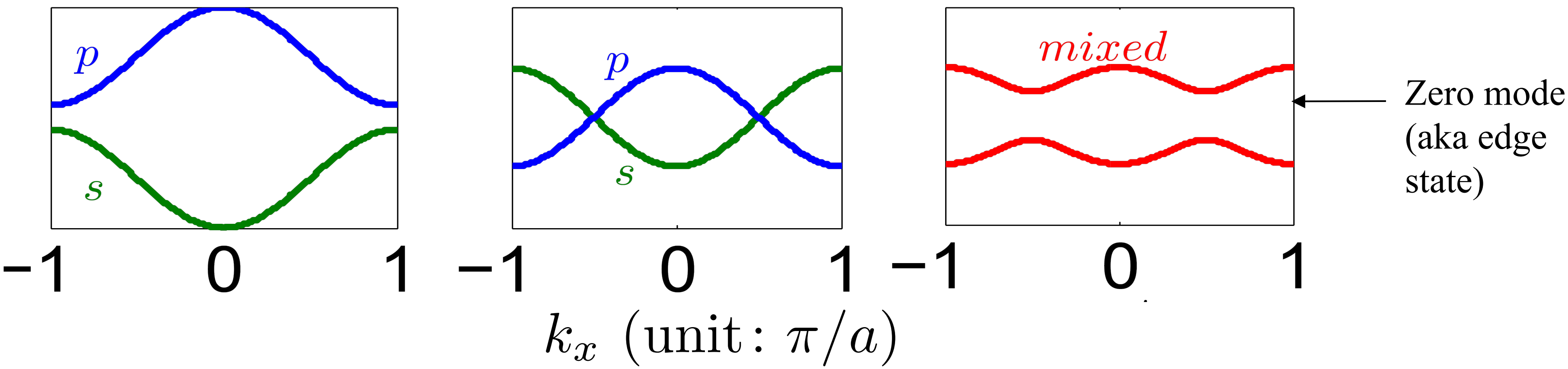
Topological orbital ladders



Xiaopeng Li, Erhai Zhao and WVL, arXiv:1205.0254

sp-mixing and topological nature

-*sp*-mixing

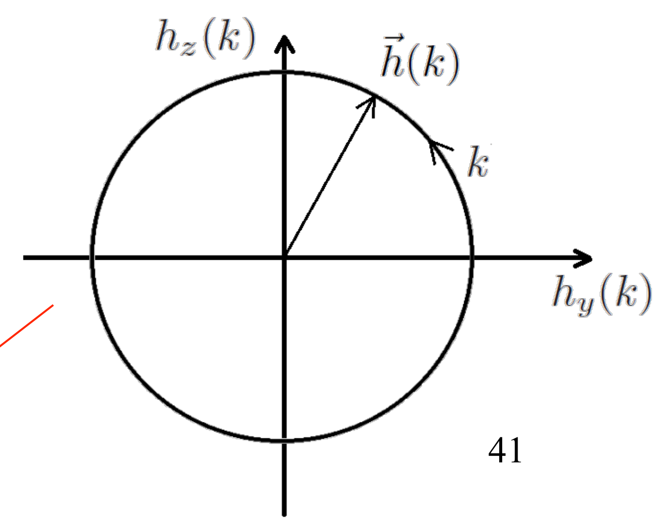


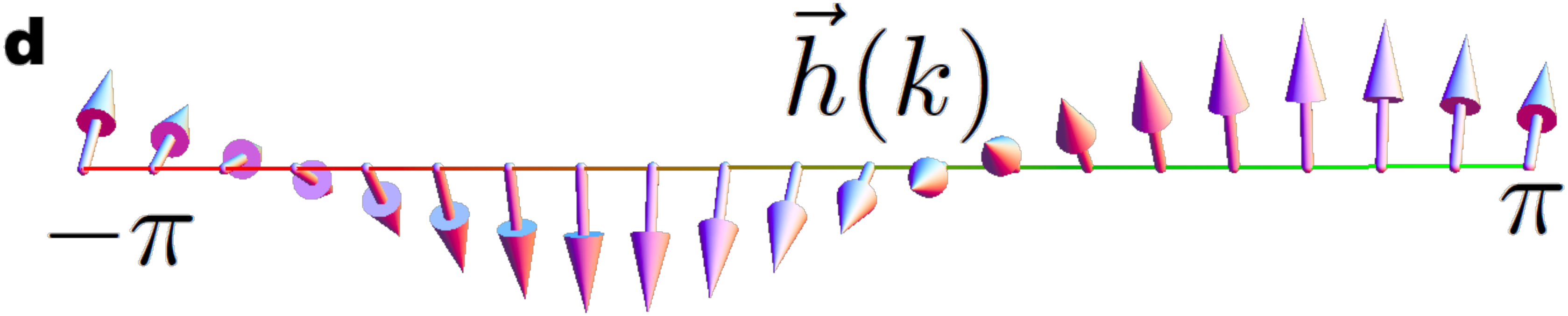
-Hamiltonian in momentum space

$$\mathcal{H}(k) = \begin{bmatrix} -2t_s \cos k & -2it_{sp} \sin k \\ 2it_{sp} \sin k & 2t_p \cos k \end{bmatrix}$$

$$\mathcal{H}(k) = h_0(k)\mathbb{I} + \vec{h}(k) \cdot \vec{\sigma}$$

Berry phase is π.





Momentum k →

(lattice constant a =1)

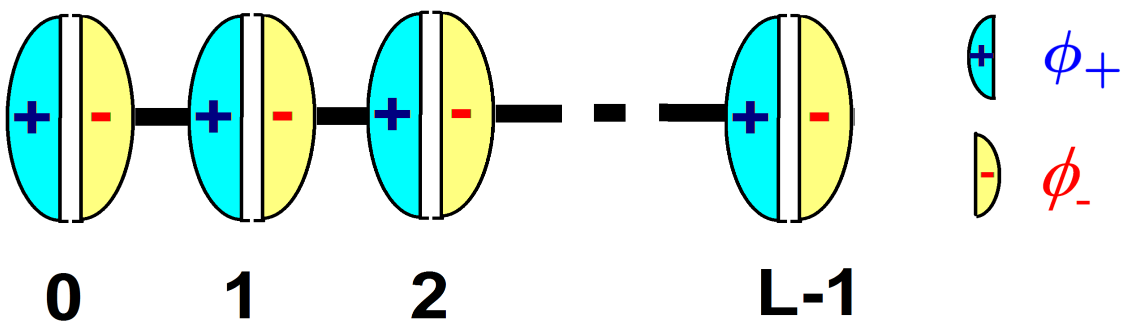
Edge states

-flat band limit (easy to show)

$$t_s = t_p = t_{sp} = t \qquad E(k) = \pm 2t$$

$$H_0 \to 2t \sum_j \phi_-^\dagger(j)\phi_+(j+1) + h.c. \qquad \phi_\pm = [a_p \pm a_s]/\sqrt{2}$$

Edge states are completely localized



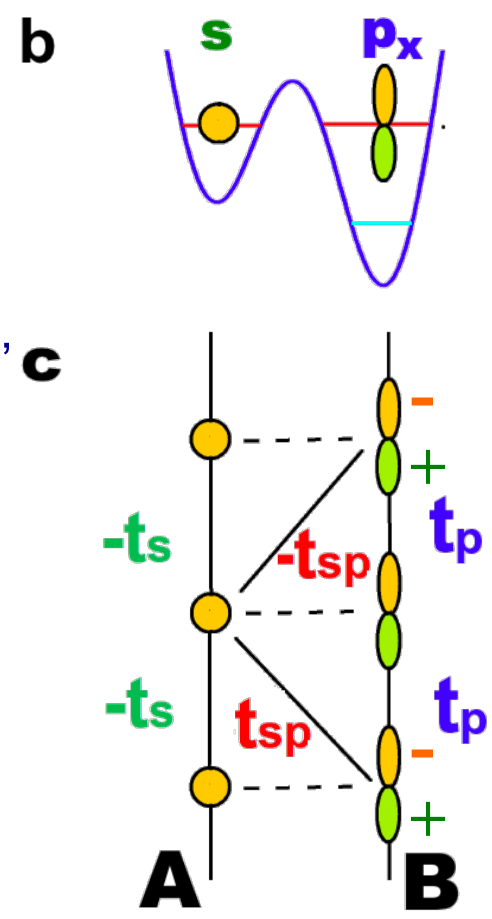
-general case

$$H_0 = \sum_j C_j^\dagger \left[\frac{t_p - t_s}{2}\mathbb{I} - \frac{t_p + t_s}{2}\sigma_z - i t_{sp}\sigma_y \right] C_{j+1} + h.c. \qquad C_j = \begin{bmatrix} a_s(j) \\ a_p(j) \end{bmatrix}$$

Edge states decay with a width $\xi = 2/\log(|(\sqrt{t_s t_p} + t_{sp})/(\sqrt{t_s t_p} - t_{sp})|)$

Summary: topological insulator from odd parity

1. Topological insulator (index group Z class) at half filling.
2. Compare with spin-orbit coupling generated by artificial gauge field in cold atoms
   - A. Pioneer experiments: NIST (I. Spielman et al), … MIT (M. Zwierlein)
   - B. First from China: USTC (S. Chen, Y. Deng, J. Pan, et al), Shanxi U (J. Zhang et al)
3. This model: No spin, but orbit. Resembles spin-orbit coupling if (s, p) space viewed pseudo-spin-1/2.
4. New result: topological phase not requiring any of previously known mechanisms: rotation, gauge field, p-wave pairing,…



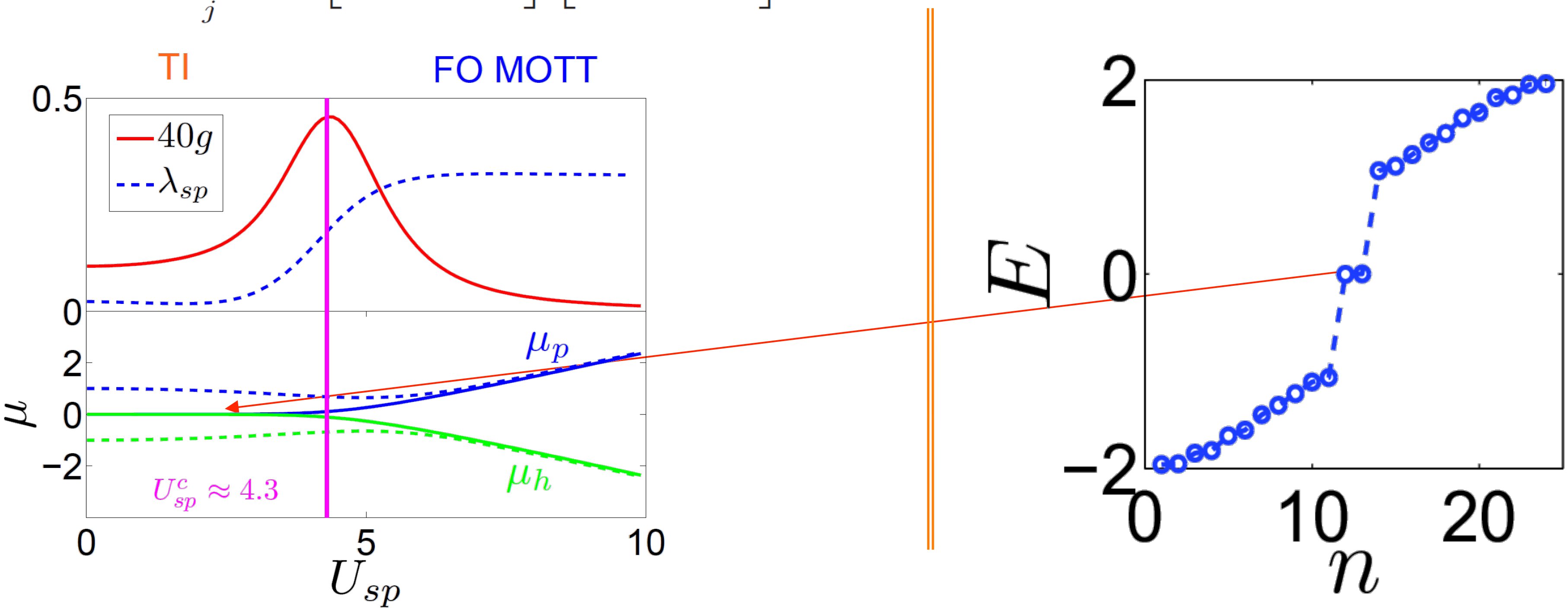
Xiaopeng Li, Erhai Zhao and WVL, arXiv:1205.0254

Topological to Ferro-orbital Mott Insulator Transition

- With inter-orbital interaction

$$H_{\rm int} = \sum_j U_{sp} \left[n_s(j) - \frac{1}{2} \right] \left[n_p(j) - \frac{1}{2} \right]$$

-spectra without interaction



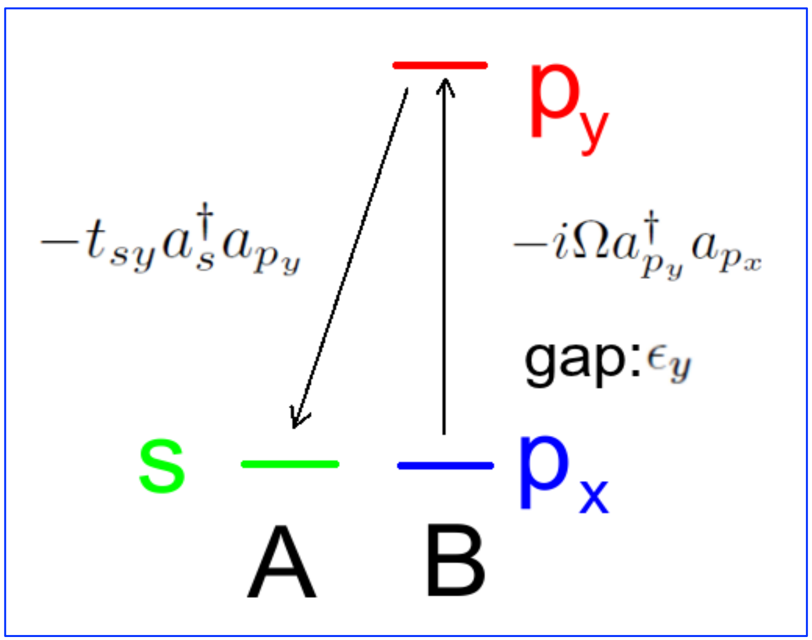
$$g \sim \frac{1 - |\langle \psi(U_{sp}) | \psi(U_{sp} + \delta U_{sp}) \rangle|}{(\delta U_{sp})^2}$$ fidelity metric

$$\lambda_{sp} \sim |\langle C_j^\dagger \sigma_x C_j \rangle|^2$$ Ferro-magnetic order (inter-orbital coherence)

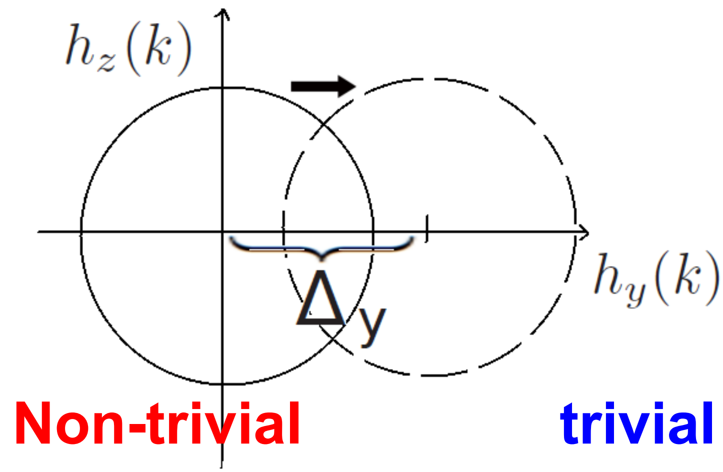
Topological phase transition – driven by rotation

-rotating individual lattice sites

$$\delta H = \frac{\Omega^2}{\epsilon_y} C_j^\dagger \sigma_y C_j \quad \Delta_y = \frac{\Omega^2}{\epsilon_y}$$



-phase transition



$$\Delta_y^c = 2t_{sp}$$

N. Gemelke et al, arXiv:1007.2677

Xiaopeng Li, Erhai Zhao and WVL, arXiv:1205.0254

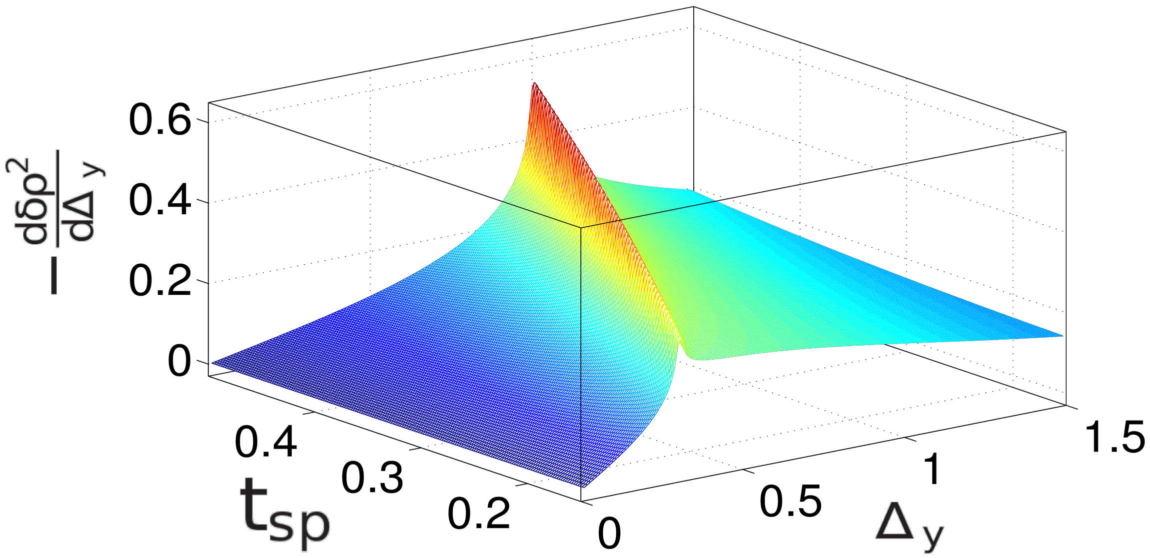
Density fluctuations as a probe

$$\rho(j) = C_j^\dagger C_j - 1$$

$$\delta\rho \equiv \frac{1}{\text{system length}} \sum_j \sqrt{\langle \rho(j)\rho(j) \rangle}$$

$$\delta\rho^2 = \frac{1}{2}\left[1 - \left(\oint \frac{dk}{2\pi} \sin(\theta(k))\right)^2\right]$$

$$\sin(\theta) = \frac{h_y(k)}{\sqrt{h_y^2 + h_z^2}}$$

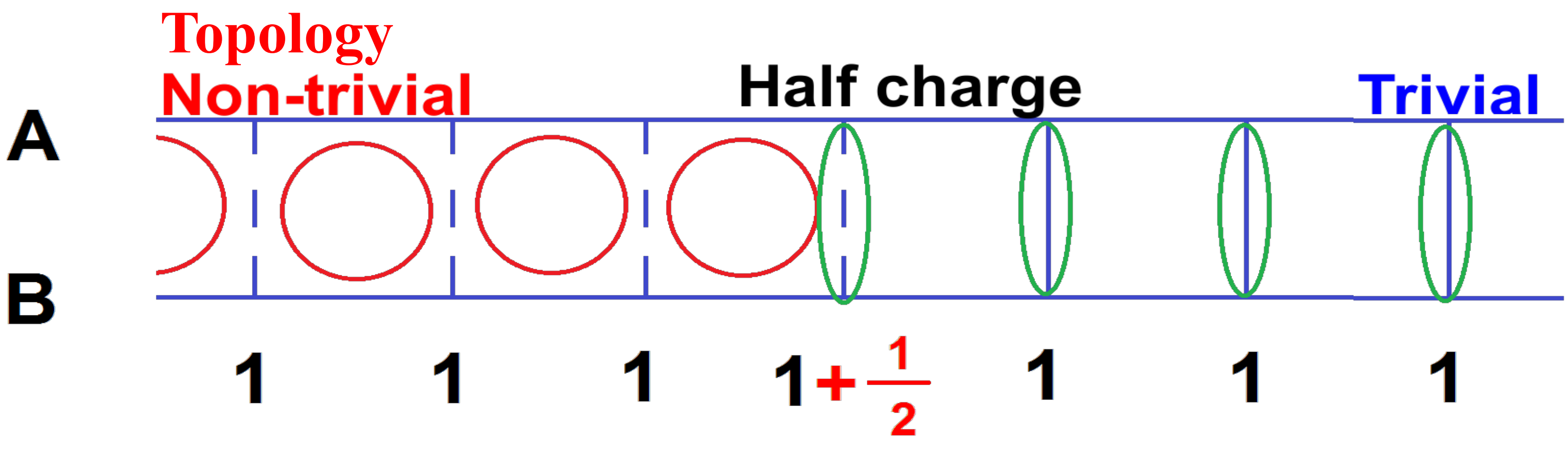


The peaks coincide with the critical line.

Domain Wall Fractional Charge

$$H_\eta = H + \frac{\Delta_y}{2} \sum_j \left[1 - \cos \eta(j)\right] C_j^\dagger \sigma_y C_j$$

$$\eta(j = -\infty) = 0 \qquad\qquad \eta(j = +\infty) = \pi$$



Firm Computation of Fractional Charge:
Background (auxiliary) gauge field method

- **Introduce background gauge field:** $(A_\tau, A_x)\,, \qquad \tau = it$

$$
\begin{aligned}
D_\tau &= \partial_\tau + iA_\tau(j,\tau), \\
\mathcal{T}_{j\,j+1} &= e^{iA_x(j+1/2,\tau)} T_{j\,j+1}, \\
T_{j\,j+1} &= \begin{bmatrix} -t_s & -t_{sp} \\ t_{sp} & t_p \end{bmatrix}, \\
\mathcal{T}_{j\,j+1} &= \mathcal{T}^\dagger_{j+1\,j}.
\end{aligned}
$$

Berry phase

- **Effective action** $\tilde{S}_{\rm eff}[A_\mu] = \int dx dt (A_x \partial_t \eta - A_t \partial_x \eta) \frac{1}{2\pi} \partial_\eta \gamma(\eta)$

- **Charge**

$$Q = \int \frac{\tilde{S}_{\rm eff}}{\delta A_t} = -\frac{1}{2\pi} \int dx \partial_x \eta \partial_\eta \gamma(\eta) = -\int \frac{d\eta}{2\pi} \partial_\eta \gamma(\eta)$$

Find: $Q = \frac{1}{2} \bmod 1$

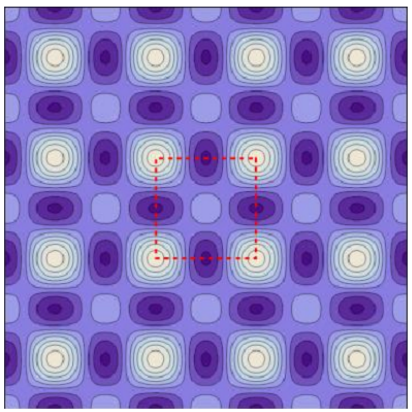
Brief note on a Related Theoretical Result:

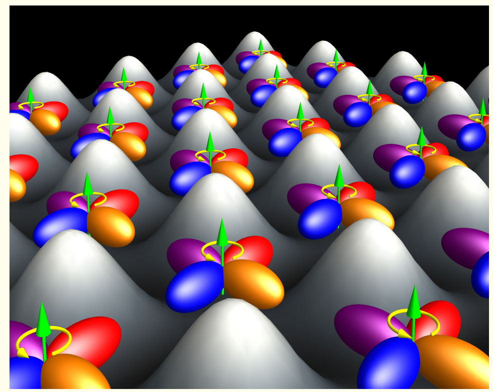
nature physics
LETTERS
PUBLISHED ONLINE: 20 NOVEMBER 2011 | DOI: 10.1038/NPHYS2134

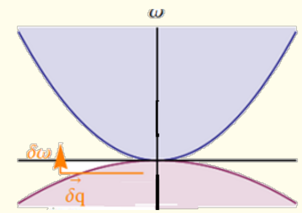
Topological semimetal in a fermionic optical lattice

Kai Sun[1], W. Vincent Liu[2,3,4]*, Andreas Hemmerich[5] and S. Das Sarma[1]

System: p-orbital fermions on Double-well lattice







Normal(topological semimetal): winding number =2, quadratic dispersion, different than Graphene

Ordered (topological insulator)

0 T_c T

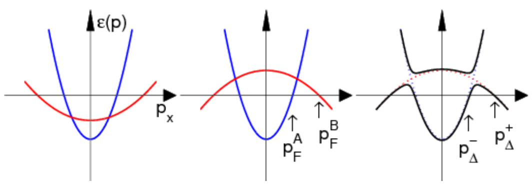
Ordered phase

- Breaks Time-reversal symmetry
- Topological Insulator
- New mechanism – interaction driven -- Differs from the previously known's: artificial gauge field, rotation, spin-orbit coupling, …

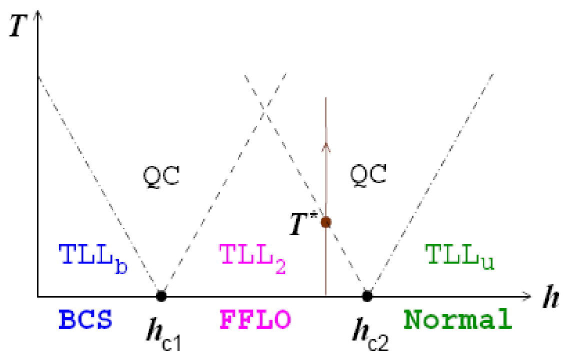
Conclusion

1. Spin imbalanced Fermi gas

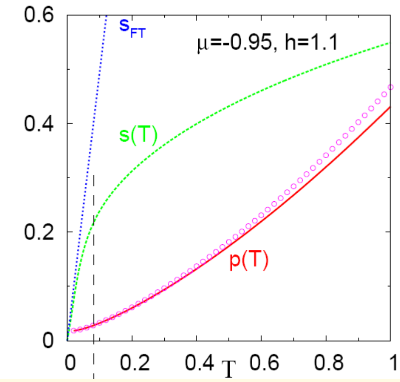
Sarma/ Breached Pair
(a homogeneous polarized superfluid)



Phase diagram of 1D polarized Fermi gas

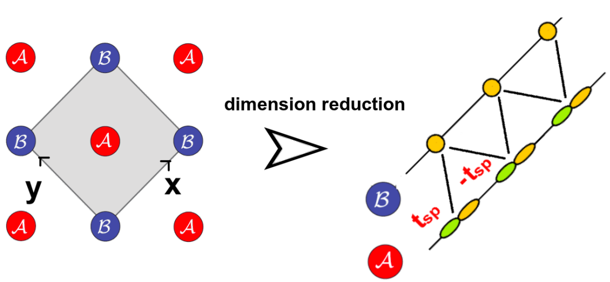


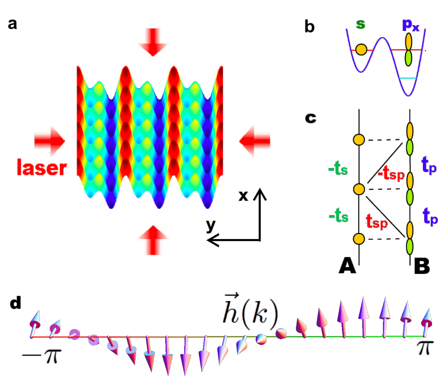
Thermo Bethe Ansatz compared to Field Theory



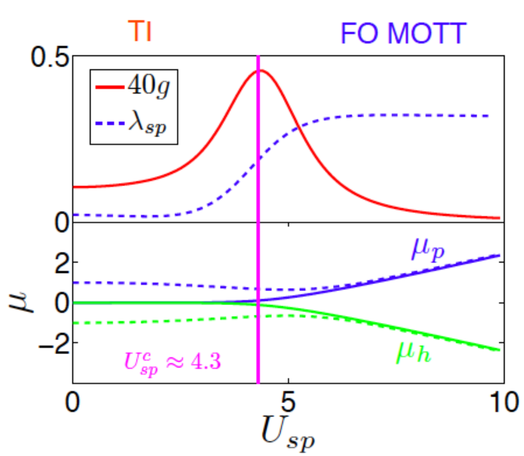
2. Topological sp-orbital ladder

Prediction: Hamburg double-well lattice, when dimension reduced, is topological insulator with fermion zero modes





Interaction drives transition to topologically trivial Mott



Acknowledgement

Collaborators

Imbalanced fermions:

Frank Wilczek (MIT)
Michael Forbes (MIT, now UW Seattle)
Elena Gubankova
Xi-Wen Guan (Australian NU)
Yong-Baek Kim (Toronto)
Masaki Oshikawa (Tokoyo)
Peter Zoller (Innsbruck)
M. T. Batchelor (Australian NU)
Experiment: R. Hulet (Rice)

Student/Postoc:

Chungwei Lin (Columbia ->Pitt->UT Austin)
Vladimir Stojanovic (student, Carnegie-Mellon, now Basel)
EZ (also on the right)

P-orbital:

Sankar Das Sarma (Maryland)
Ivan H Deutsch & Krittika Goyal (New Mexico)
Philipp Hauke (ICFO Spain)
Maciej Lewenstein (ICFO Spain)
Joel Moore (Berkeley)
Kai Sun (Maryland-> U Michigan)
Congjun Wu (UCSD)
Exp: A. Hemmerich (Hamburg)

Students & Postdocs

C. M. Ho (Pitt-> UC Berkeley)
H. H. Hung (Pitt->UCSD->UIUC)
Xiaopeng Li (Pittsburgh)
Zixu Zhang (Pitt-> finance)
Erhai Zhao (now faculty at George Mason U, USA)

Acknowledge Support by ***U.S. ARO***, ***AFOSR***, and ***DARPA***-OLE
And ***NSF of China*** Overseas Scholar Program (sponsor: Peking Univ/Prof. **Biao Wu**)