Optical Control in Fractional Quantum Hall Systems

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ABSTRACT:

Light-matter interactions provide a powerful tool for controlling the electronic properties of a material. Here, we demonstrate the possibility of light-induced topological phase transitions for graphene in the fractional quantum Hall regime. The optical coupling mimics an artificial bilayer scenario with tunable pseudopotentials giving rise to exotic non-Abelian phases. They include the gapless Haldane-Rezayi phase at filling 1/2, and the Fibonacci anyon phase at filling 2/3. For both Dirac materials and non-relativistic quantum Hall systems, we show that coupling to light with orbital angular momentum can be used as a synthetic "flux" pump. This enables the controlled insertion of individual quasiparticles in a quantum Hall system. Moreover, light-induced potentials, based on AC Stark shift, can trap such quasiparticles.

LANDAU LEVEL COUPLING IN GRAPHENE

Selection rules: $|n| \leftrightarrow \pm(|n|\pm 1)$ for circularly polarized light

$m \leftrightarrow m+\ell$ for light with orbital angular momentum ℓ

n: Landau level index
m: orbital quantum number

Hamiltonian in rotating wave approximation:

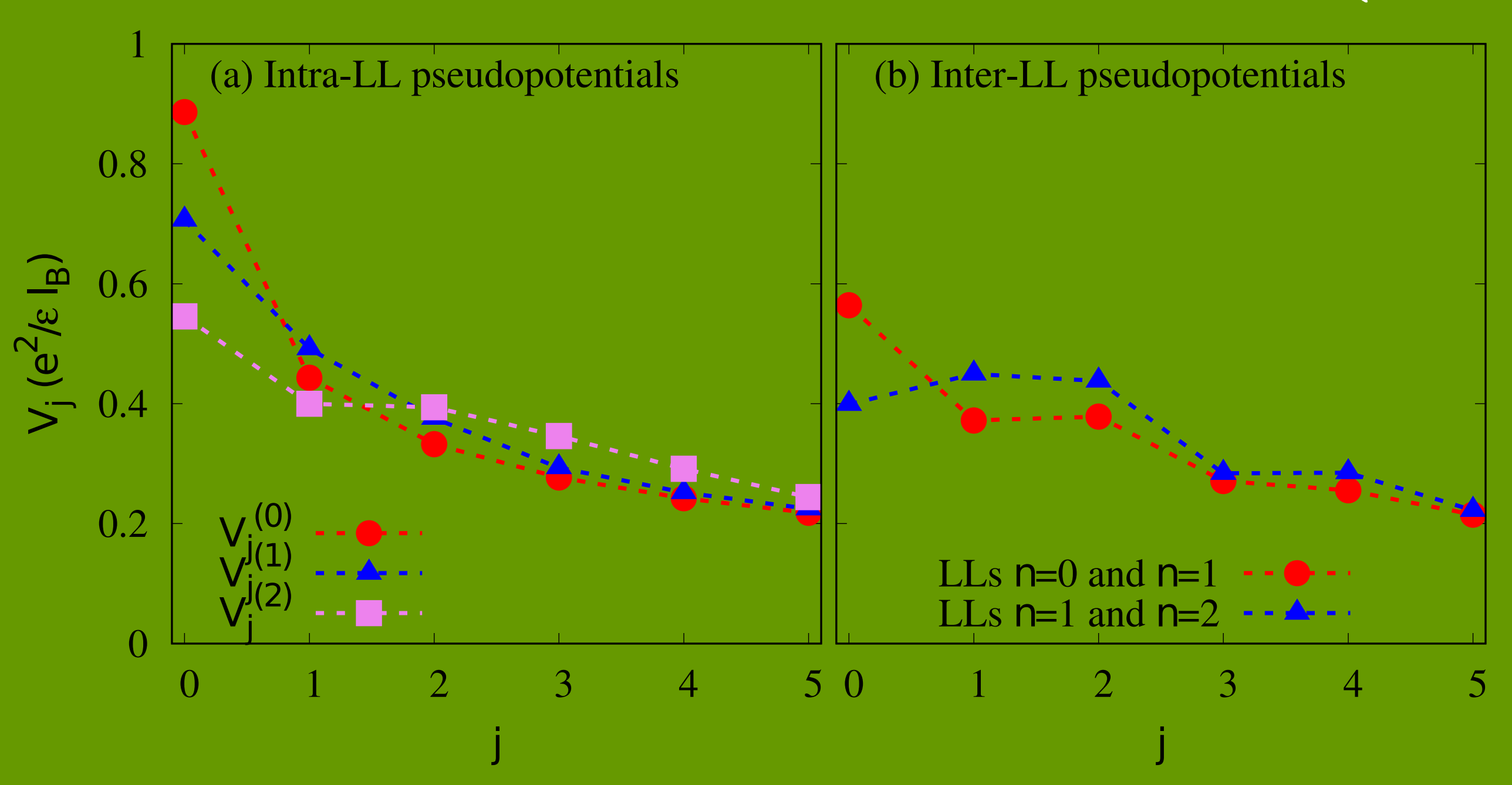
$$H_0 = \sum_m \left[\hbar\delta c^\dagger_{n+1,m} c_{n+1,m} + \hbar\Omega c^\dagger_{n+1,m+\ell} c_{n,m}\right] + \text{h.c.}$$

Strong coupling $\left(\Omega \gtrapprox 0.1\frac{e^2}{\epsilon l_B}\right)$: System frozen in lower dressed Landau level

Weak coupling $\left(\Omega \lessapprox 0.1\frac{e^2}{\epsilon l_B}\right)$: Synthetic bilayer structure

PSEUDOPOTENTIALS OF COUPLED LLs

- Coulomb scattering conserves sum of Landau level indices (in RWA)
- Exchange interaction V^{ex} between Landau levels occur: antiferromagnetic; not present in standard bilayer / spin systems
- Symmetric / antisymmetric contributions to pseudopotentials between Landau levels: $V_j^{\text{inter}} = \begin{cases} V_j^{\text{dd}} + V_j^{\text{ex}} & \text{for } j \text{ even} \\ V_j^{\text{dd}} - V_j^{\text{ex}} & \text{for } j \text{ odd} \end{cases}$



When LL1 ↔ LL2 are coupled: Electrons in different Landau levels repel each other strongest at relative angular momentum *j*=1. This favors fully antisymmetric pseudospin wave functions, i.e. **singlet states**.

LIGHT-INDUCED PHASE TRANSITIONS

For LL1 ↔ LL2 coupling: Phase transition from polarized phase to singlet phase when Rabi frequency is decreased

For LL0 ↔ LL1 coupling: No transition, always polarized

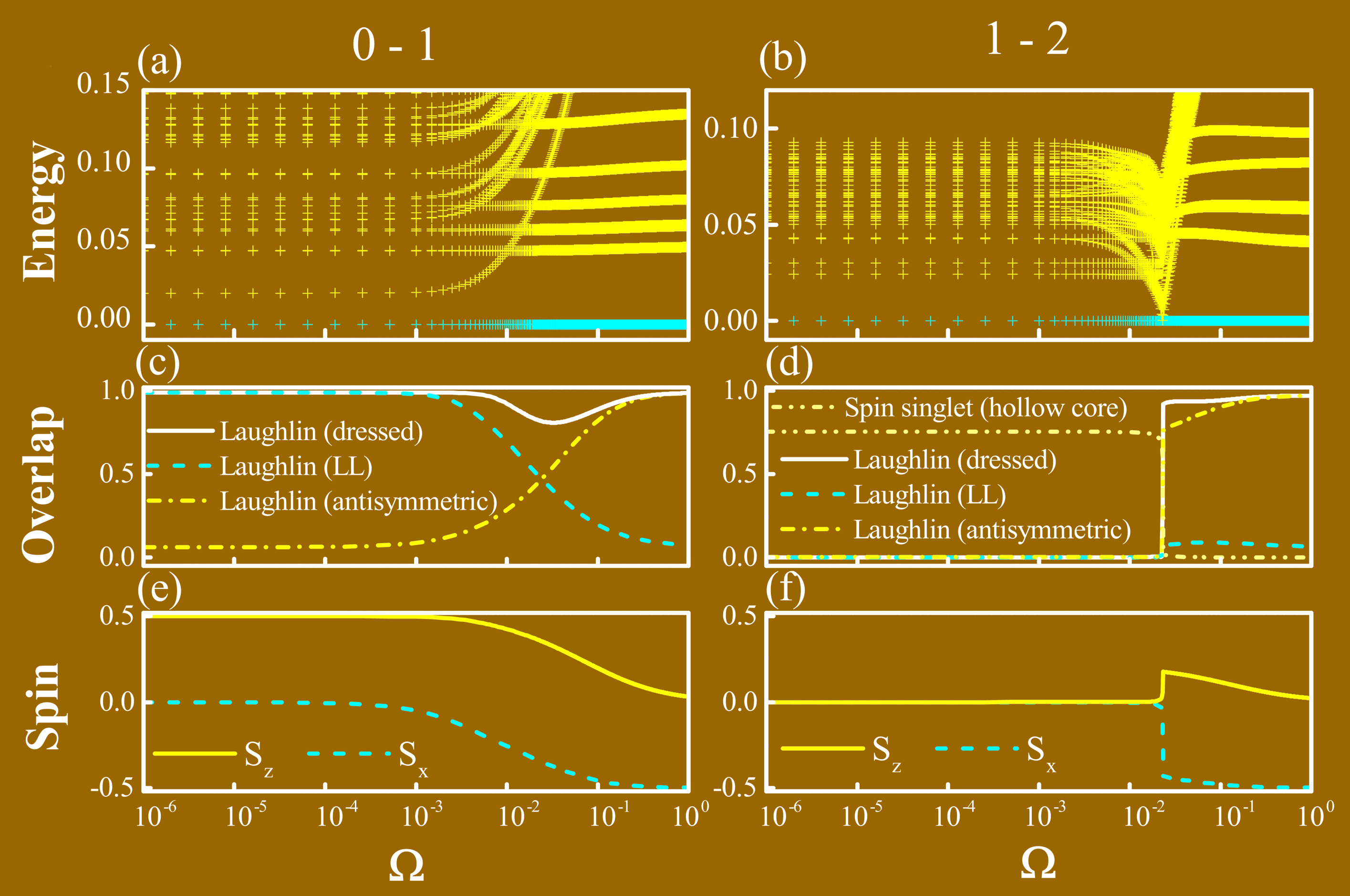


FIG: Data for 8 electrons on a square torus at filling ν=2/3

Overlaps of the singlet phases with different trial states:

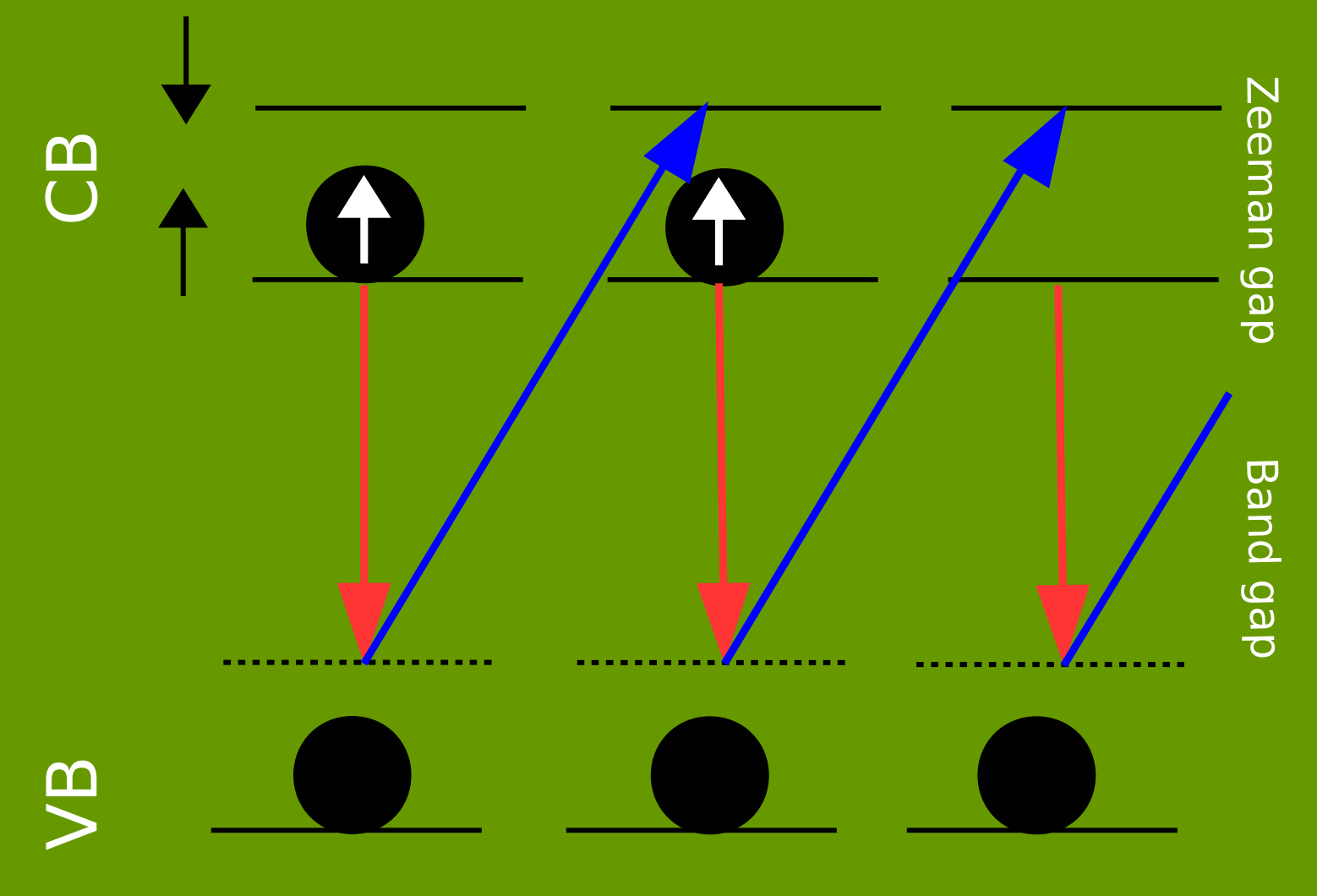
ν=1/2	Sphere	Torus	Disk
Haldane-Rezayi	0.85 (*N*=6) 0.75 (*N*=8) 0.72 (*N*=10)	0.83 (**K**=0) 0.72 (**K**≠0) (*N*=8)	0.97 (*N*=6, *L*=24)
Composite fermions	0.1 (*N*=8) 0.02 (*N*=10)		

ν=2/3	Sphere	Disk	Torus
Interlayer-Pfaffian	0.99 (*N*=4) 0.55 (*N*=8) 0.39 (*N*=12)	0.81 (*N*=6, *L*=24) 0.63 (*N*=6, *L*=24)	
Fibonacci	0.62 (*N*=8)		0.76 and 0.81 (*N*=8)

COUPLING TO VALENCE BAND IN GaAs

GaAs: Harmonic Landau level spectrum → direct selective coupling not possible

- Raman coupling between conduction band (CB) and valence band (VB)
- *E.g.:* Couple (fractionally) filled ↑-level to empty ↓-level [both in CB] via VB level
- Requires spin-orbit coupling in VB
- Both spin manifolds can be metastable



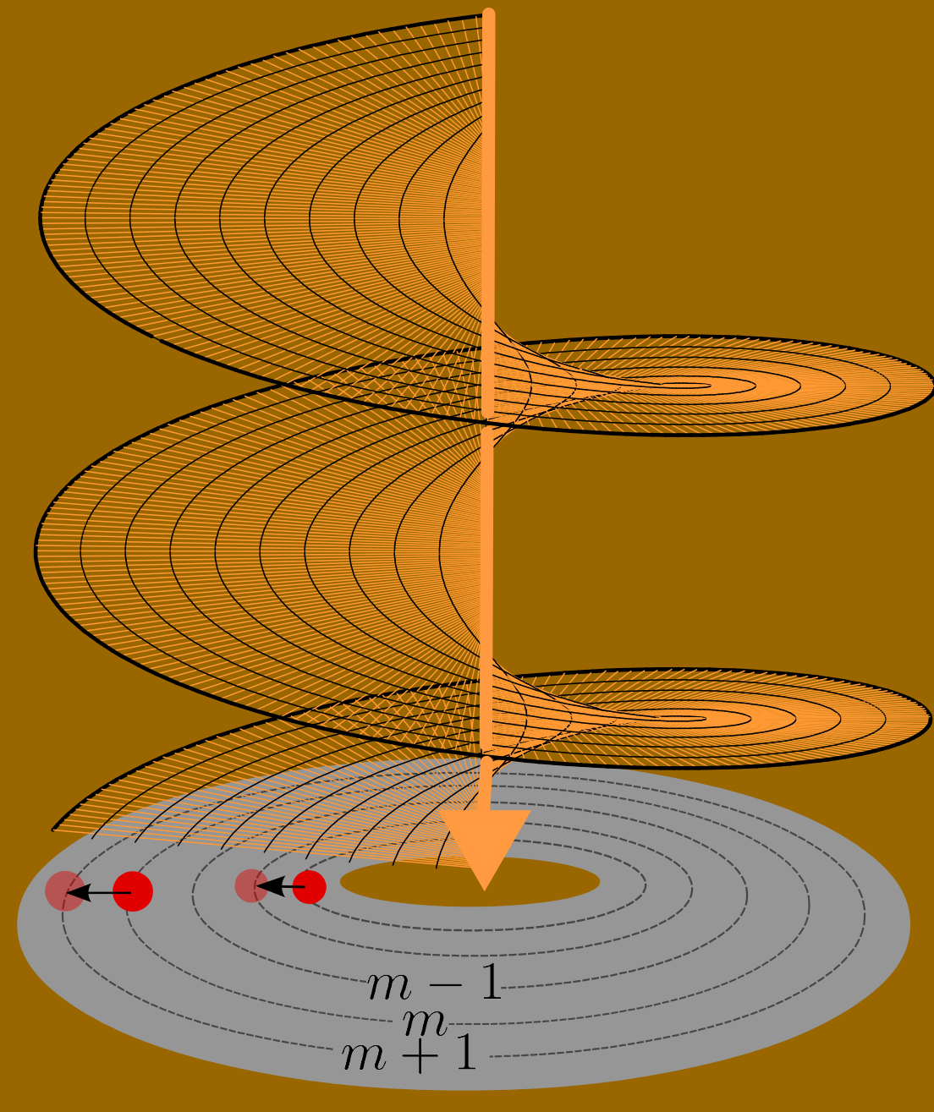
SYNTHETIC FLUX INSERTION

Light pulse with OAM=1: $\Psi_{\text{ini}}(z_1,\ldots,z_N) \rightarrow \left(\prod_{i=1}^{N}\sigma_i^x b_i^\dagger\right)\Psi_{\text{ini}(}z_1,\ldots,z_N)$

$$\text{where} \quad b^\dagger|n,m,s\rangle = \sqrt{m+1}|n,m+1,s\rangle \propto z|n,m,s\rangle$$

$$\Rightarrow \Psi_{\text{ini}} \tilde{\rightarrow} \left(\prod_i \sigma_i^x\right)\left(\prod_i z_i\right)\Psi_{\text{ini}}$$

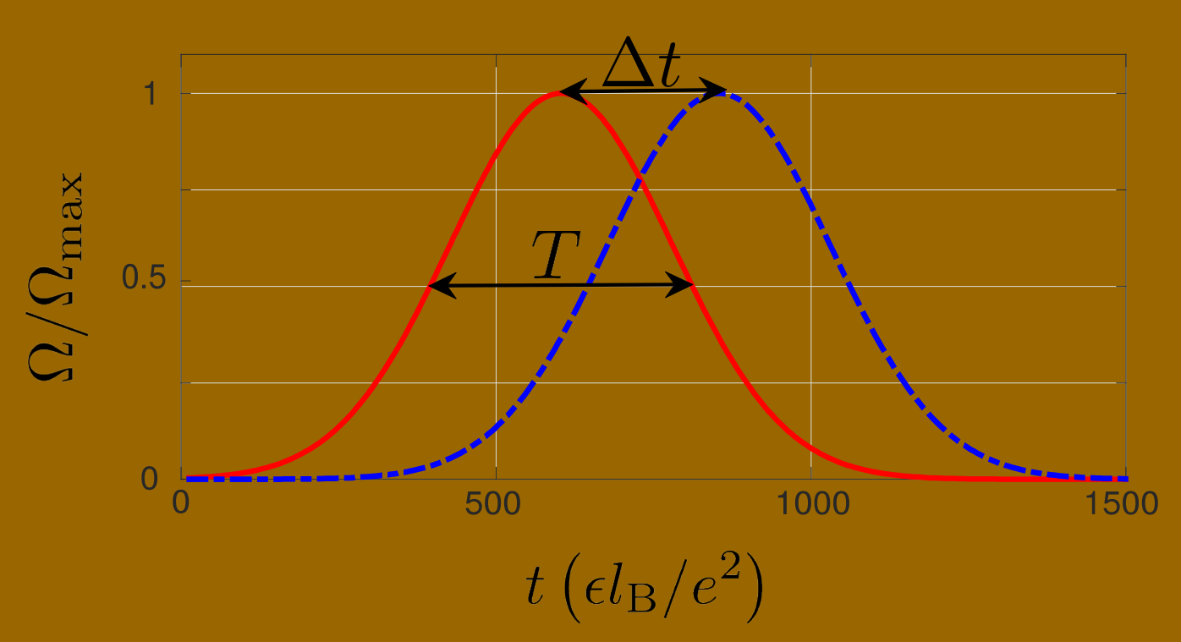
Quasihole excitations: $\Psi_{\text{qh}} = \prod_i (z_i - z_{\text{qh}})\,\Psi$



- → Light pulse transfers electron population into empty spin manifold
- → OAM of light creates a quasihole at position z_{qh}=0
- → Charge transport from center to edge
- → In *fractional* quantum Hall system: transport of *fractional* charge
- → Detection of fractional charge *q*=*ν*e:
  - * Connect two edges of Corbino disk
  - * 1/ν pump cycles produce flow of 1 electron

STIRAP: Full population transfer via coupling to third level without populating it. Possible pulse schedule:

Two processes:
(a) 1 hole: normal STIRAP
(b) 2 holes: needs detuning

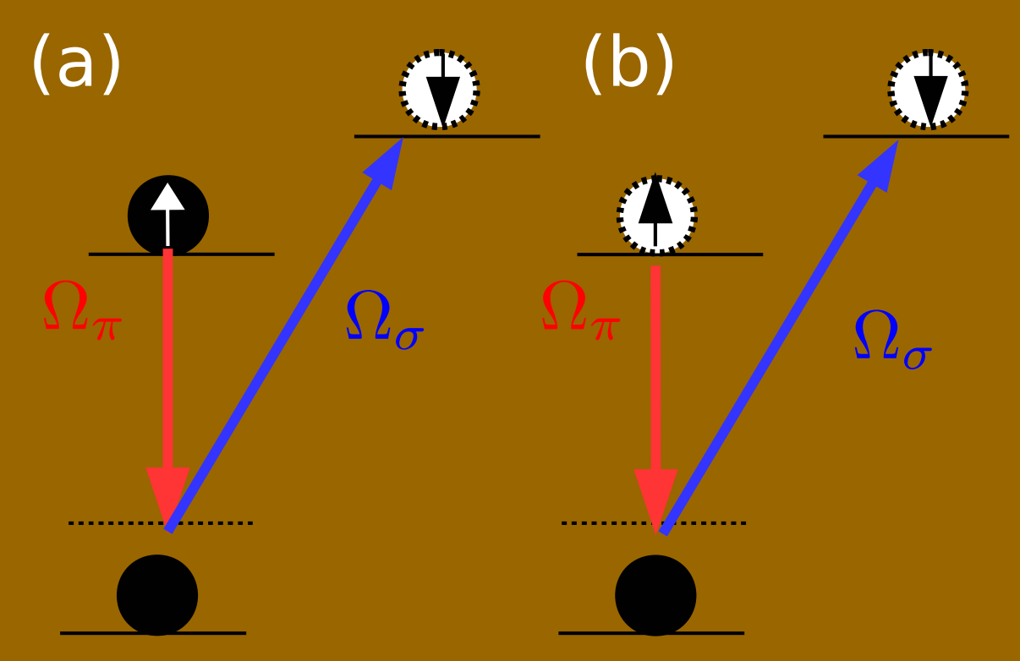


$\delta > \Omega \gg 1/T$

$T \ll \text{ns}$

Possible choice:

$\Omega_{\max}, \delta \gtrapprox 0.1\frac{e^2}{\epsilon l_B}$

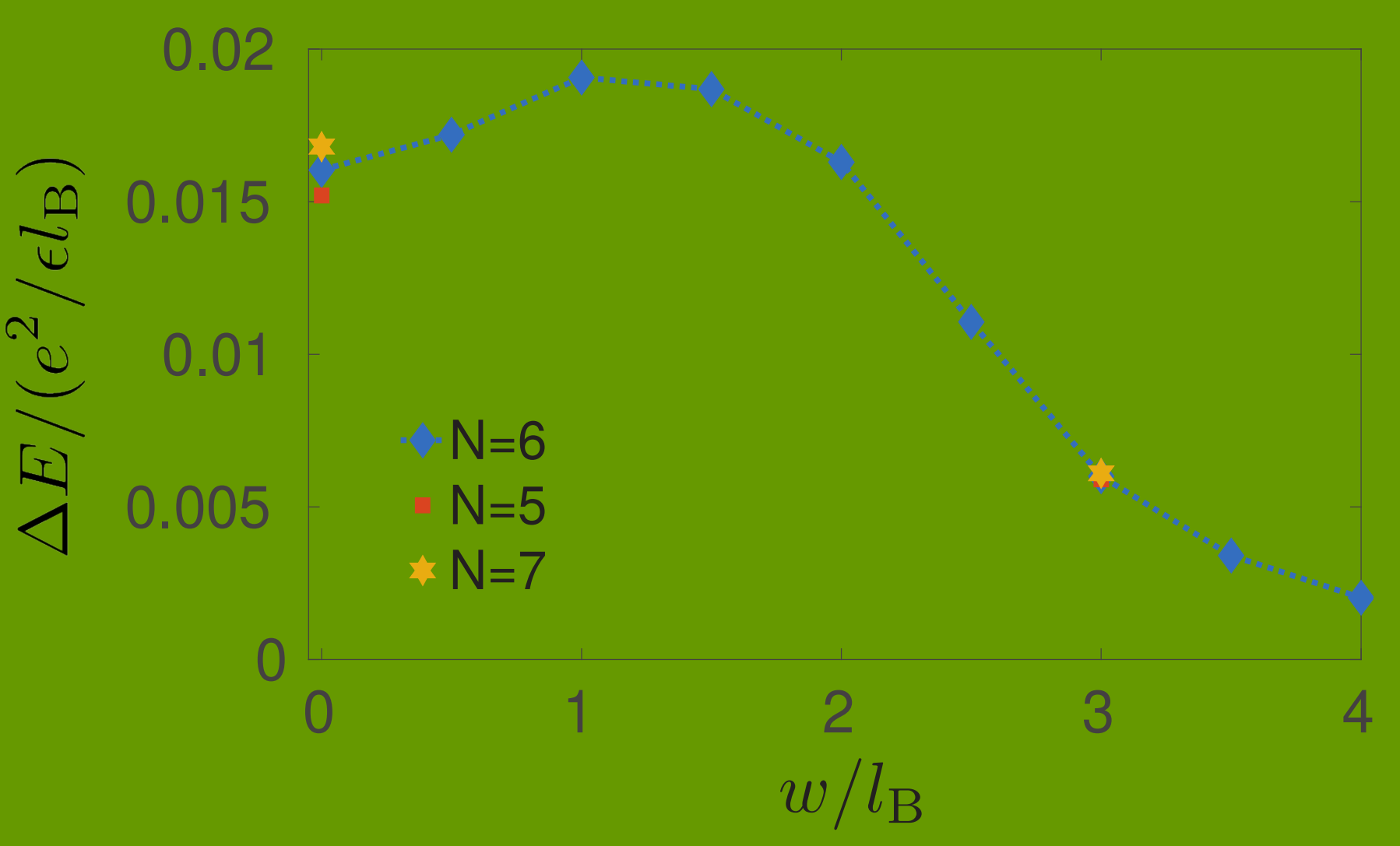


LIGHT-INDUCED POTENTIALS

- Blue-detuned local coupling to empty level repels electrons via AC Stark shift

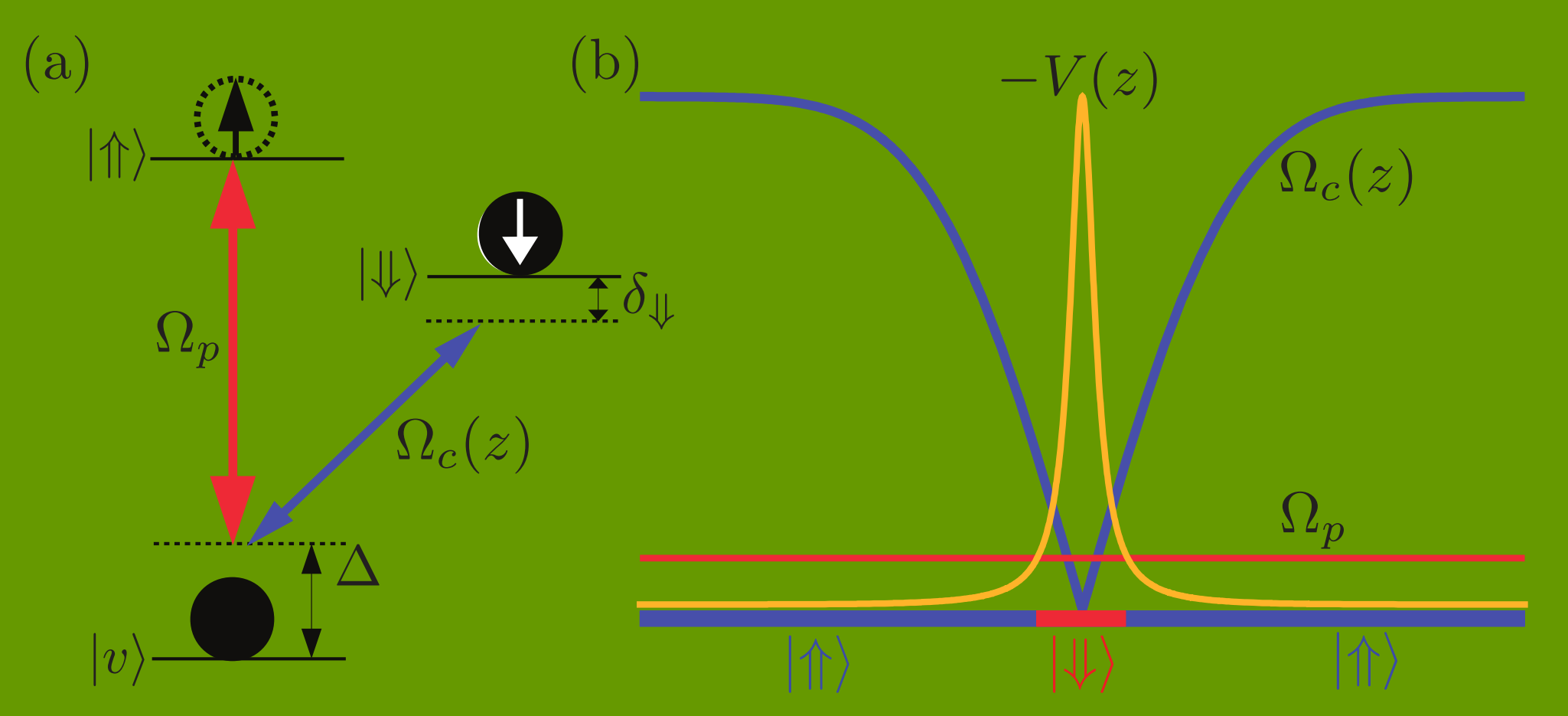
Will it localize a quasihole excitation?

- Energy scale: Typical many-body gap in Laughlin state ~ 20 meV
- Length scale: Magnetic length 26 nm / (magnetic field [Tesla])$^{1/2}$
- Shallow trap ($w \gg l_B$) leads to small gap above the quasihole state *(see figure)*



Sub-wavelength trap:

- Three-level coupling scheme
- EIT for the spin-up hole
- Tightening trap width by a factor of 10 is realistic (in GaAs)



References:
A. Ghazaryan, T. Graß, M. Gullans, P. Ghaemi, and M. Hafezi, *Phys. Rev. Lett.* **119**, 247403 (2017)
T. Graß, M. Gullans, P. Bienias, G. Zhu, A. Ghazaryan, P. Ghaemi, and M. Hafezi, *in preparation*