Topology and many-body physics in synthetic lattices

ICFO Institut de Ciències Fotòniques

Alessio Celi

Synthetic Hofstadter strips as minimal quantum Hall *experimental* systems

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Synthetic dimensions workshop, Zurich 20-23/11/17

Plan

- Synthetic lattice (Extradimension)
- Synthetic strip as minimal integer quantum Hall systems

  Edge states in narrow strips

  Topological response in narrow strips

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- Interacting flux ladder from ion chains *and a puzzle*
- Prospects and *philosophical view*

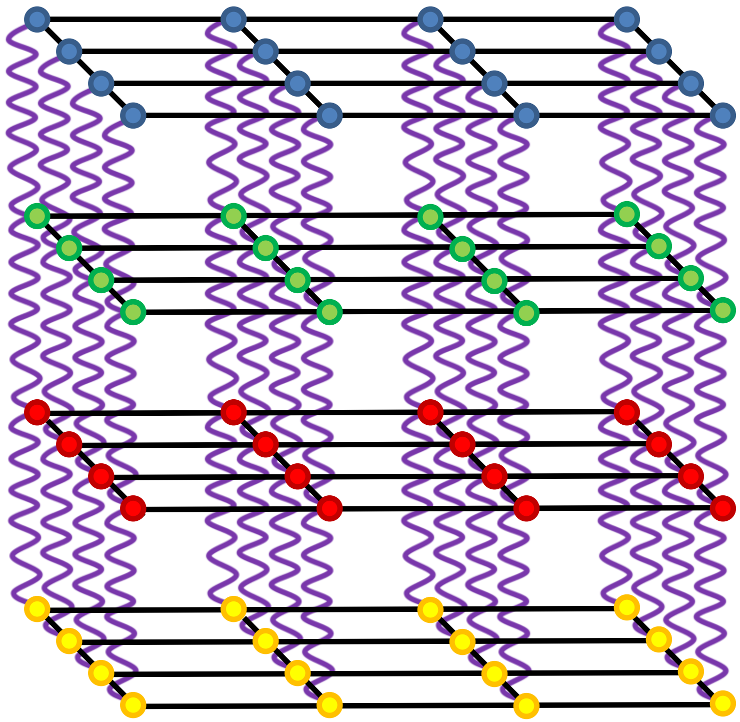
Simulating an extra dimension

[Boada,AC,Latorre,Lewenstein, PRL 108, 133001 (2012)]

In optical lattices 1D-3D Hubbard model by tuning optical potential

And > 3D? In a lattice Dimensionality ≡ Connectivity

Atoms in D+1-lattice = coherently coupled atomic states in *D*-lattices

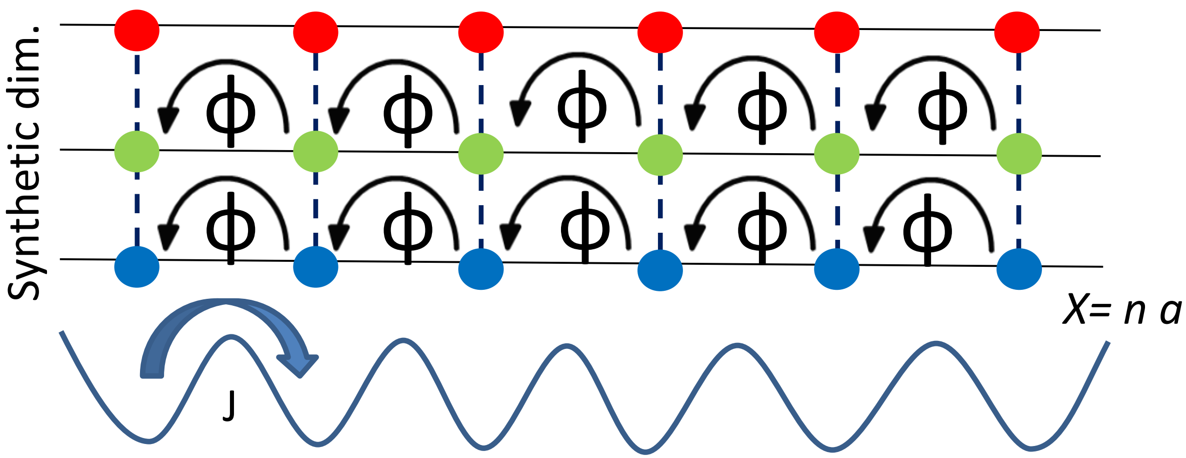


Not only spin states
Momentum states
Trap modes…

Not only atoms
Cold molecules,
Photonic crystal,
Ring resonators…

Synthetic gauge fields in synthetic dimension

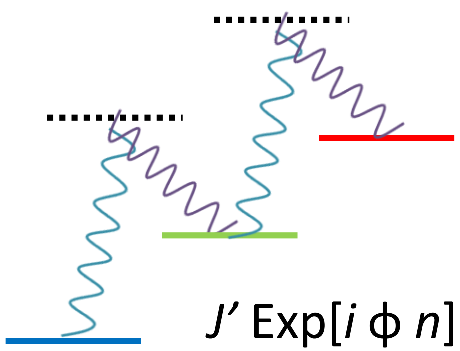
[AC et al PRL 112, 043001 (2014)]



1d-lattice loaded e.g. with ^{87}Rb (F=1, m=-1,0,1)

+

Raman dressing



Constant magnetic flux ϕ!

Minimal instance of a quantum Hall system!

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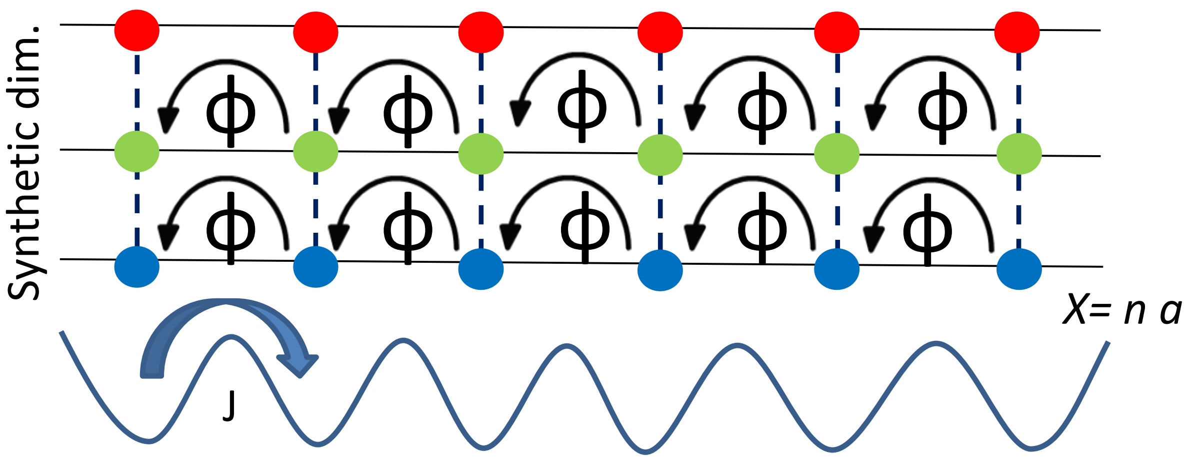

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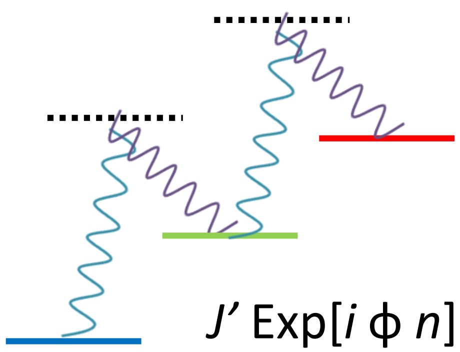

Sharp Boundaries ➡ Edge currents (hard to get in real 2d lattice)

signal of Topological nature of quantum Hall

(bulk-boundary correspondence)

Synthetic gauge fields in synthetic dimension

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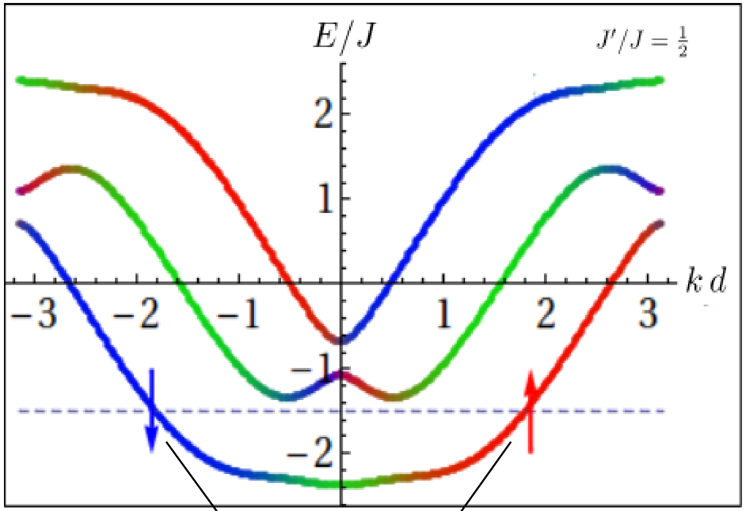
Spectrum



"Genuine" Edge states for small J'/J:

-live in the gap,

-have linear dispersion

-have well defined spin

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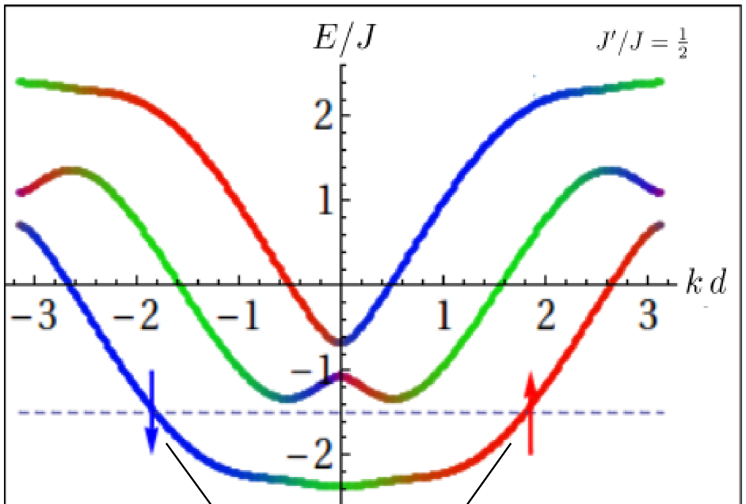

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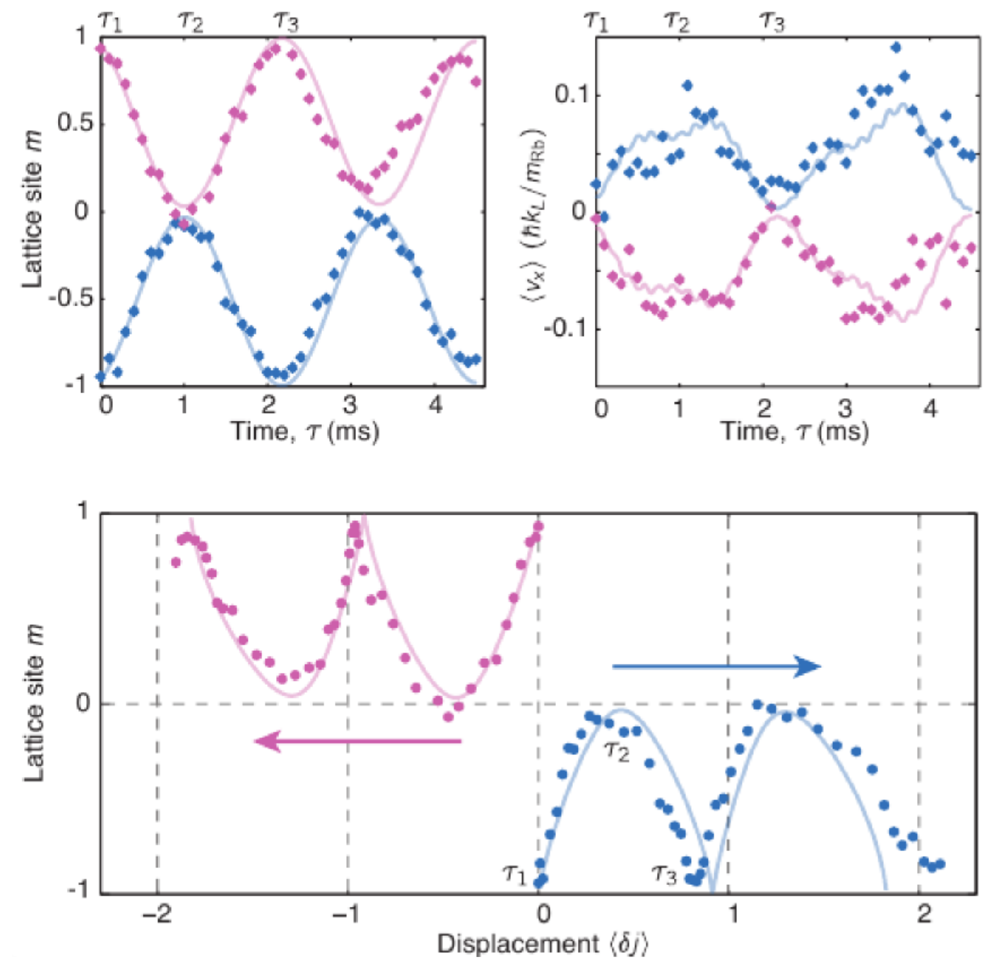
Experimental Realizations:

I) Bosons: NIST Spielman group ^{87}Rb [*Science* (2015)]



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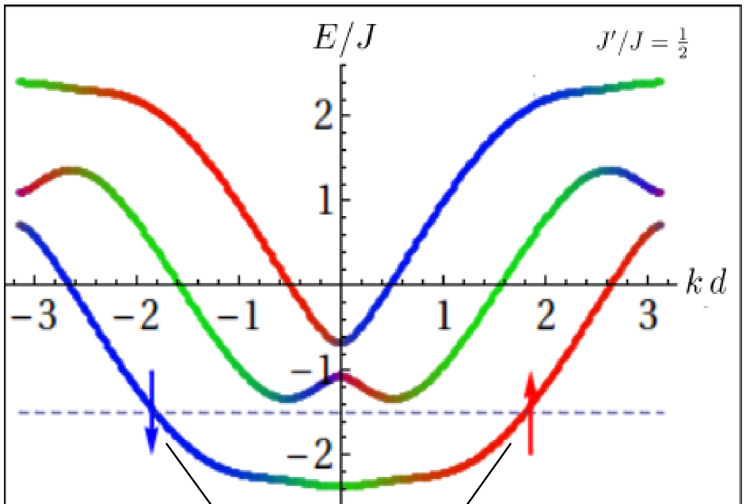

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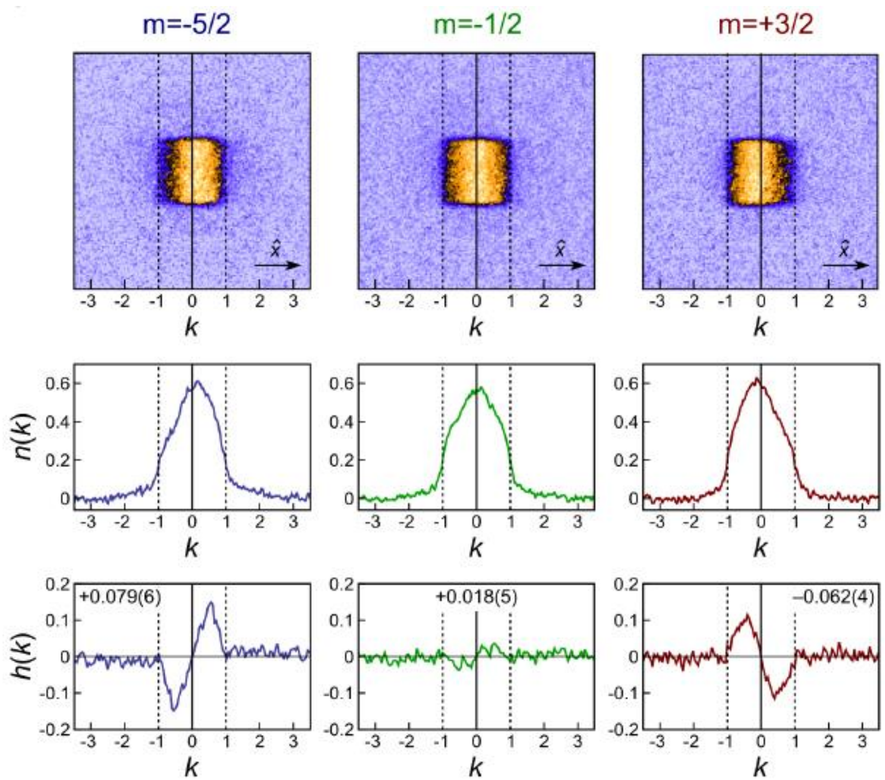

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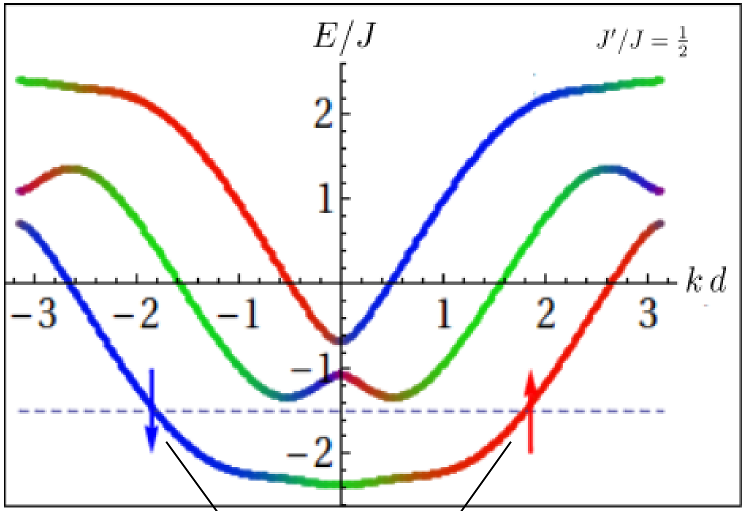

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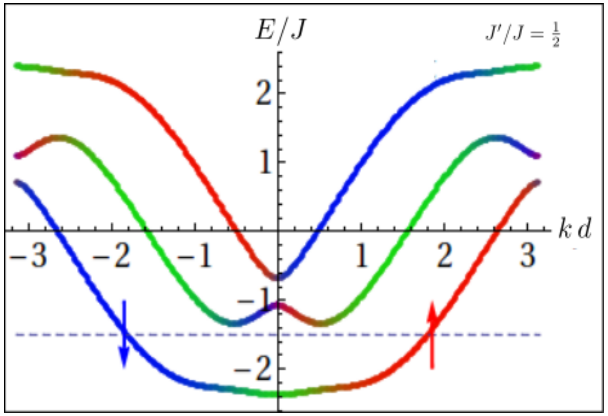
Also with clock states (ladder)
LENS: Livi et al. PRL 117, 220401 (2016)
JILA: Kolkowitz et al. Nature 542 66 (2017)

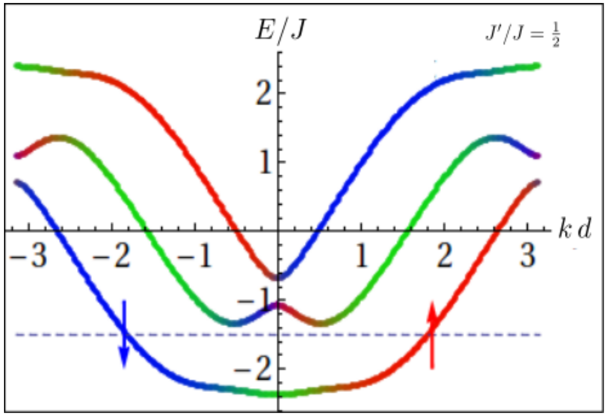
Topology in narrow strips



Narrow Hofstadter strips have edge states

What about the “bulk”?

Topology in narrow strips



Narrow Hofstadter strips have edge states

What about the “bulk”?

How big should it be to display topological properties?

Is there some reminiscence of open/closed boundary correspondence?

Is Chern number defined? / Can we measure it?

Measuring Chern numbers in (narrow) Hofstadter strips, S.Mugel,….AC, SciPost 3, 012, (2017)

Pragmatic approach: measure transverse displacement to a force after a Bloch oscillation, Laughlin pump argument

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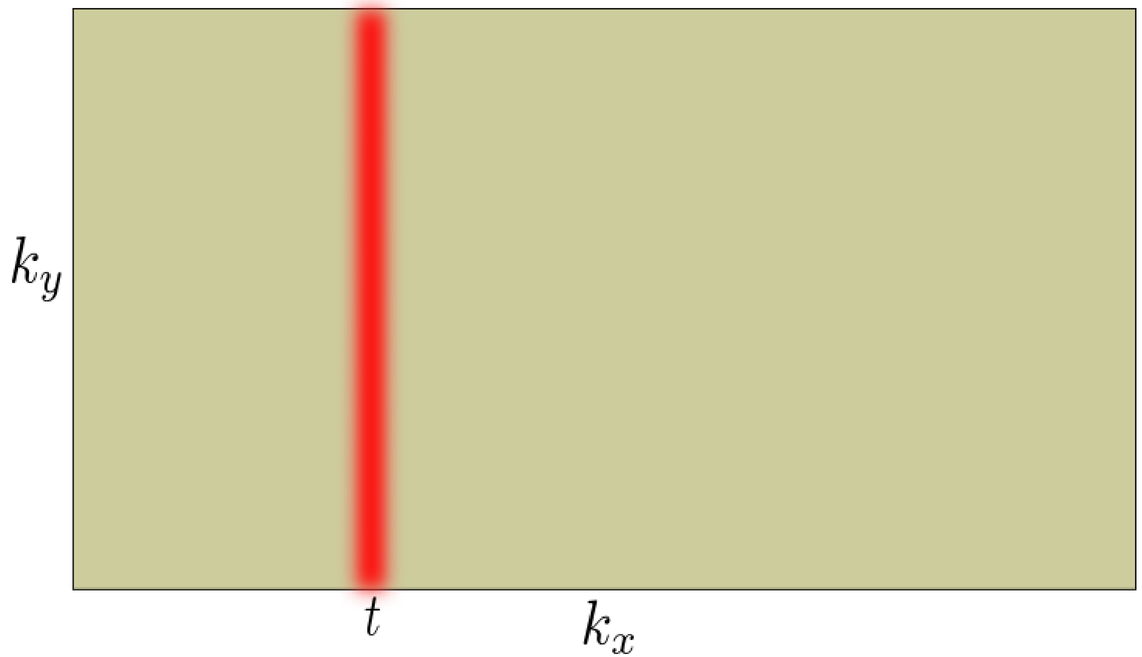
- Large (periodic) system, a lowest band state well localized in *y* and spread in *x*
- Apply a force along *x*

Brillouin sketch



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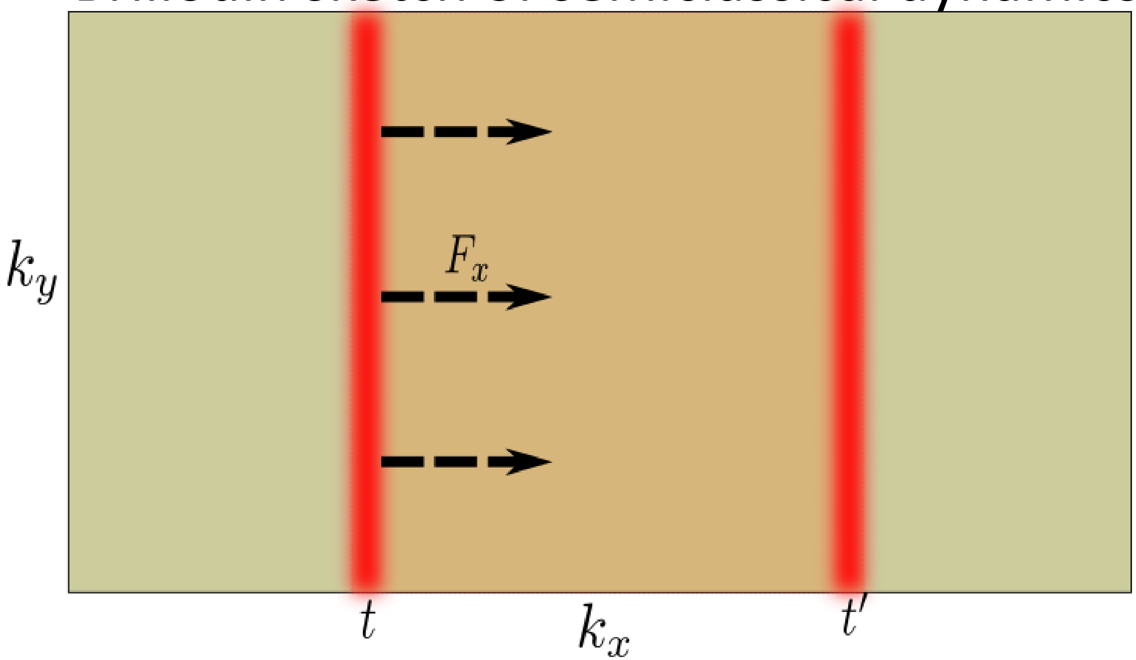
Brillouin sketch of semiclassical dynamics



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- Apply a force along *x*
- After a Bloch oscillation observe the displacement

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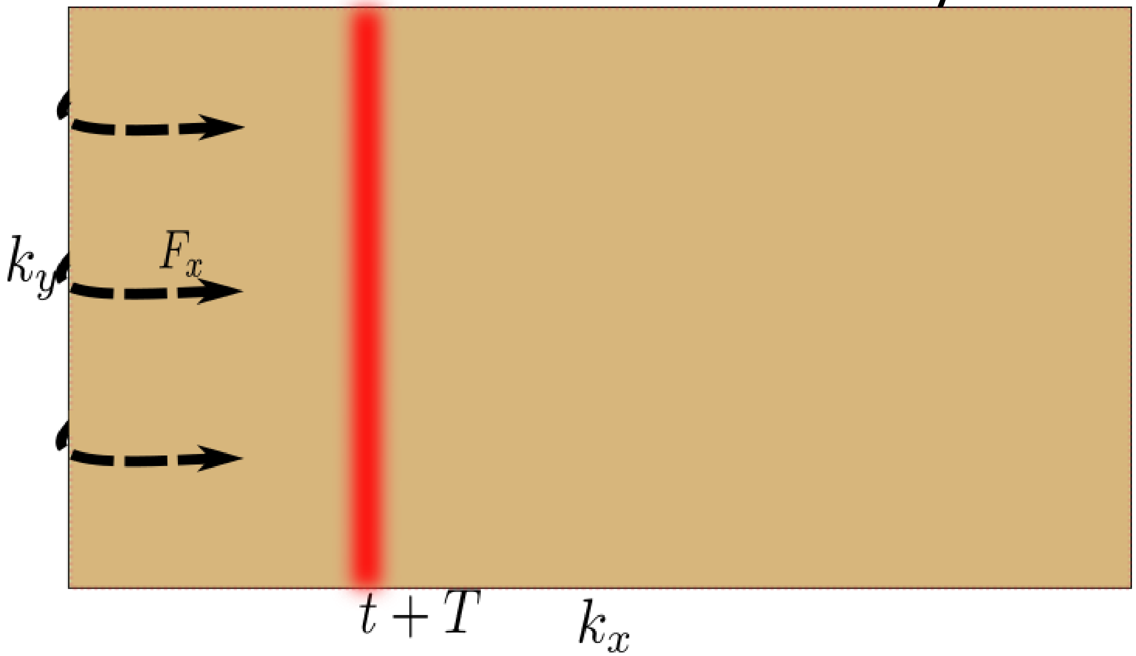

Displacement in *y* due to anomalous velocity!

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In formulae: semiclassical approach

$$\mathbf{k}(t) = \mathbf{k}_0 + \frac{t}{\hbar d} F_x \, \mathbf{e}_x \longrightarrow \mathbf{v}(\mathbf{k}) = \frac{1}{\hbar}\partial_{\mathbf{k}} E(\mathbf{k}) + \frac{F_x}{\hbar d}\mathcal{F}(\mathbf{k})\mathbf{e}_y$$

$$|\psi(\mathbf{k})|^2 \sim \tfrac{1}{A_{BZ}}\delta(k_x - k_x(t))$$

Wave packet:

$$\langle \mathbf{r}(T) - \mathbf{r}(0)\rangle = \int_0^T \langle \mathbf{v}(t)\rangle = \tfrac{\hbar d}{|F_x|}\int_{BZ} \mathbf{v}(\mathbf{k}) = \mathrm{sgn}(F_x)\mathcal{C}\, d\, \mathbf{e}_y$$

State easy to prepare if the coupling $J_y \ll J_x$

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Applicable also to strips until we don’t reach the boundary…

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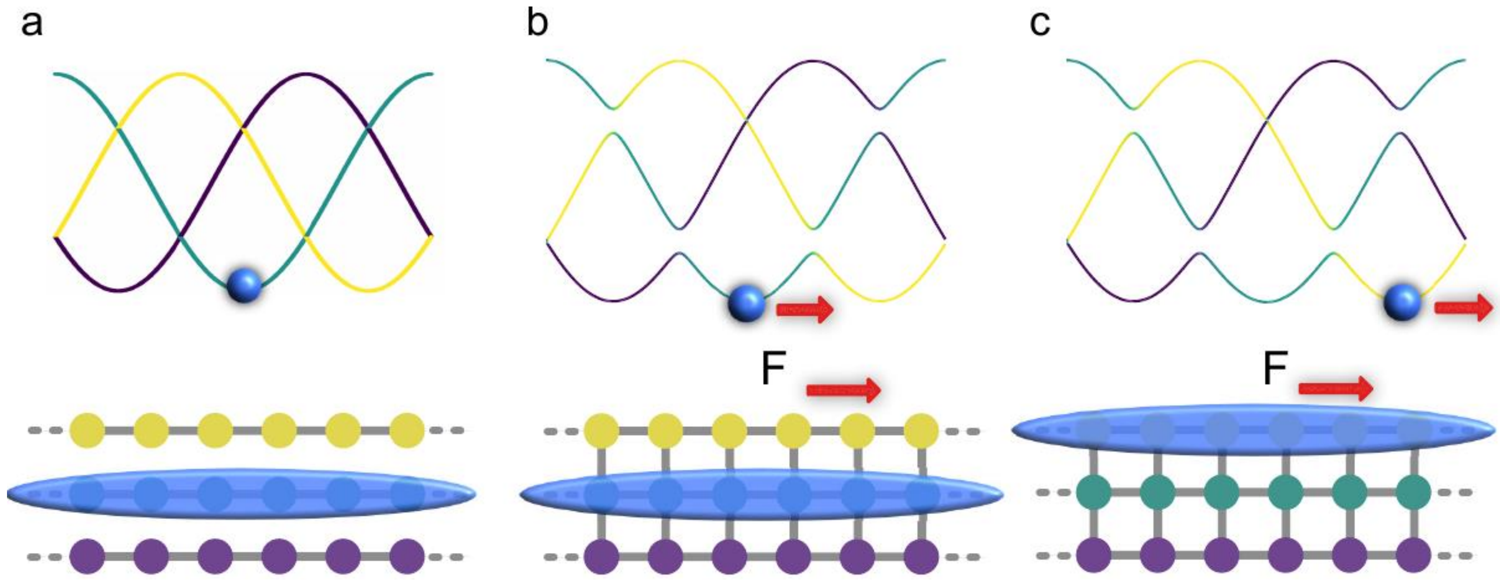
Scheme:



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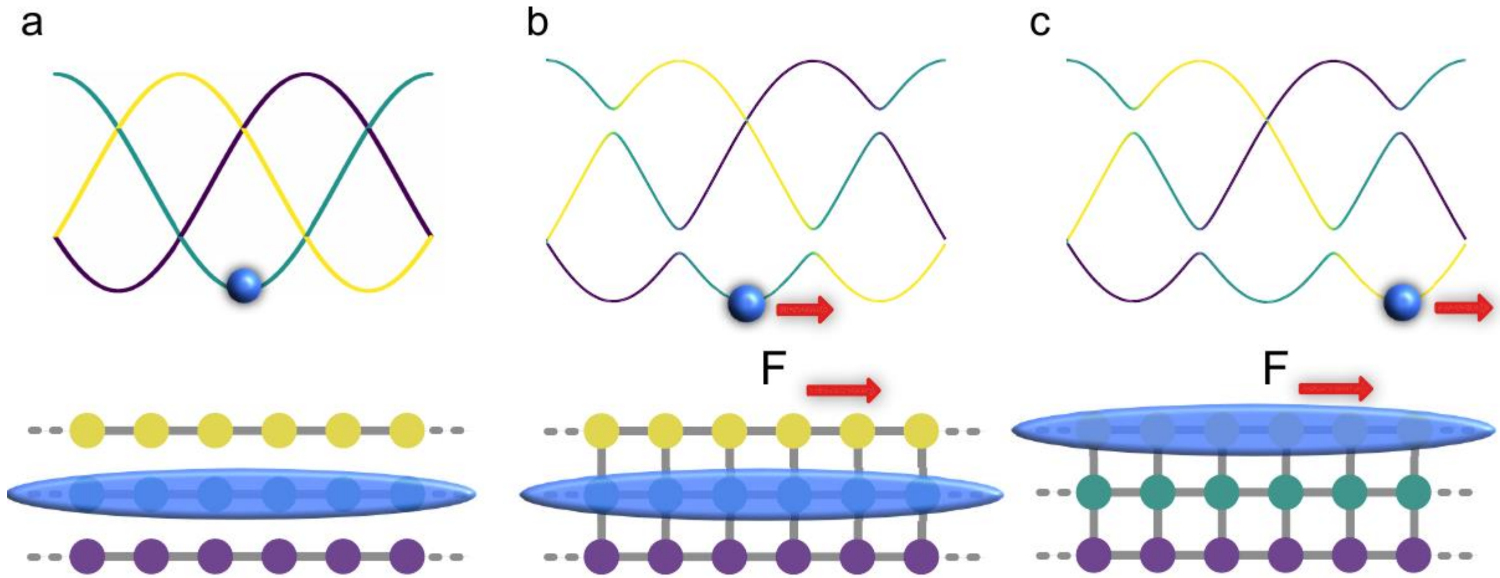
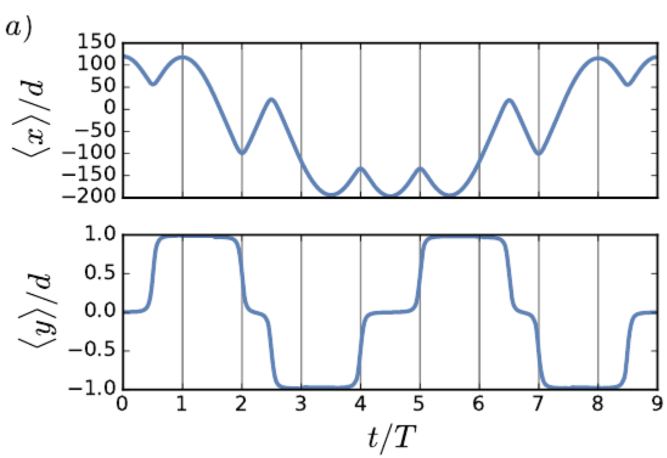
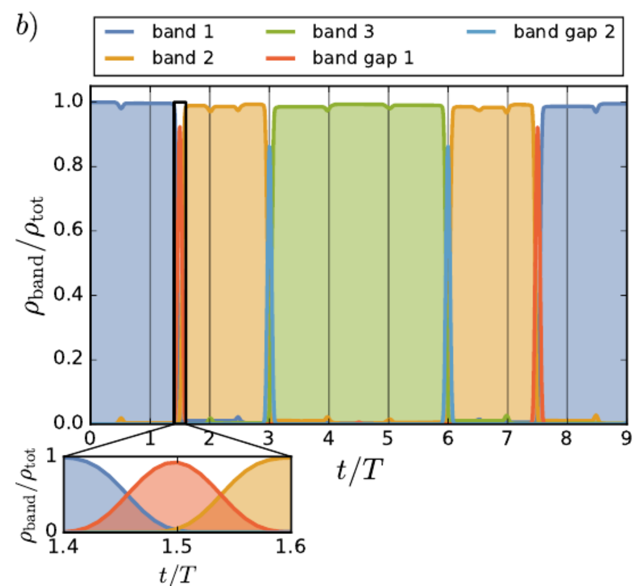


Results: $J_y = \frac{1}{5} J_x, \quad \Phi = \frac{2\pi}{3} \quad N_y = 3$





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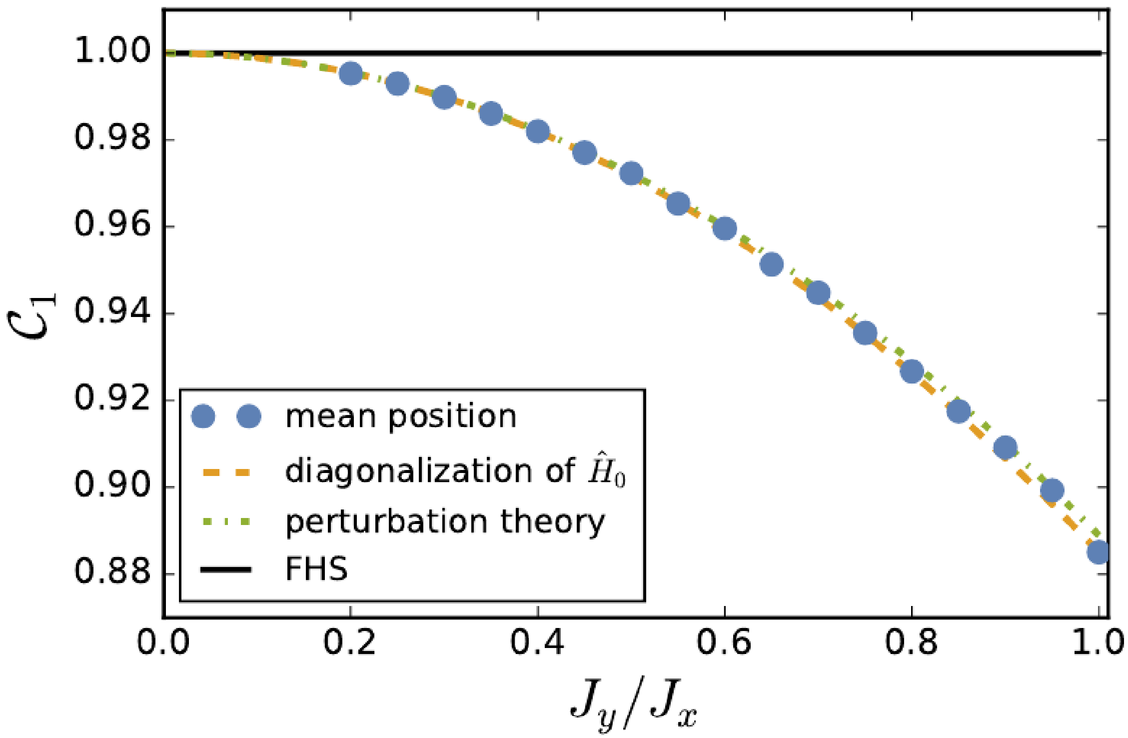
Why does it work? Perturbative argument as for the edge states:

- Gap linear in J_y/J_x
- Hybridization spin states (spreading in y) quadratic in J_y/J_x



Quadratic degradation of the measurement

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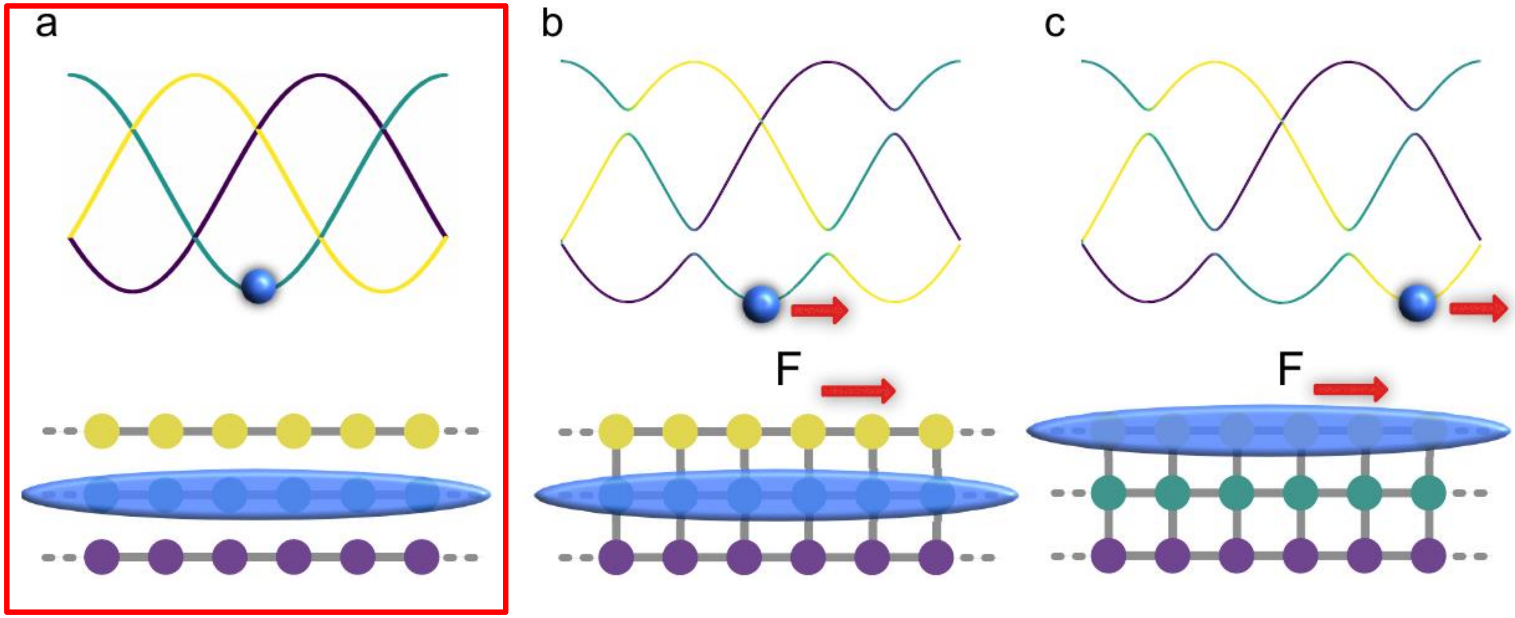

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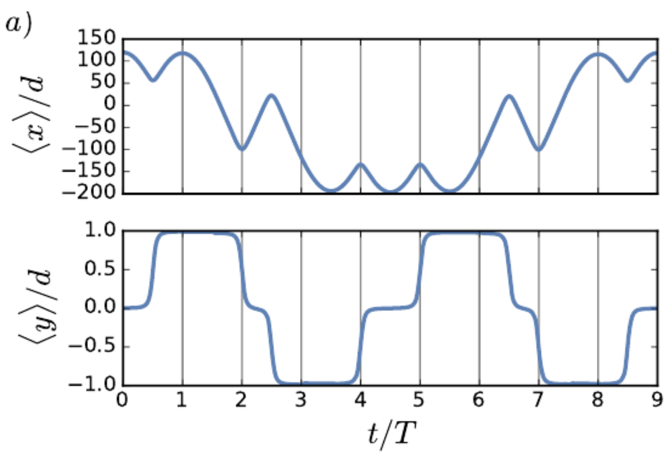

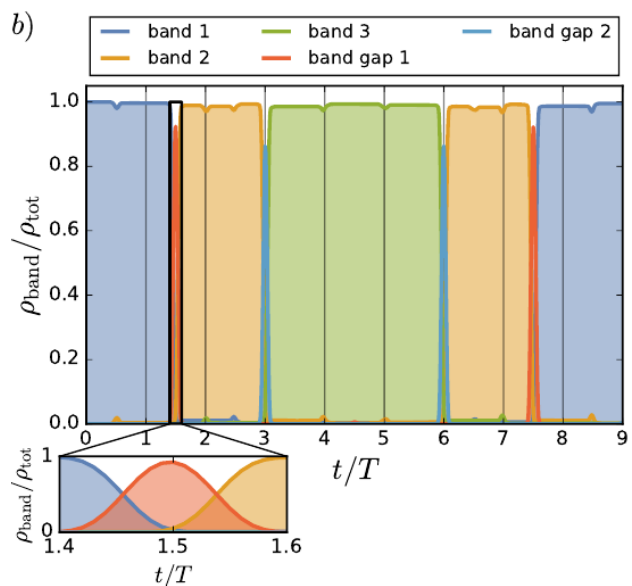

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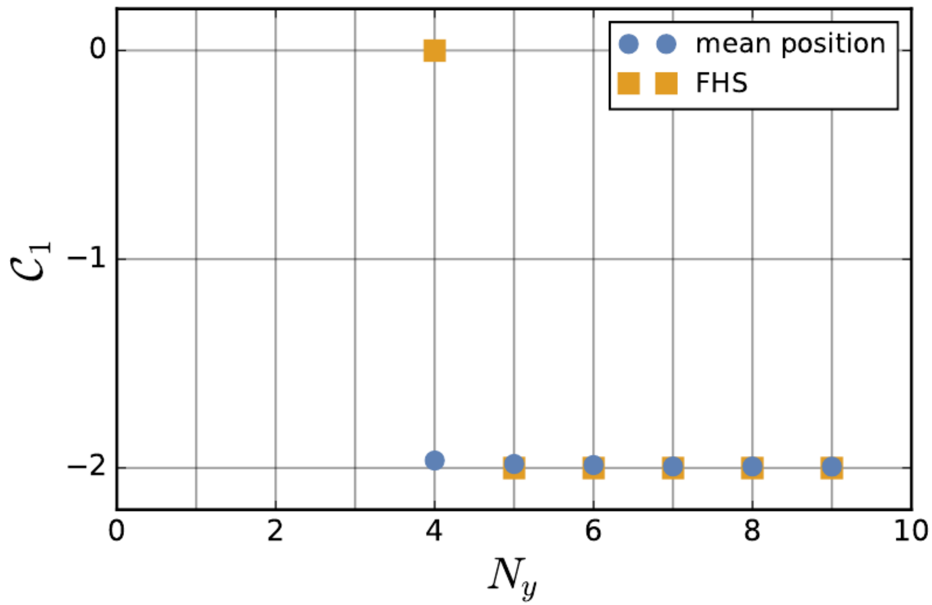
Higher $\mathcal{C}$ possible for $N_y \geq \mathcal{C} + 2$

Ex: $\Phi = \frac{4\pi}{5} \to \mathcal{C}_1 = -2$



"Better" than Fukui-Hatsugai-Suzuki algorithm J. Phys. Soc. Jpn. (2005)

Robust to disorder (< gap) and typical harmonic confinement

Interactions? Gap small (although may hold thought adiabatic argument, see later)

Synthetic lattices in interaction

- Interesting route to interaction -> Fractional QH effect?!
  -> many-body localization?!
  No heating expected

- Peculiarity: Interactions are naturally long range in the synthetic dimension

- Quasi 1D approach to 2D interesting both theoretically & practically

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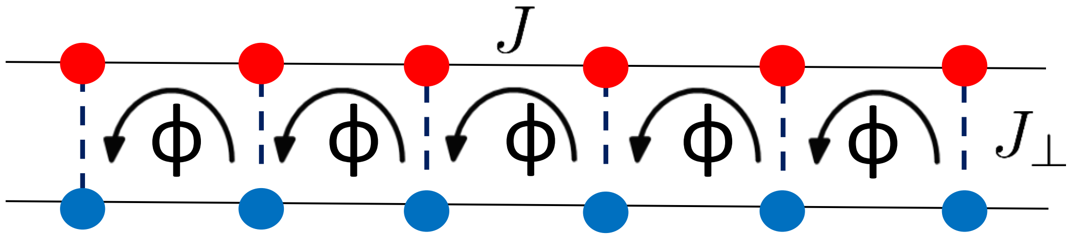
Many studies: Meissner-vortex and commensurable incommensurable transitions, Fractional pumping, Laughlin like states, pseudo Majorana…

Here: effect of dimerization on synthetic Hofstadter ladder

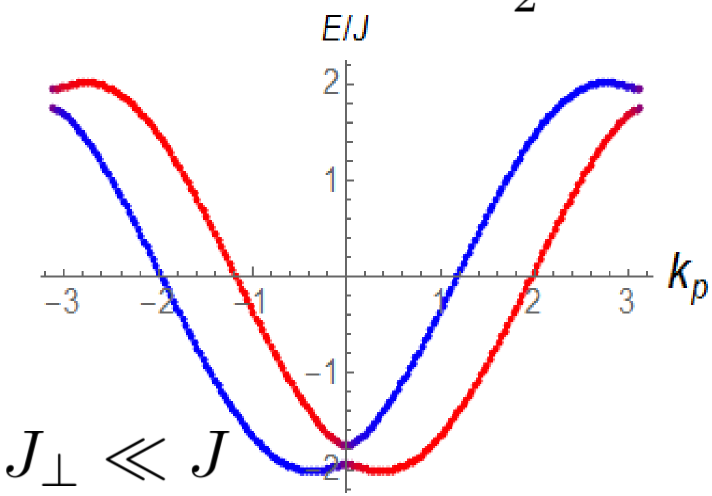
Meissner/Vortex phase in flux ladder



No interactions: real = synthetic ladder

Weak interleg (Raman) coupling:

2 minima, $k_m \sim \pm\frac{\phi}{2}$



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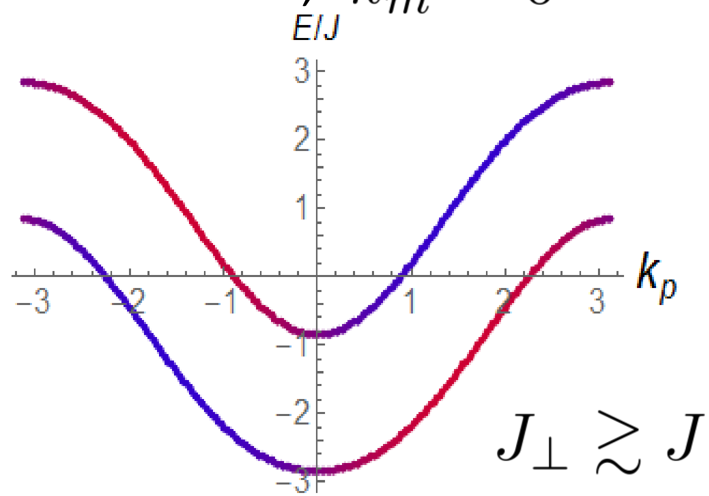

[Orignac,Giamarchi, PRB 2001] Analogous to type II, also in presence interactions

Real ladder experiment [Atala et, Nature Phys. 2014]

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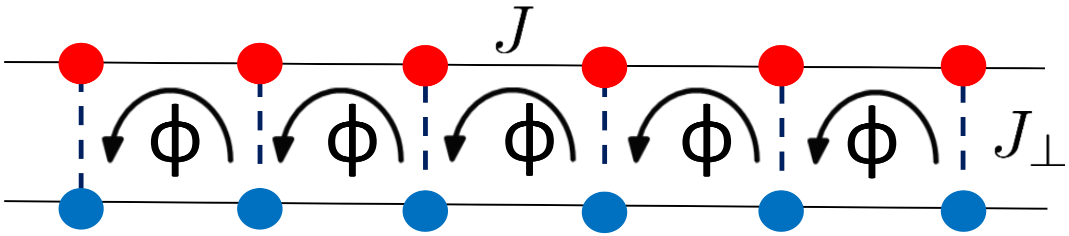

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Observables

$$J_c(j,m) = i\,\langle \hat{a}^\dagger_{j+1,m}\hat{a}_{j,m}\rangle + H.c.$$

$$J_\perp(j) = i\,\langle \hat{a}^\dagger_{j,1/2}\hat{a}_{j,-1/2}\rangle + H.c.$$

$J_\perp \ll J$

$J_\perp \gtrsim J$

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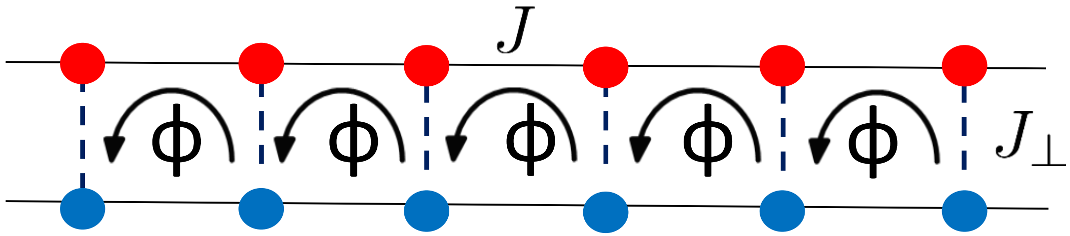

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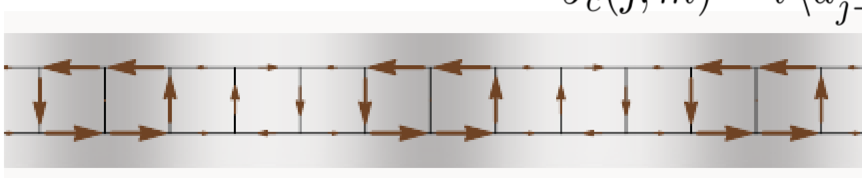

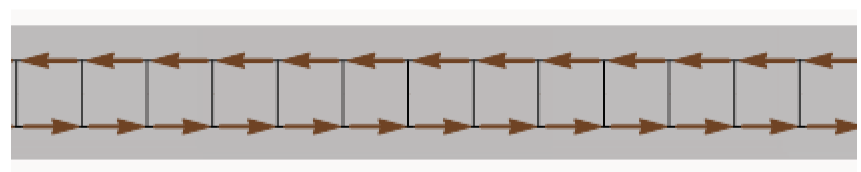

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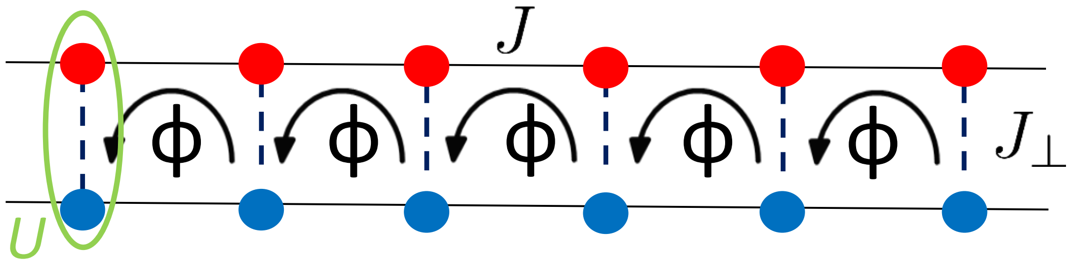


Effect of interactions: suppress vortex phase

Real ladder: vortex phase survives in the hard-core limit for ϕ large

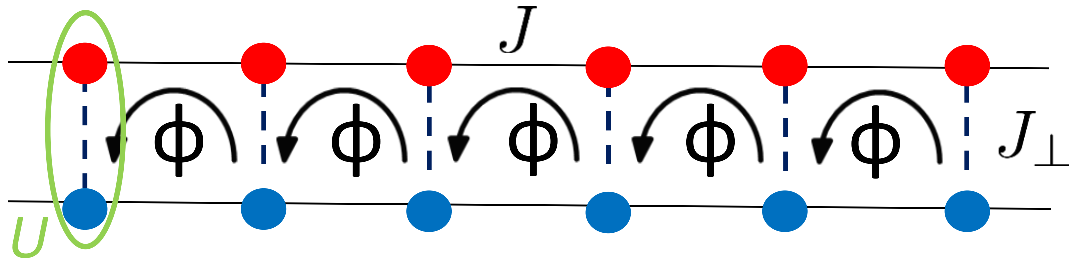
more phases at $U \neq \infty$

see [Petrescu, Le Hur,PRL 2013]
[Piraud et al, PRB 2015]

Synthetic ladder: vortex phase disappears in the hard-core limit

more phases at $U \neq \infty$ ....

Meissner/Vortex phase in flux ladder



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Synthetic ladder: vortex phase disappears in the hard-core limit

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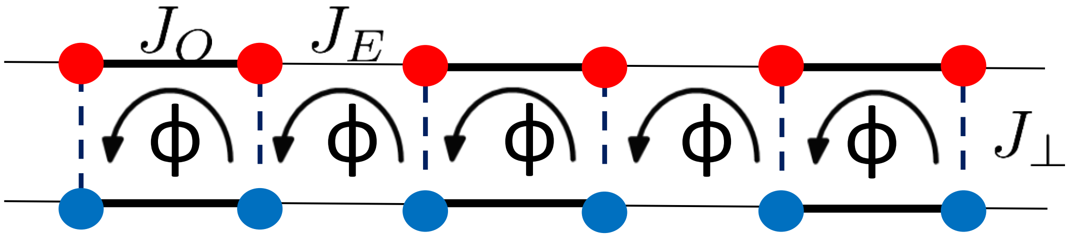
Idea: enhance vortex phase by dimerizing the lattice (“easy” exp. handle)

Vortex Nesting and Melting in synthetic ladders, E. Tirrito, R. Citro, M. Lewenstein, AC *in progress*

$J = \frac{J_O + J_E}{2}$



Effect of dimerization: new handle $\Delta = \frac{J_O - J_E}{J_O + J_E}$

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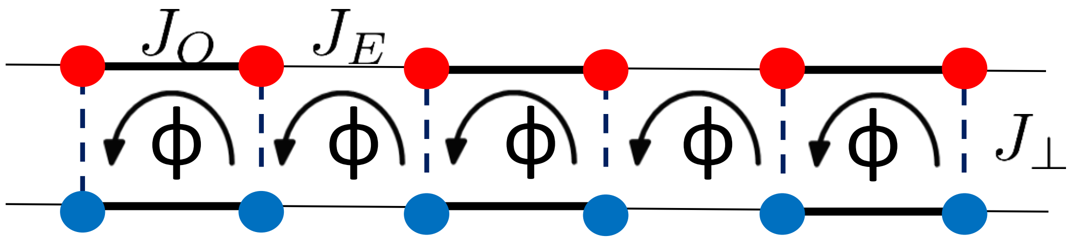
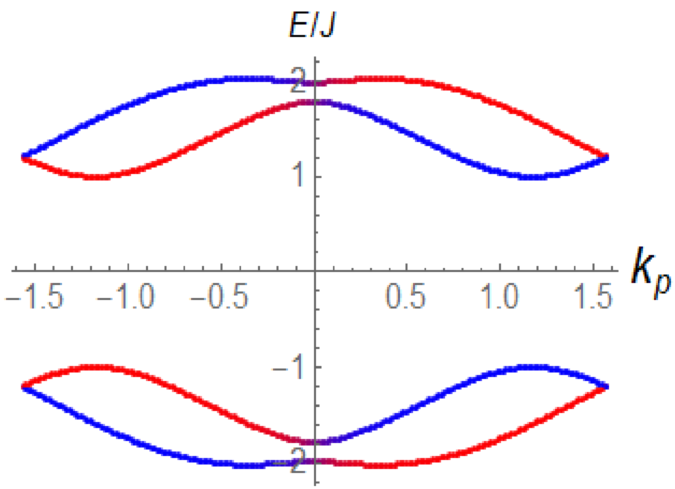


Effect of dimerization: new handle $\Delta = \frac{J_O - J_E}{J_O + J_E}$

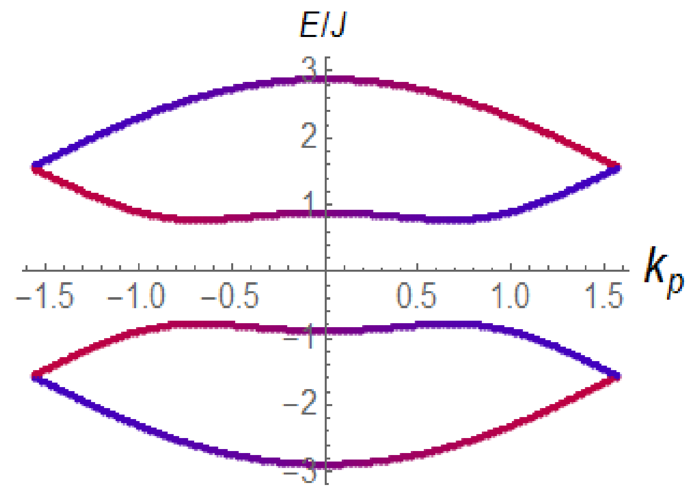
No interactions: 4 bands



$J_\perp \ll J$

$\Delta = 0.5$

Bands deform & mix



$J_\perp \gtrsim J$

Minima separate: dimerization enhances vortex phase!

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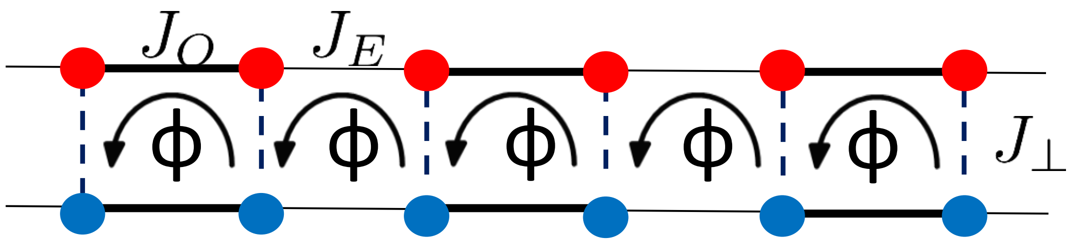
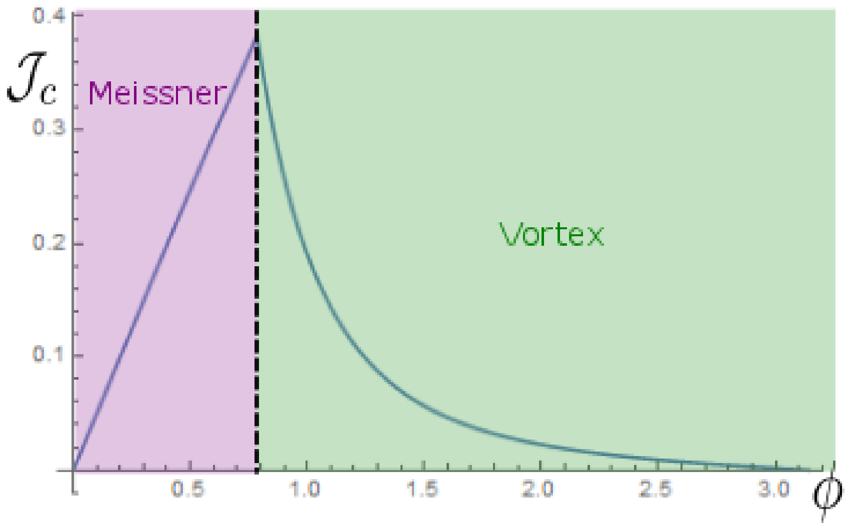
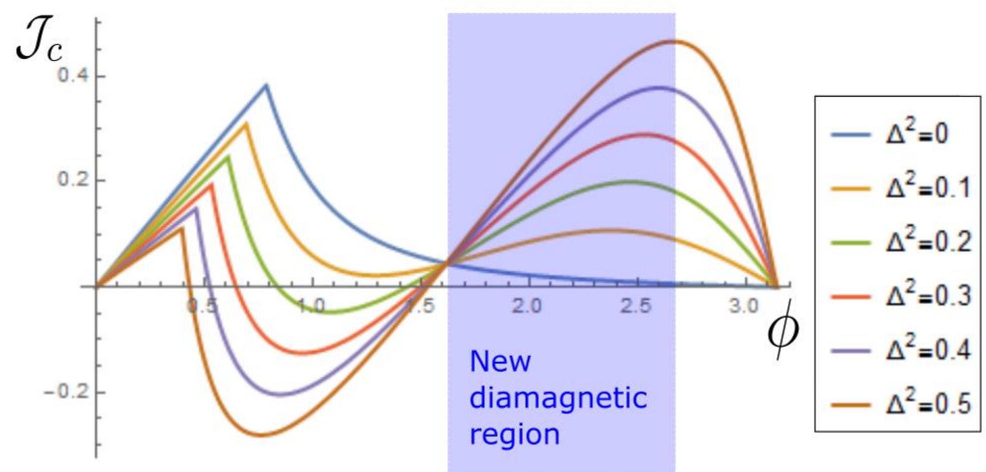


Effect of dimerization: new handle $\Delta = \frac{J_O - J_E}{J_O + J_E}$

No interactions: Reverse of chiral current



$\Delta = 0$

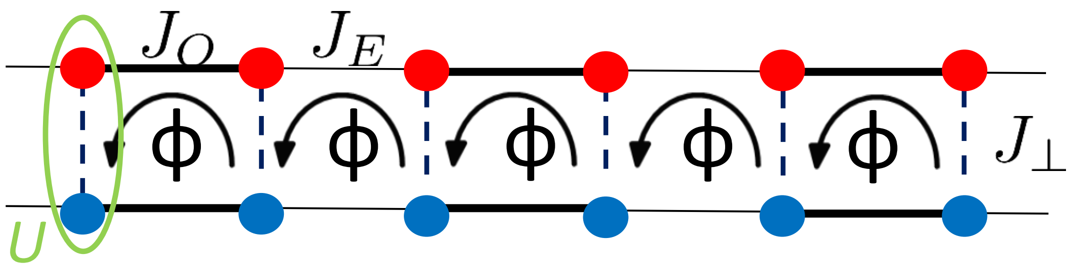


$\Delta \neq 0$

Current behavior confirms vortex enhancement!

Vortex Nesting and Melting in synthetic ladders, E. Tirrito, R. Citro, M. Lewenstein, AC *in progress*

$J = \frac{J_O + J_E}{2}$



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Interactions: $U \to \infty$ 3 states per rung

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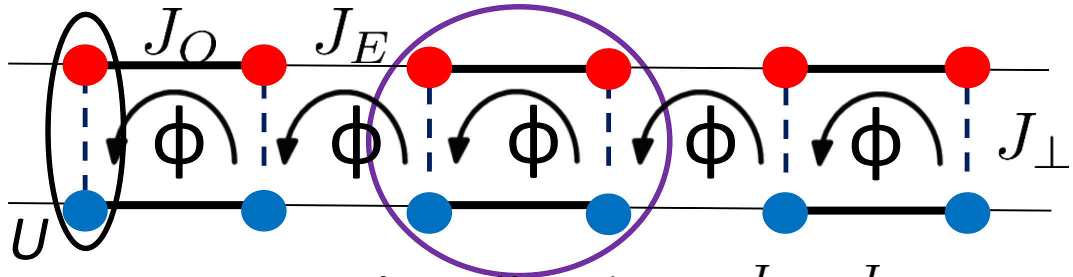

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Interactions: $U \to \infty$ 3 states per rung

$J_E \ll J_O$ 9 states per plaquette

	1 *n=0,*	4 *n=1,*	4 *n=2*
Spectrum plaquette	0	$\pm J_\perp \sqrt{1 + \left(\frac{J_O}{J_\perp}\right)^2 - 2\cos\frac{\phi}{2}\left(\frac{J_O}{J_\perp}\right)}$	$\pm 2J_\perp$
		$\pm J_\perp \sqrt{1 + \left(\frac{J_O}{J_\perp}\right)^2 + 2\cos\frac{\phi}{2}\left(\frac{J_O}{J_\perp}\right)}$	± 0

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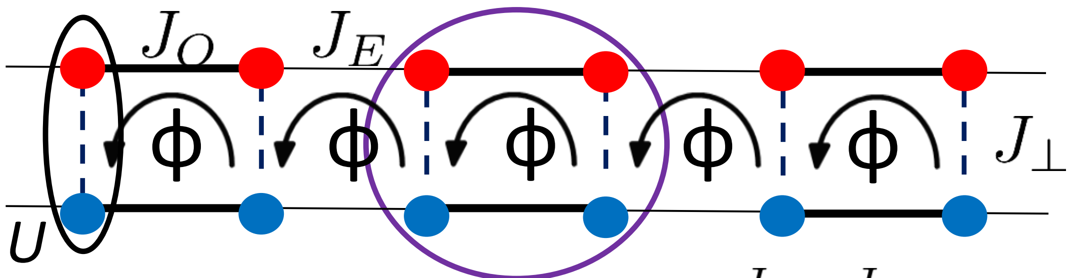

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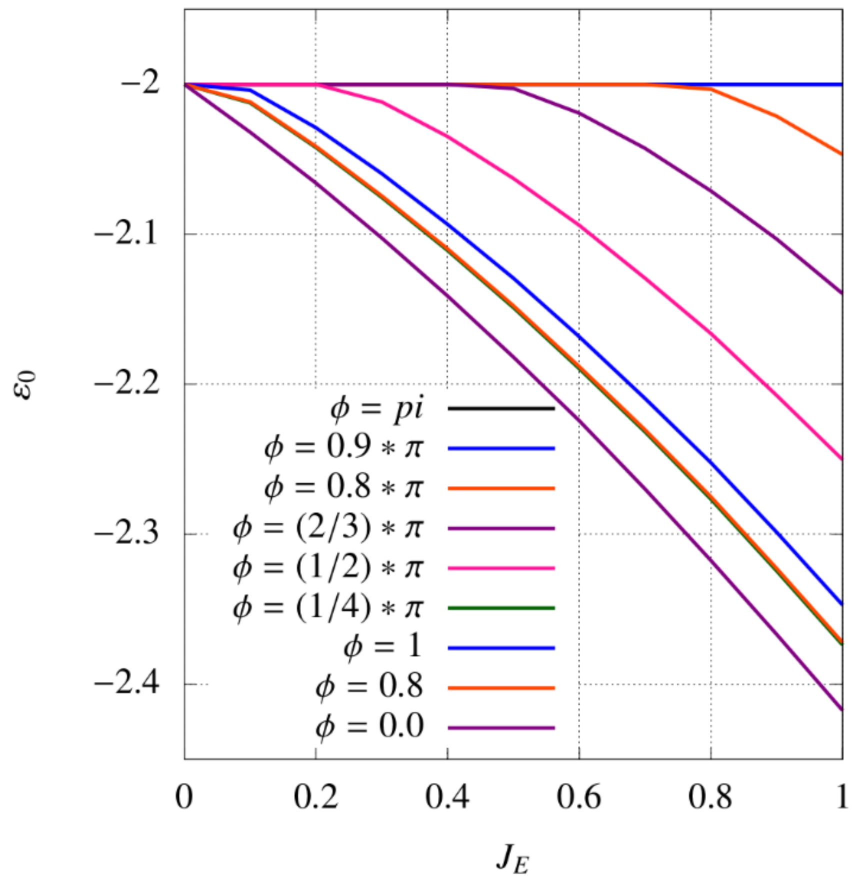
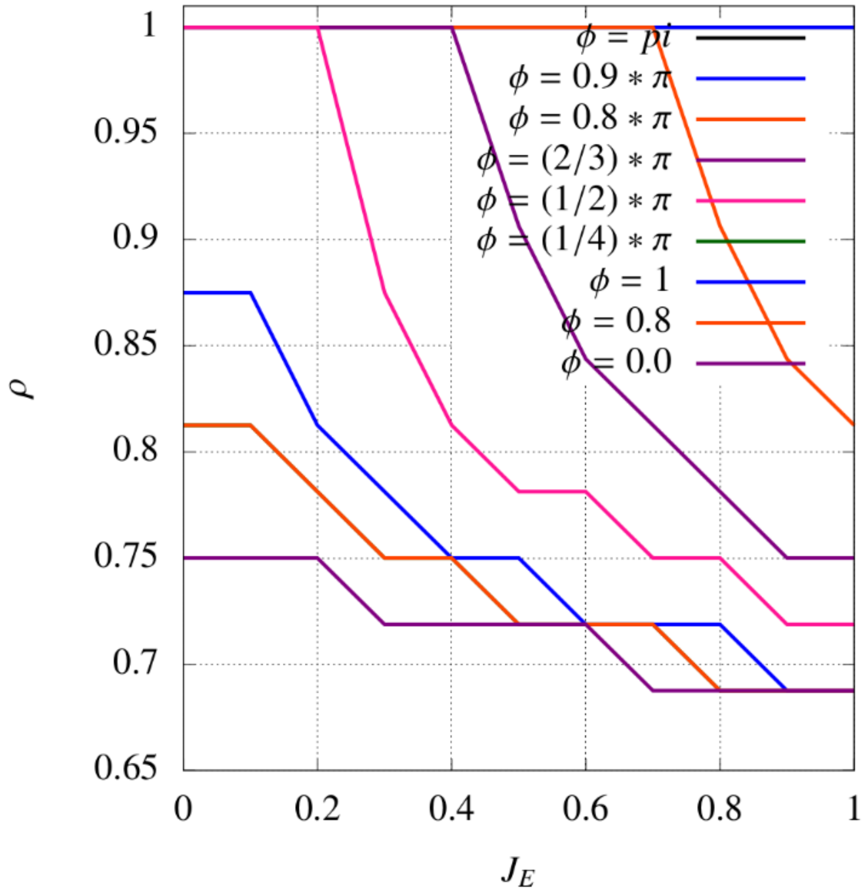
$J_\perp \gtrsim J_O$ Plaquette in *n=2* $\longrightarrow$ Band insulator

$J_\perp < J_O$ Plaquette in *n=1* $\longrightarrow$ Imprinted vortex

Vortex Nesting and Melting in synthetic ladders, E. Tirrito, R. Citro, M. Lewenstein, AC *in progress*

DMRG calculations confirm perturbative expectations Ex. $J_{\perp} = J_O = 1$

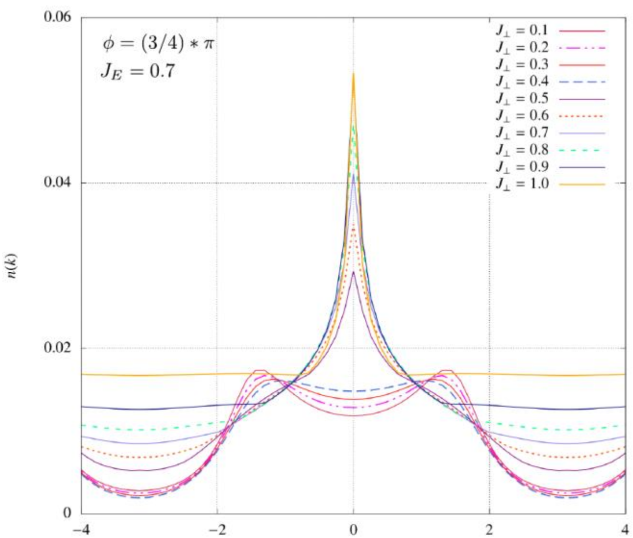


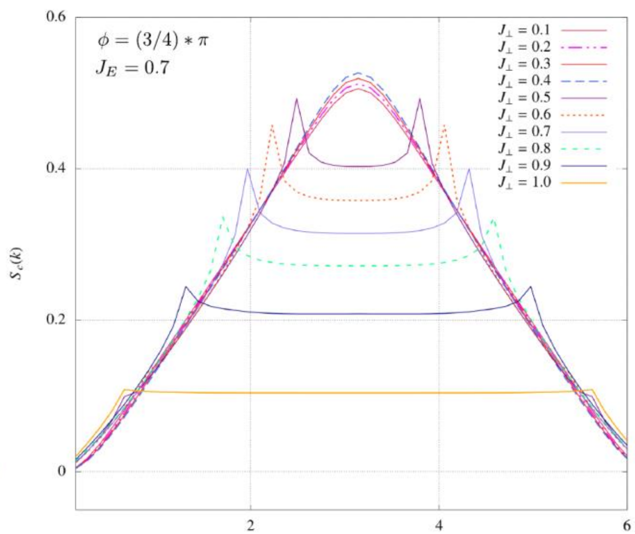


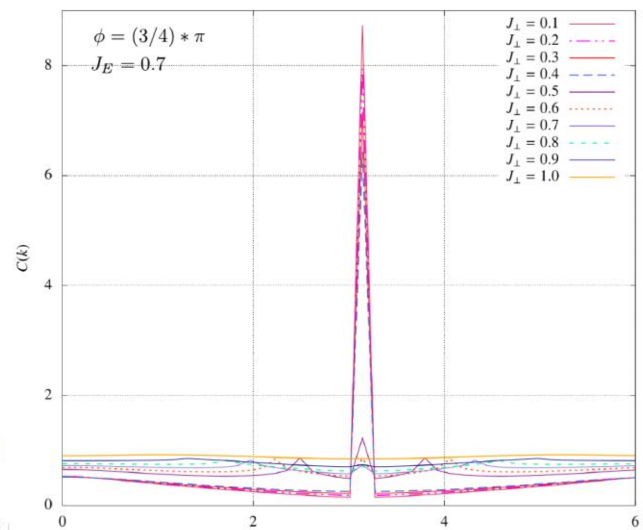
Phase diagram through calculation of currents and structure factors

Vortex Nesting and Melting in synthetic ladders, E. Tirrito, R. Citro, M. Lewenstein, AC *in progress*

Ex. $\phi = 3\pi/4$







$0 \longrightarrow J_E \longrightarrow J_O$

Imprinted vortex → Melted vortex → Meissner charge density wave → Meissner

Similar to attractive interleg interaction, [Orignac et al, PRB 96, 014518 (2017)]

Evidence of commensurate-incommensurate transition

Further steps

- No hard-core boson limit: bosons different fermions

- Study the accessible experimental parameters

- Search for “visible” Laughlin-like states in such regimes

  cf. [Calvanese et al, PRX 7, 021033 (2017)],[Petrescu et al, PRB 96, 014524 (2017)]

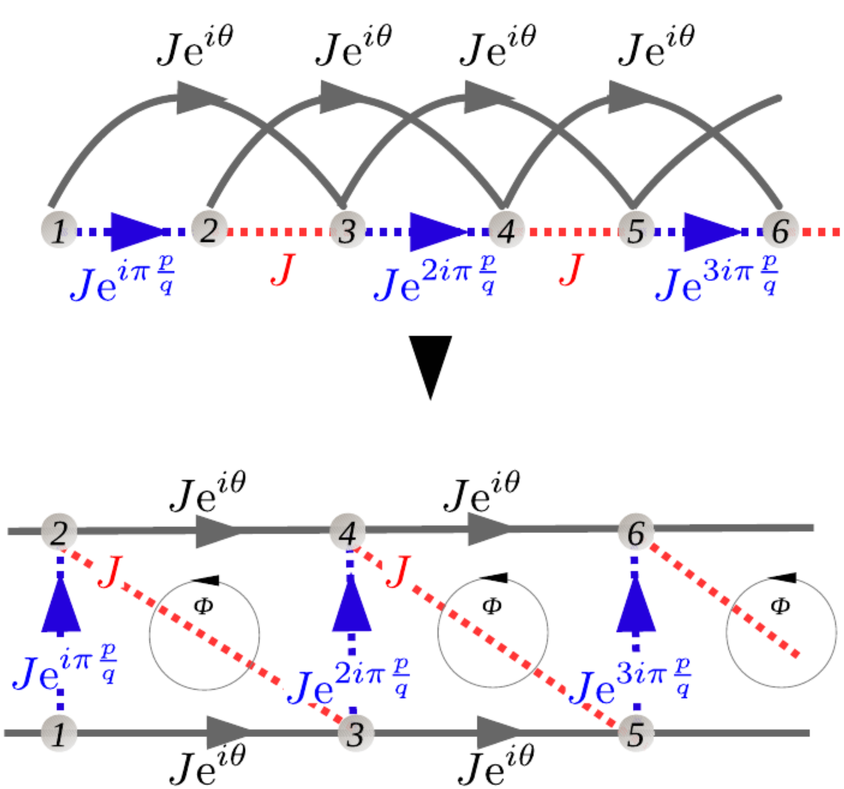
- *…Toy model for many-body localization?*

Alternative route to synthetic interacting ladders… long range interactions!

PHYSICAL REVIEW A **91**, 063612 (2015)

Synthetic magnetic fluxes and topological order in one-dimensional spin systems

Tobias Graß,[1] Christine Muschik,[1,2,3] Alessio Celi,[1] Ravindra W. Chhajlany,[1,4] and Maciej Lewenstein[1,5]
[1]*ICFO-Institut de Ciències Fotòniques, Av. Carl Friedrich Gauss 3, 08860 Barcelona, Spain*



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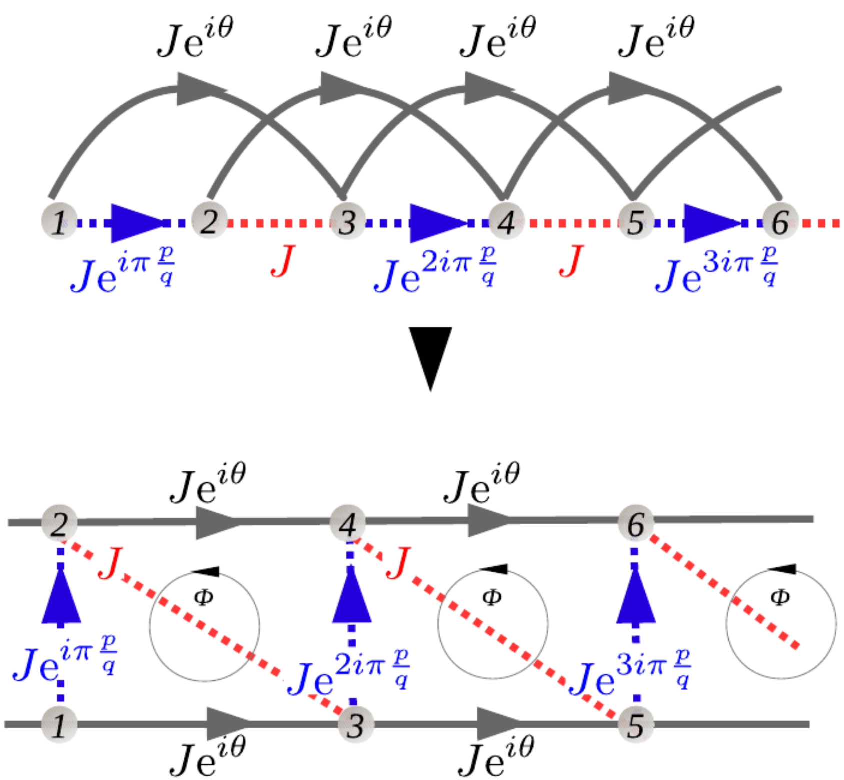
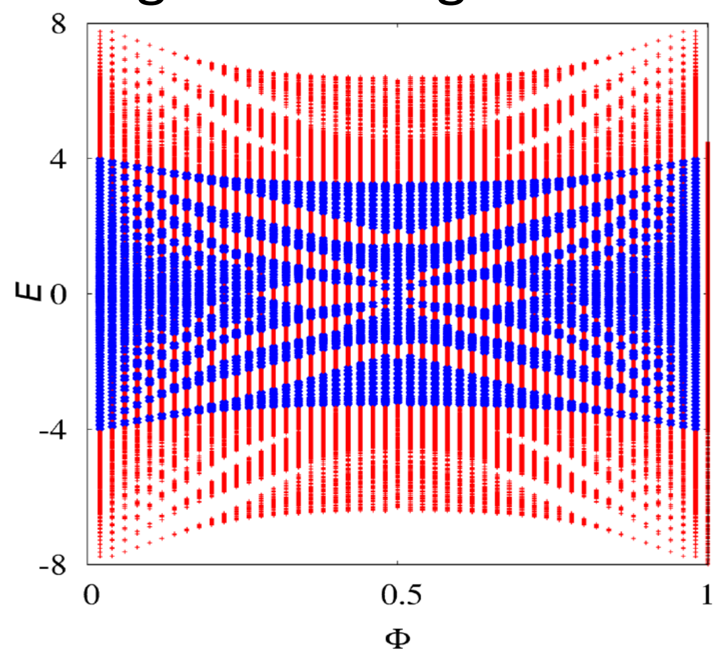


How? E.g. ion analogue simulation

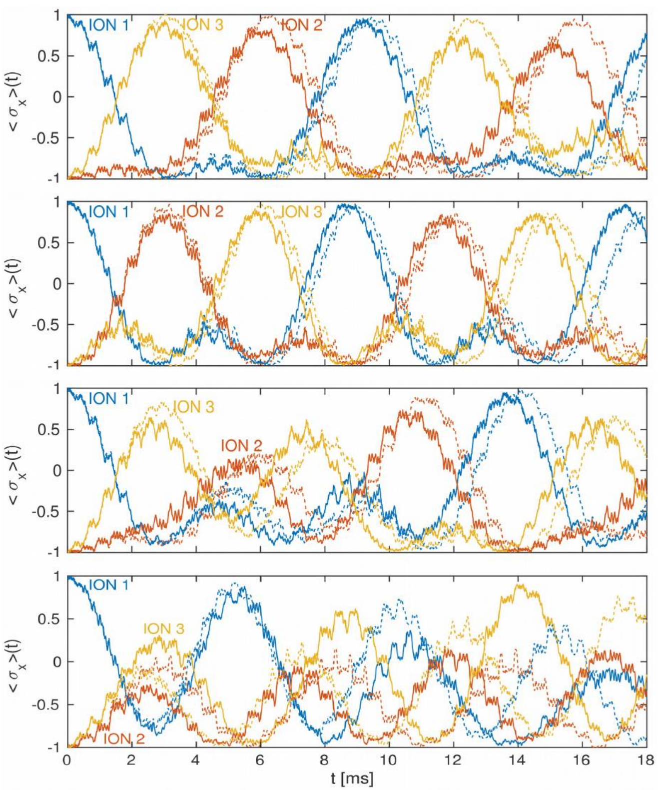


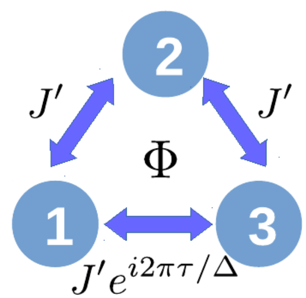
Alternative route to synthetic interacting ladders… long range interactions!

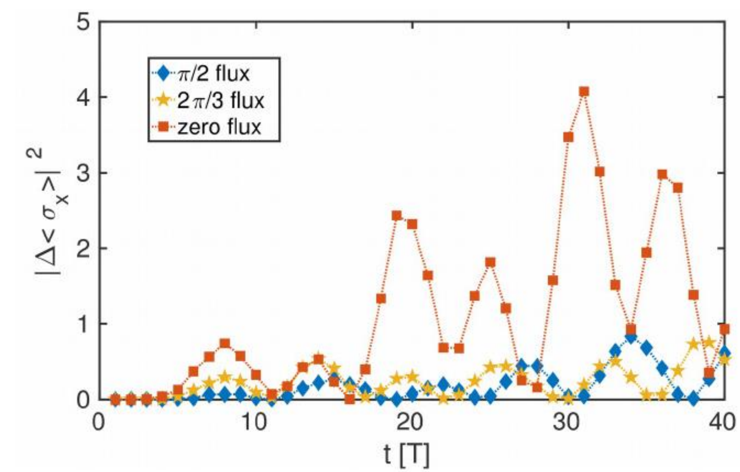
Driven Dicke model with "fluxes" seems robust to photon heating!

$$H_0(t) = \sum_m \hbar\omega_m a_m^\dagger a_m + \sum_{i,m} \hbar\Omega_i \eta_{i,m}(a_m + a_m^\dagger)\sigma_i^x \sin(\omega t) + \sum_i B_i(t)\sigma_i^z$$

Special instance: Triangle! [T. Grass,AC,G. Pagano,M. Lewenstein, arXiv:1708.01882]







Deviation from the effective spin model are suppressed also for strong driving in presence of fluxes! *Topological protection?*

Summary

- Synthetic edge state in synthetic Hofstadter strips
- “Bulk topology” in synthetic Hofstadter strips
- Effect of dimerization in synthetic Hofstadter ladder w/o interactions
- Synthetic fluxes in driven ion chain

A bit of philosophy…

Synthetic lattices: practical tool for reshaping degrees of freedom in experimentally convenient way…

Same Hamiltonian = Same model

Useful approach for questioning conventions, ease detection, suggest new models…

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Synthetic lattices: practical tool for reshaping degrees of freedom in experimentally convenient way…

Same Hamiltonian = Same model

Useful approach for questioning conventions, ease detection, suggest new models…

Pushing it further…

Same time evolution = Same model

Synthetic lattices naturally combine with the Floquet approach…

Realization of quantum simulation paradigm

“Extradimensional” collaborators


J.I. Latorre


O. Boada


M. Lewenstein

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T. Grass

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