Flux lattices and topological flat bands in dipolar spin systems

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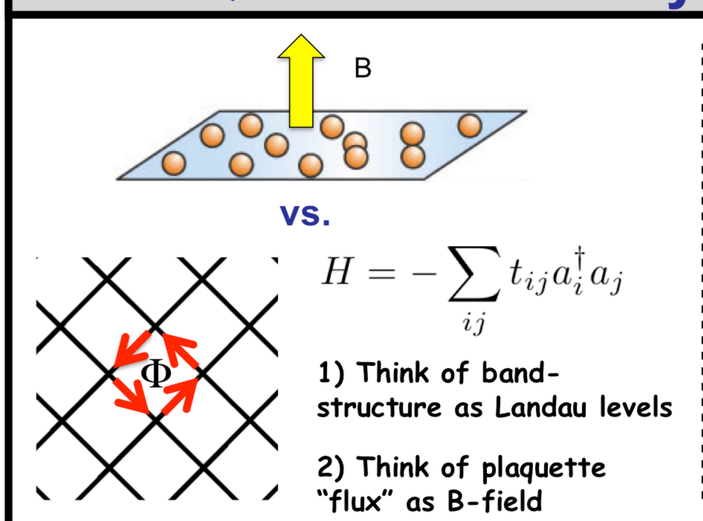
Abstract

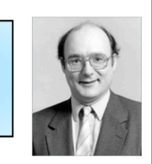
We propose and analyze a physical system that naturally admits two-dimensional topological nearly flat bands. Our approach utilizes an array of three-level dipoles (effective S=1 spins) driven by inhomogeneous electromagnetic fields. The dipolar interactions produce arbitrary uniform background gauge fields for an effective collection of conserved hardcore bosons, namely, the dressed spin-flips. These gauge fields result in topological band structures, whose bandgap can be larger than the corresponding bandwidth. Exact diagonalization of the full interacting Hamiltonian at half-filling reveals the existence of superfluid, crystalline, and supersolid phases. An experimental realization using either ultra-cold polar molecules or spins in the solid state is considered.

Quantum Hall Physics without Landau Levels



independent electrons in *filled* Chern band ⟷ independent electrons in *filled* Landau level

interacting particles in *fractionally filled* Chern band ⟷ ? interacting electrons in *fractionally filled* Landau level



Yes!

Motivation and Overview

Topological Flat Bands:
- Hopping interference
- Background synthetic gauge field to break time reversal symmetry

→ **Engineered Lattice Models:** PRL 106, 236802 (2011), PRL 106, 236804 (2011), PRL 106, 236803 (2011)

Natural System Yielding TFBs?
- 2D System of Pinned 3-level Dipoles
- Dipole-Dipole interaction is anisotropic
- Phases associated and with d⁺d⁺ and d⁻d⁻

→ **Ultra-cold polar molecules:** PRL 108, 080405 (2012), PRL 101, 133004 (2008).

→ **Spins in the solid state:** Science 314, 281 (2006)

→ **Rydbergs and Magnetic Atoms:** PRL 104, 063001(2010), PRL 105, 193603 (2010).

Fractional Chern Insulators: Lattice Quantum Hall states

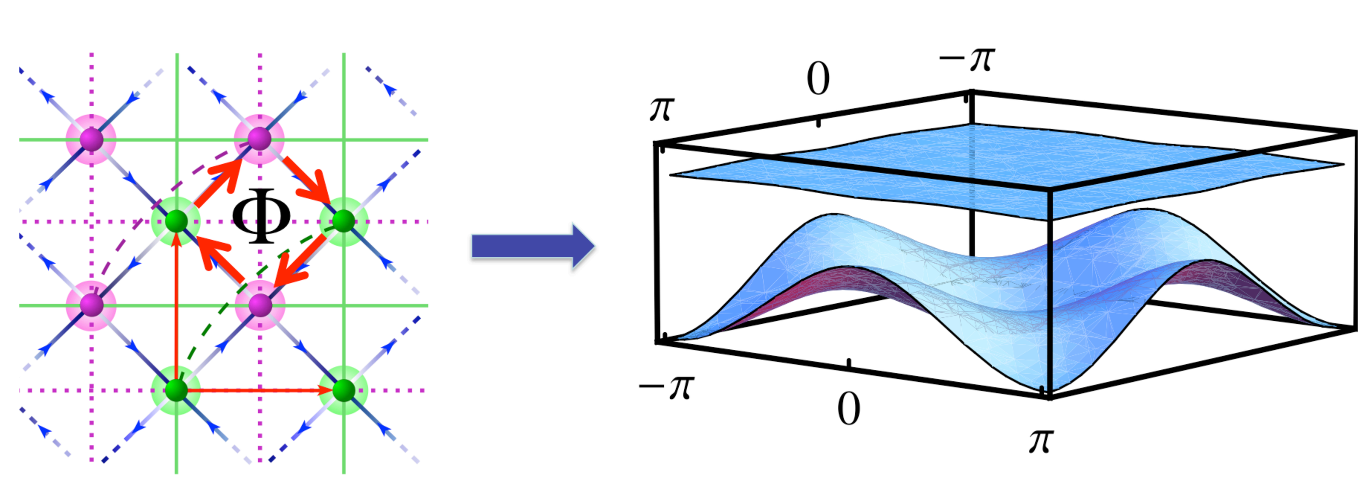
→ **Protected State transfer, quantum memories and topological q. computing**

Non-abelian Hall states ← Higher Chern bands?

Engineered Flat Bands

Ingredients: 1) flat-bands enabling interactions to dominate vs. dispersion
2) topologically non-trivial

Current approaches: engineer simple lattice models to enforce flat bands

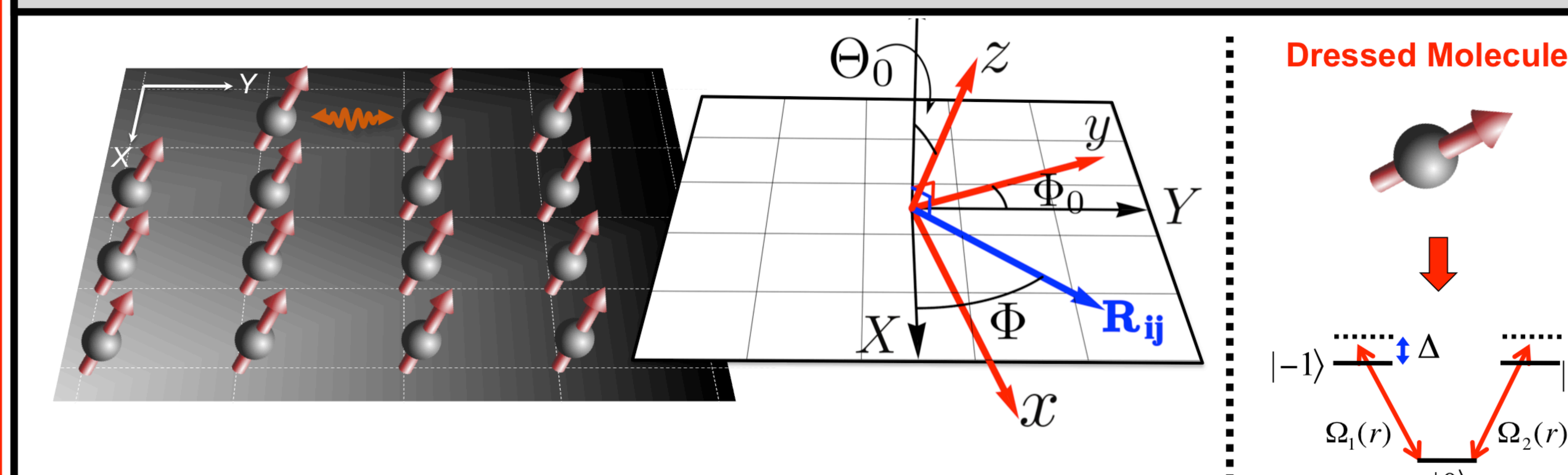


Introduce phases for a hopping particle (e.g. breaking time-reversal)

PRL, 106, 236803 (2011); PRL, 107 146803 (2011)

Topological Flat Bands from 2D Dipolar Spin Systems

Ultra-cold Polar Molecules



2D Lattice of pinned polar molecules aligned by DC electric field

Dipolar Interactions: Anisotropy + Phases

Workhorse:
$$H_{dd} = \frac{1}{2}\sum_{i\neq j}\frac{\kappa}{R_{ij}^3}\left[\mathbf{d_i}\cdot\mathbf{d_j} - 3(\mathbf{d_i}\cdot\hat{\mathbf{R}}_{\mathbf{ij}})(\mathbf{d_j}\cdot\hat{\mathbf{R}}_{\mathbf{ij}})\right]$$
Ingredient #1 ?

Typically rewritten:
$$H_{dd} = \frac{\kappa}{R_{ij}^3}\sum_{q=-2}^{q=2}(-1)^q C_{-q}^2(\theta,\phi)\,T_q^2(d^i,d^j)$$
Ingredient #2 ?

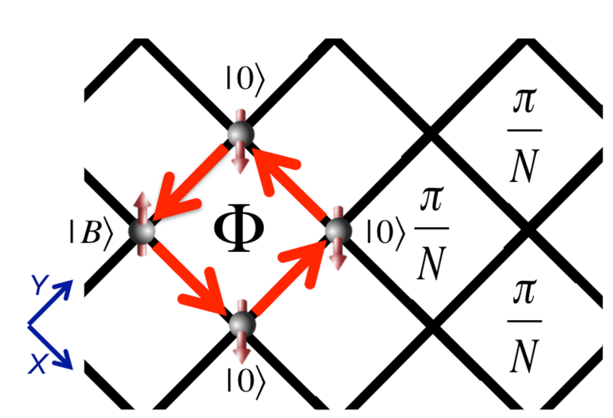
Concept: dress the dipolar excitations with microwave fields or optical Raman

$$|0\rangle\,,\;|B\rangle = \Omega_1|-1\rangle + \Omega_2|1\rangle\;\;|D\rangle$$

Naturally define a hardcore boson: $a_i^\dagger = |B\rangle\langle 0|_i$

Dipolar Interactions →
$$H_B = -\sum_{ij} t_{ij} a_i^\dagger a_j + \frac{1}{2}\sum_{i\neq j} V_{ij} n_i n_j$$

With: $t_{ij} \sim \langle B_i, 0_j | H_{dd} | 0_i, B_j\rangle$ & $V_{ij} \sim \langle B_i B_j | H_{dd} | B_i B_j\rangle$

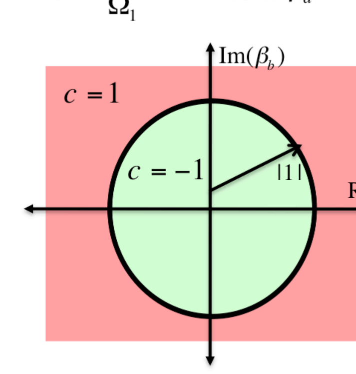


Interplay between driving and dipolar interactions:

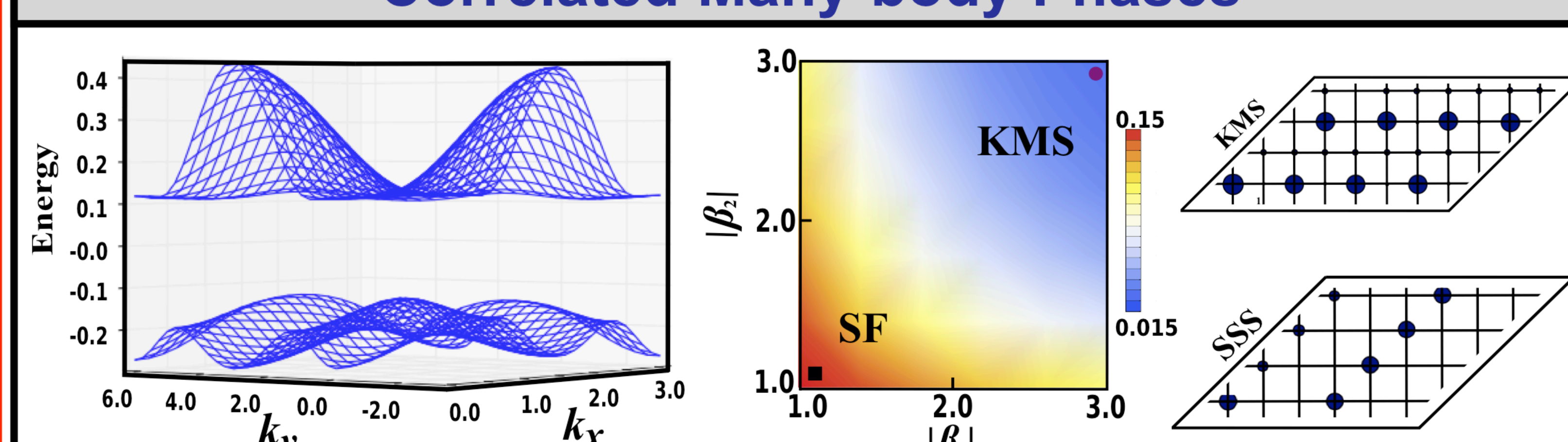
$$t_{ij}^{\hat{X}} = \Omega_{1,i}^*\Omega_{2,j}e^{i\pi/3} + \Omega_{2,i}^*\Omega_{1,j}e^{-i\pi/3}$$
$$t_{ij}^{\hat{Y}} = \Omega_{1,i}^*\Omega_{2,j}e^{-i\pi/3} + \Omega_{2,i}^*\Omega_{1,j}e^{i\pi/3}.$$

Punchline: varying a single MW in a periodic fashion allows the generation of uniform π/N flux per plaquette

$\beta = \frac{\Omega_2}{\Omega_1}$ **Pick:** $\beta_o = 1$

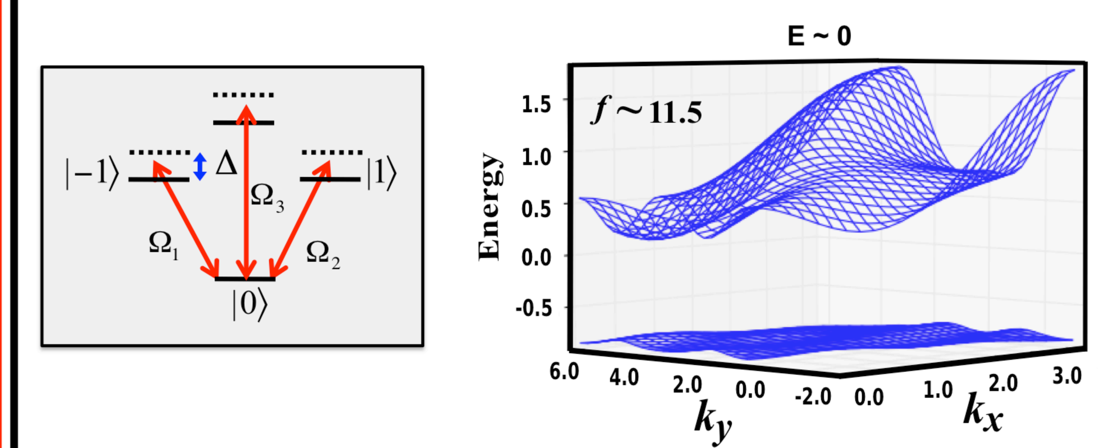


Correlated Many-body Phases

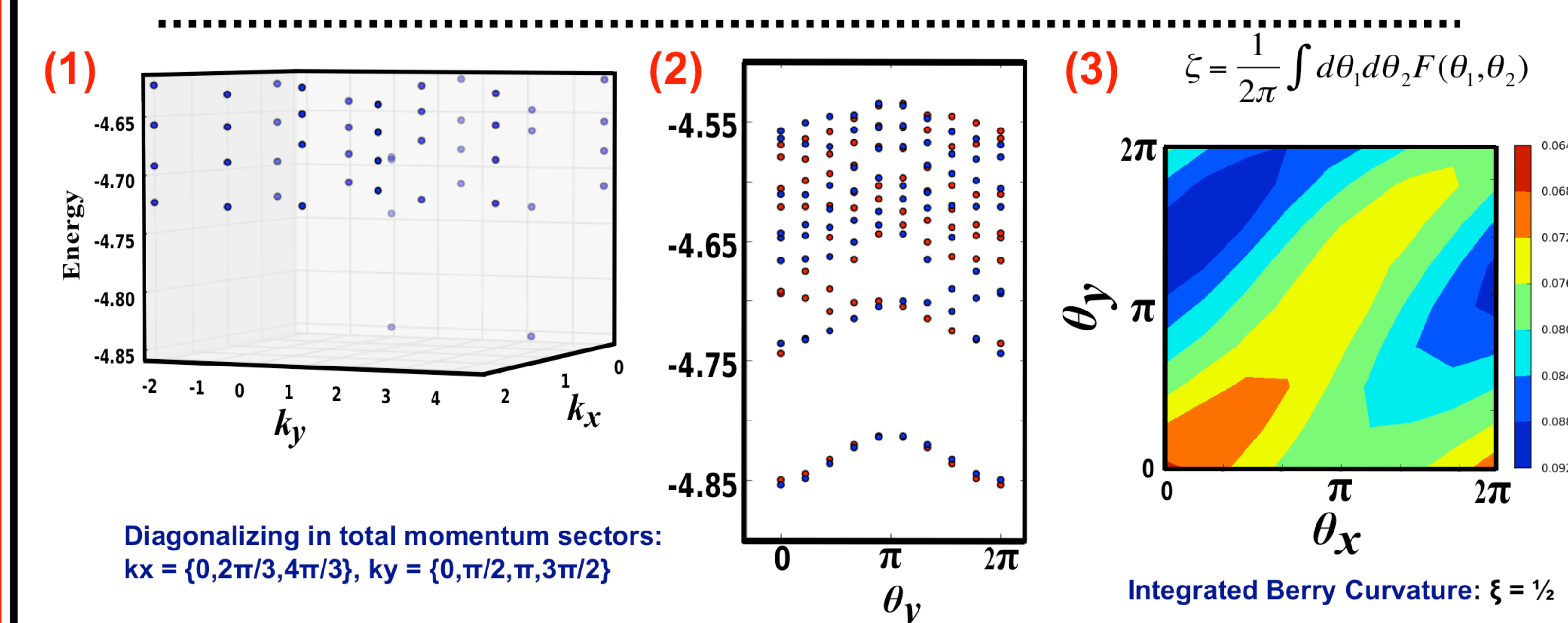


Diagnosing Fractional Chern Insulators and Beyond Landau Level Physics

υ = ½ Fractional Chern Insulator



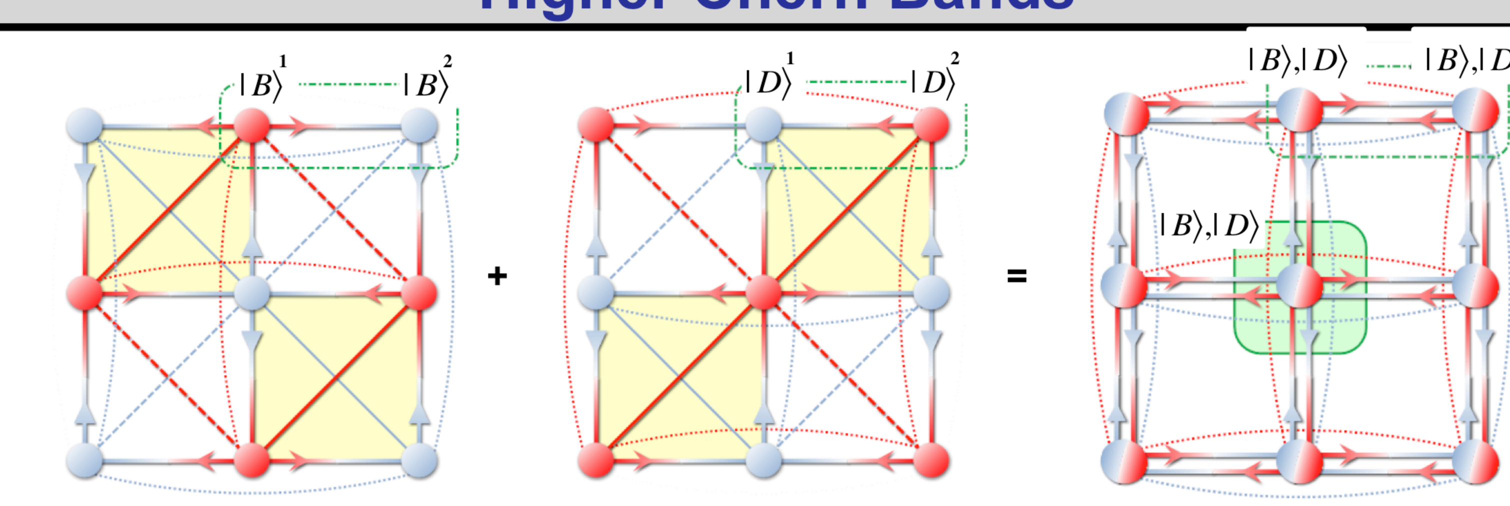
Signatures of υ = ½ FQH:
1) Two degenerate ground states (on torus)
2) Ground states twist into one another (boundary condition)
3) Each g.s. should have an integrated berry curvature ½

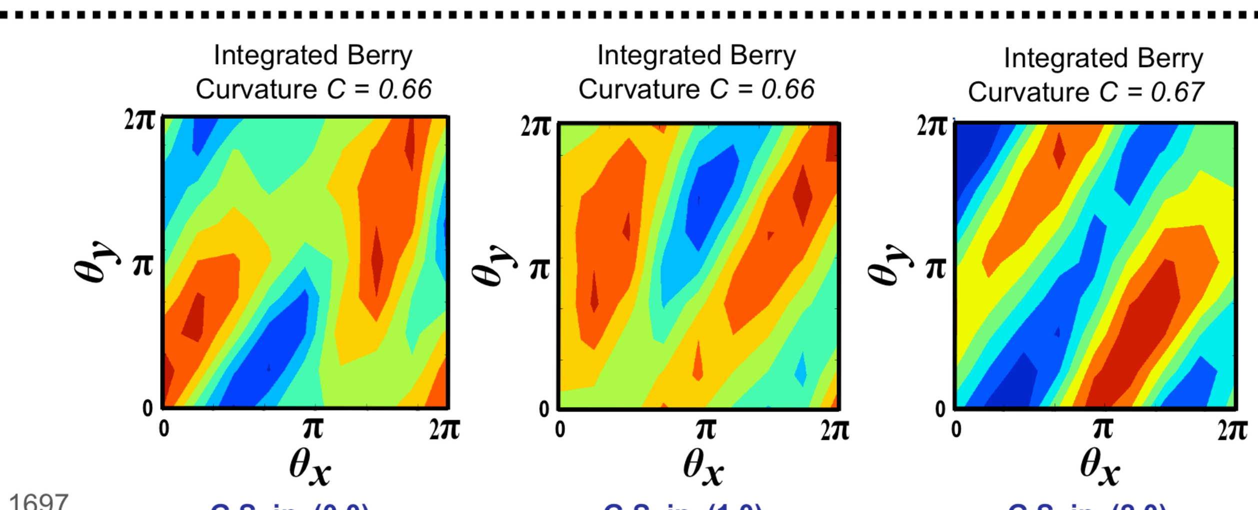


Diagonalizing in total momentum sectors: kx = {0,2π/3,4π/3}, ky = {0,π/2,π,3π/2}

Integrated Berry Curvature: ξ = ½

Higher Chern Bands





arXiv:1204.1697,
arXiv:1205.5792

Outlook

- Non-abelian Hall States in higher Chern bands
- Theory of the critical point + many-body state preparation

Acknowledgements

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