CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

INSTITUTO DE CIENCIA DE MATERIALES DE MADRID (ICMM)

Dynamics of interacting electrons in ac-driven dimer chains

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Mainz July 2017

ICMM

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OUTLINE

Motivation:

Quantum Transfer between distant sites at the nanoscale: Long range electron transport in quantum dot arrays

ac-driven systems

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Dynamics of interacting electrons (Doublons) in dimer chains: interplay between interaction, topology and driving.

Doublon dynamics in 2D lattices

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Doublon dynamics in 2D lattices

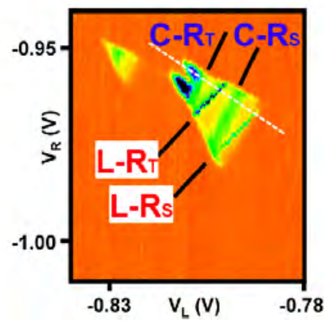
Electron transport in a dimer chain: edge state current blockade

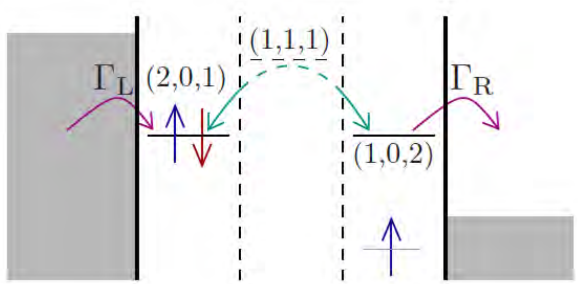
Transport statistics: current and shot noise in ac driven dimer chains

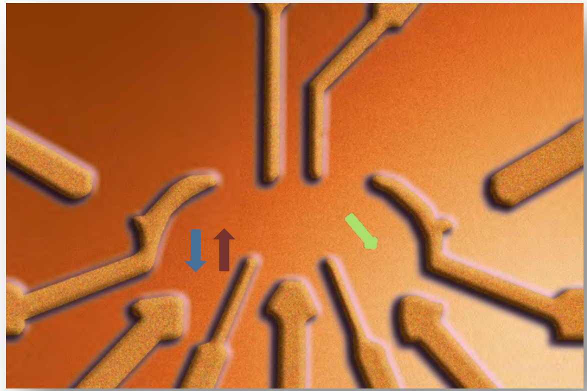
Long range quantum transfer in TQDs

L-R resonance of (2,0,1) and (1,0,2)

intermediate (1,1,1) far in energy





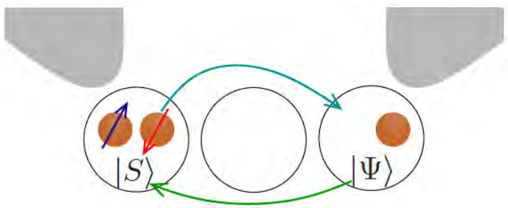


$$\Delta E \gg \tau$$

$$|LR_-\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow,0,\psi\rangle - |\psi,0,\uparrow\downarrow\rangle\right)$$

As an electron tunnels from one extreme to the other an arbitrary spin state ψ is transferred in the opposite direction:

$$|\psi\rangle_{l=L,R} = c_\uparrow|\uparrow\rangle_l + c_\downarrow|\downarrow\rangle_l$$



M. Busl et al.,Nature Nanotech, 8, 262 (2013)

R. Sánchez et al., PRL, 112, 176803 (2014)

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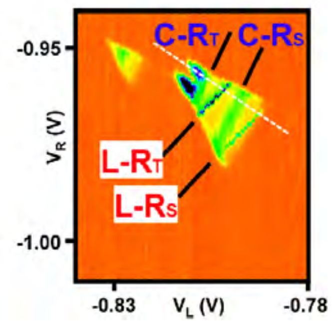

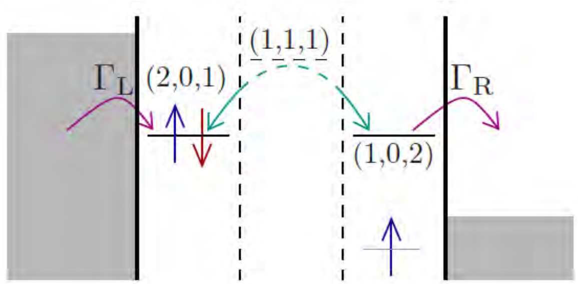

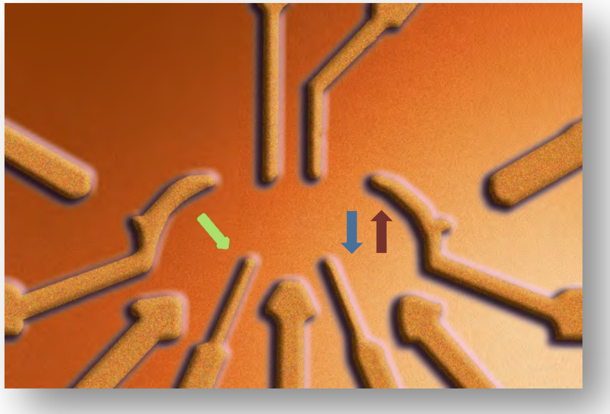

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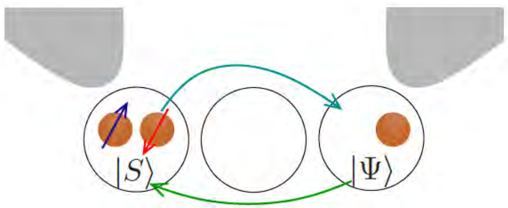

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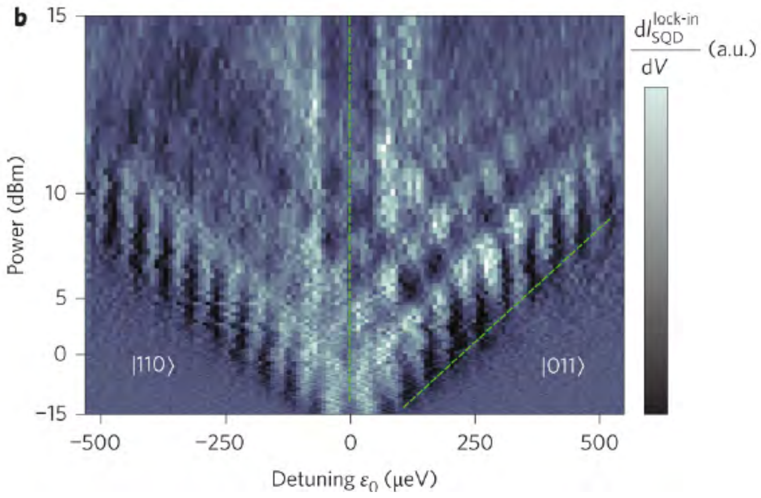
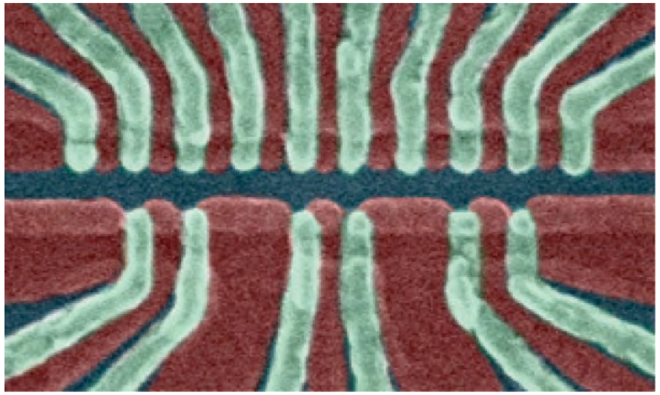


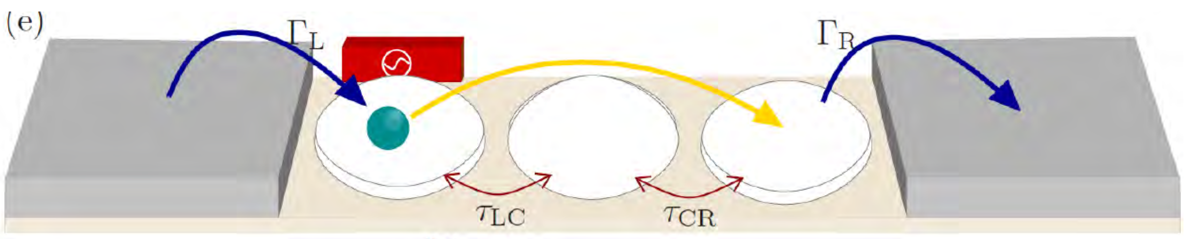
F.R. Braakman et al, Nature Nanotech, 8, 432 (2013)

9 QDs in Si/Ge heterostructure



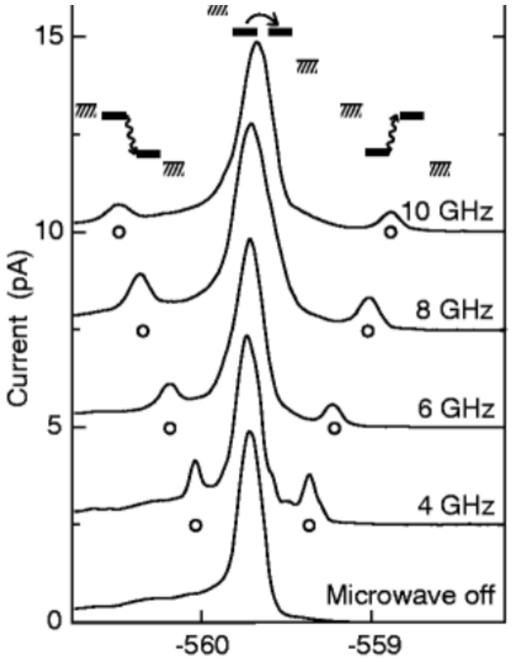
PHYSICAL REVIEW APPLIED 6, 054013 (2016)

J. Petta



Driving with periodic AC electric fields

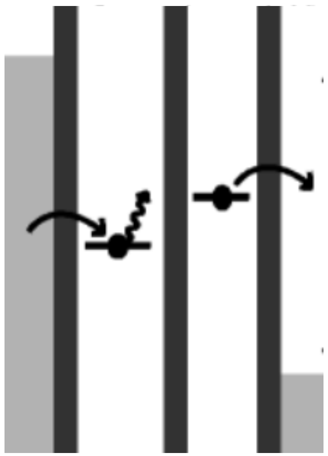
Photoassisted Tunneling (PAT) in quantum dots



Coherent destruction of tunnel
P. Hänggi, PRL, 1991

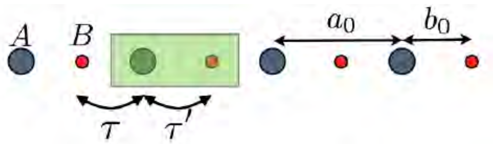
↓

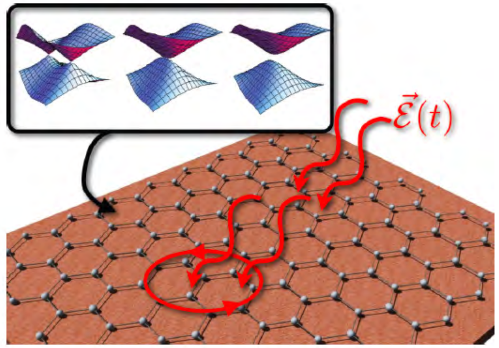
Bonds renormalization



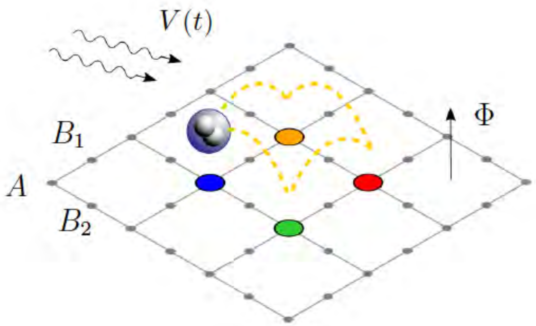
T. H. Oosterkamp
et al., Nature 395, 873-876, 1998

Floquet-Bloch Theory and Topology in Periodically Driven Lattices,
A. Gómez-León and G. P. , PRL, 110,200403 (2013)





P. Delplace, A. Gómez-León and G. P., PRB, 88,245 (2013)



M. Bello,
C.E. Creffield ,
G.P., PRB 2017

Floquet Theory

Analog to Bloch theory, but in time: time periodic hamiltonians $H(t) = H(t+T)$

Solutions: $\left|\Psi_\alpha(t)\right\rangle = e^{-i\varepsilon_\alpha t}\left|u_\alpha(t)\right\rangle$

Floquet States: $\left|u_\alpha(t+T)\right\rangle = \left|u_\alpha(t)\right\rangle$

Quasi-energies: $\varepsilon_\alpha \in [-\omega/2, \omega/2]$

Floquet Equation: $\boldsymbol{H}(t)\left|u_\alpha\right\rangle = \varepsilon_\alpha\left|u_\alpha\right\rangle$ where $\boldsymbol{H}(t) = H(t) - i\partial_t$

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Floquet-Bloch Theory

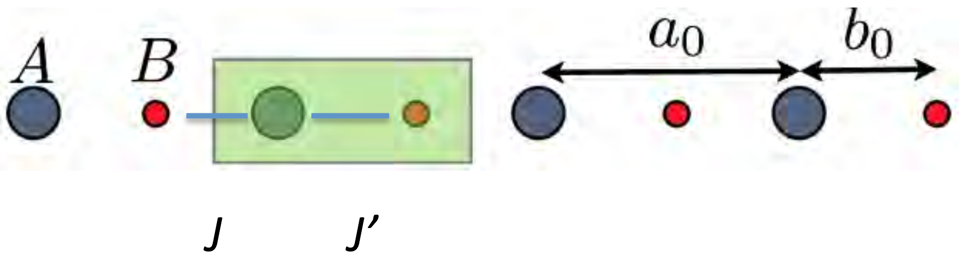
$$H(x+a_i, t+T) = H(x+a_i, t) = H(x, t+T)$$

Solutions in the Floquet-Bloch form: $\left|\Psi_{\alpha,k}(x,t)\right\rangle = e^{ikx - i\varepsilon_{\alpha,k}t}\left|u_{\alpha,k}(x,t)\right\rangle$

$\boldsymbol{H}(k,t)\left|u_{\alpha,k}\right\rangle = \varepsilon_{\alpha,k}\left|u_{\alpha,k}\right\rangle$ $\qquad$ $\boldsymbol{H}(k,t) = e^{-ikx}\left(H(t) - i\partial_t\right)e^{ikx} = H(k,t) - i\partial_t$

Peierls substitution $k \to K(t) = k + A(t)$

Finite dimer chains: role of edge states in the charge dynamics



$$H = -J' \sum_{i=1,\sigma}^{M} c_{2i\sigma}^{\dagger} c_{2i-1\sigma} - J \sum_{i=1,\sigma}^{M-1} c_{2i+1\sigma}^{\dagger} c_{2i\sigma} + H.c.$$

Su-Schrieffer-Heeger Model (SSH)

W. P. Su, J. R. Schrieffer, and A. J. Heeger, Phys. Rev. Lett. 42,1698 (1979).

nature physics

ARTICLES

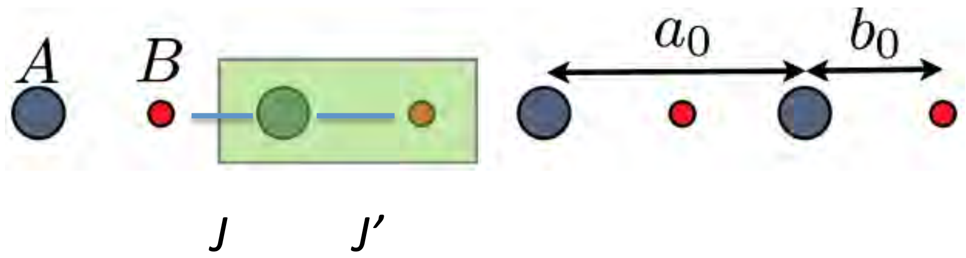
PUBLISHED ONLINE: 3 NOVEMBER 2013 | DOI: 10.1038/NPHYS2790

M.Atala et al. 2013

Direct measurement of the Zak phase in topological Bloch bands

Ramsey interferometry combined with coherent Bloch oscillations

Finite dimer chains: role of edge states in the charge dynamics



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Su-Schrieffer-Heeger Model (SSH)

Topological invariant in 1 D: The Zak phase

$$Z = \oint \langle u_{\alpha,\kappa} | i\partial_k | u_{\alpha,\kappa} \rangle dk$$

Zak phase : the Berry's phase picked up by a particle moving accross the Brillouin zone.
It characterizes the topological properties of 1D solids.

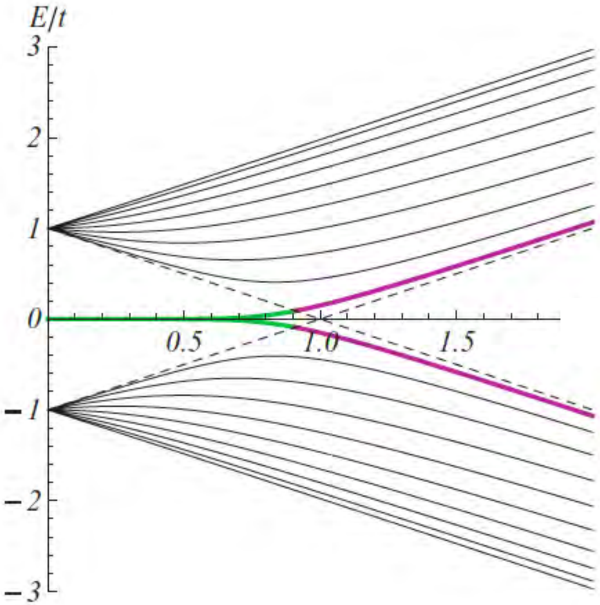
$Z = 0$ Trivial phase

$\frac{J'}{J} > 1$

$Z = \pi$ Non trivial topological phase: edge states

$\frac{J'}{J} < 1$

Finite system



$$\left(\frac{J'}{J}\right)_C = 1 - \frac{1}{M+1}$$

$N_{bulk} = 2M$ J'/J>(J'/J)$_c$

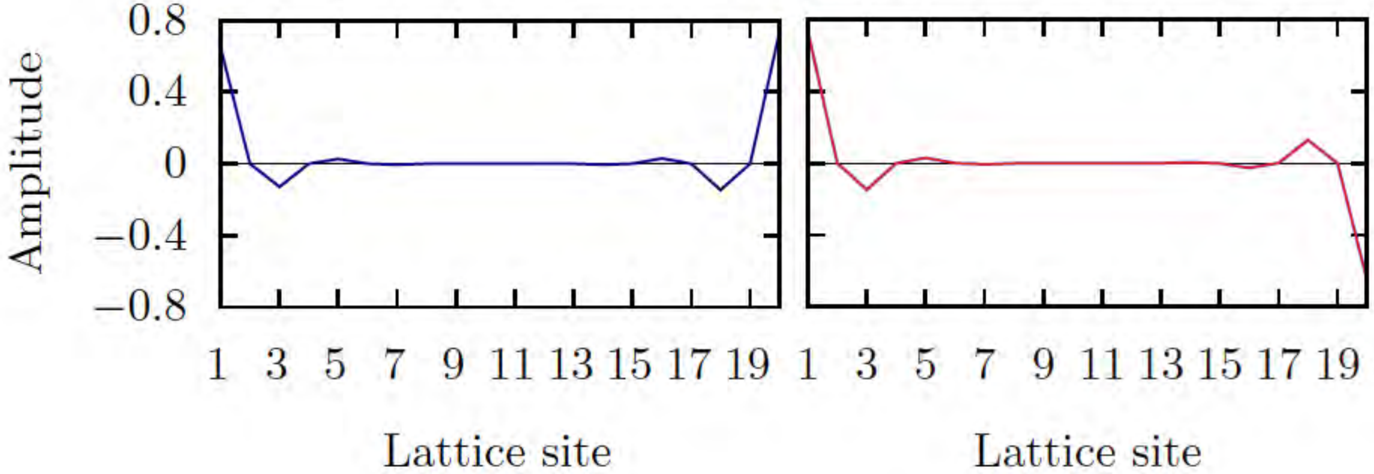
$N_{bulk} = 2(M-1)$ J'/J<(J'/J)$_c$

P. Delplace et al. PRB, 84, 195452

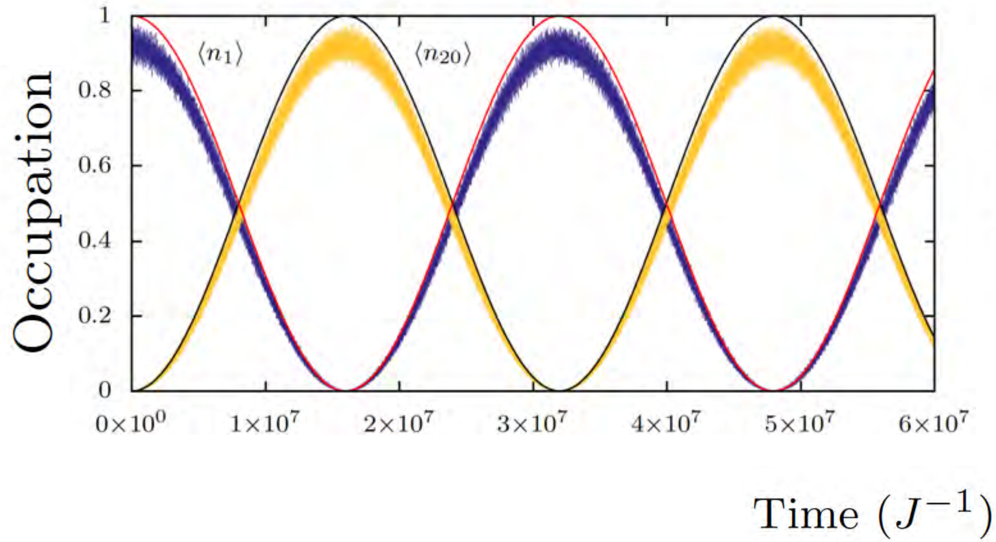
$$\lambda = \frac{J'}{J}$$

$$\frac{J'}{J}$$

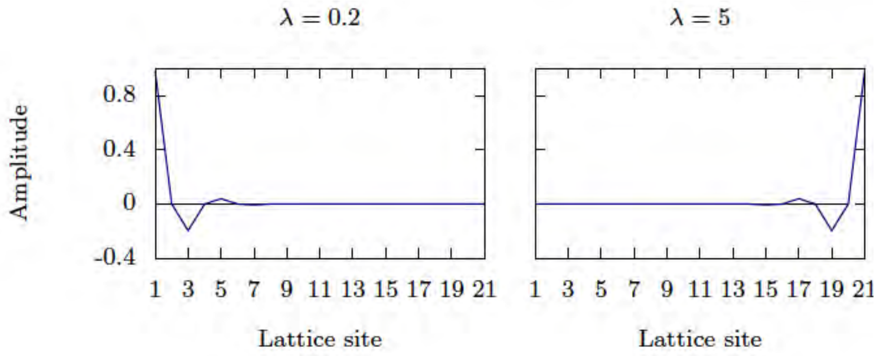
Edge states form a non-local two-level system.
Long-range transfer



$$|1\rangle \simeq \frac{1}{\sqrt{2}}(|e_+\rangle + |e_-\rangle), \quad |N\rangle \simeq \frac{1}{\sqrt{2}}(|e_+\rangle - |e_-\rangle)$$



Odd number of sites



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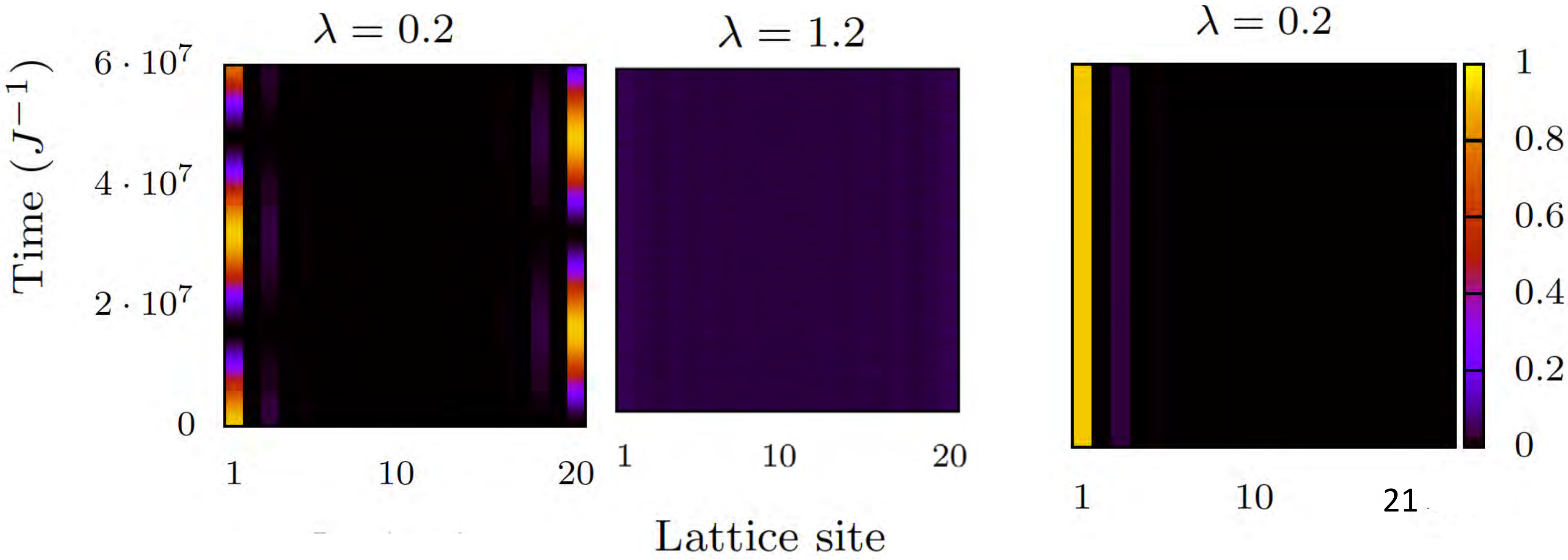
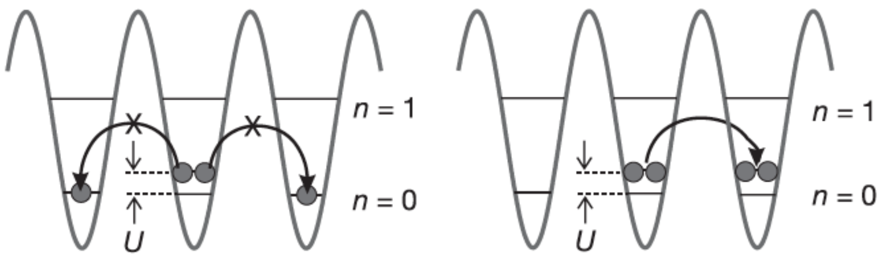


Transfer of interacting electrons in a dimer chain

Repulsively bound atom pairs in an optical lattice

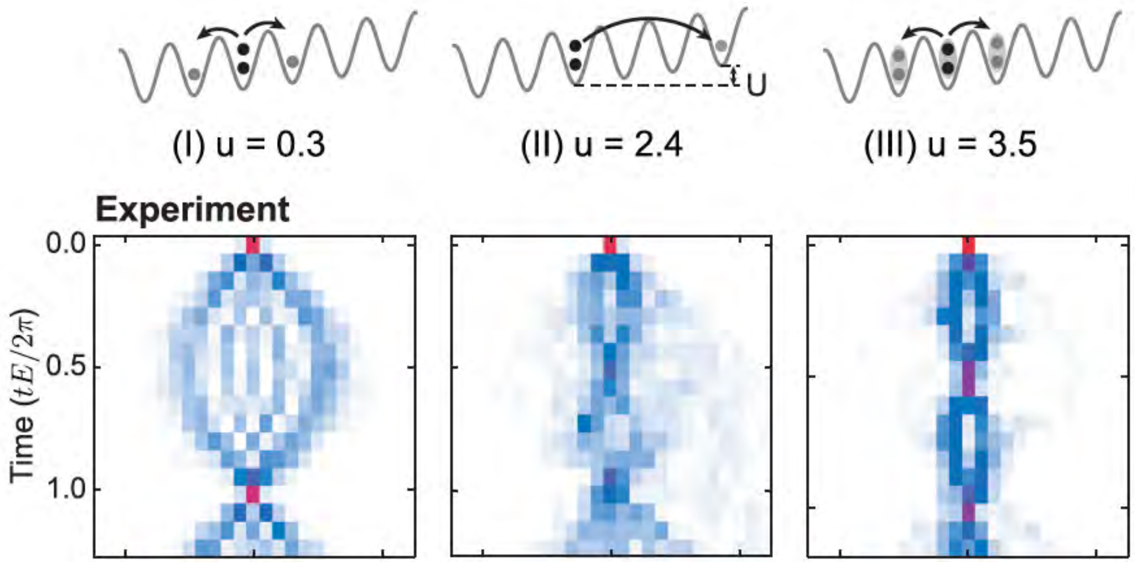


Vol 441|15 June 2006|**doi:10.1038/nature04918**

K. Wrinkler et al.

Strongly correlated quantum walks in optical lattices

Philipp M. Preiss,[1] Ruichao Ma,[1] M. Eric Tai,[1] Alexander Lukin,[1] Matthew Rispoli,[1] Philip Zupancic,[1*] Yoav Lahini,[2] Rajibul Islam,[1] Markus Greiner[1†]



Science Vol. 347, Issue 6227, pp. 1229-1233 (2015)

SSH-Hubbard model

$$H = -J' \sum_{i=1,\sigma}^{M} c^{\dagger}_{2i\sigma} c_{2i-1\sigma} - J \sum_{i=1,\sigma}^{M-1} c^{\dagger}_{2i+1\sigma} c_{2i\sigma} + H.c. + \boxed{U \sum_{i=1}^{2M} n_{i\uparrow} n_{i\downarrow}}$$

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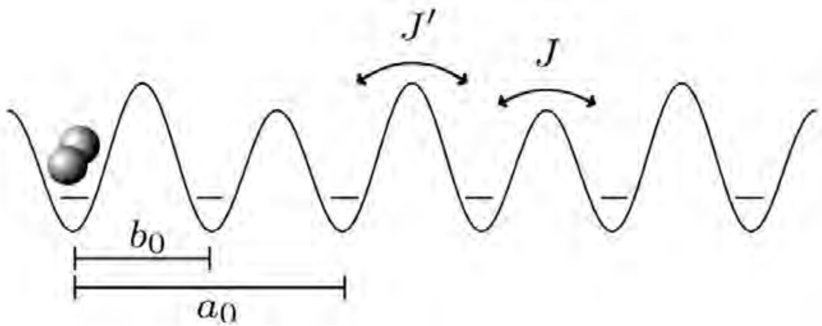
- Strongly interacting regime: $U > 4J$



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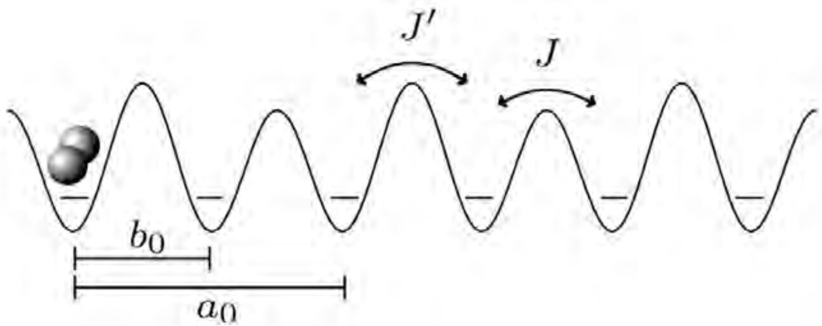
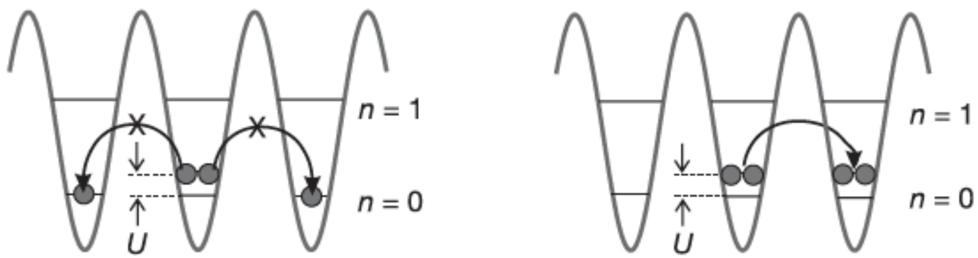


- Doublons cannot decay due to energy conservation



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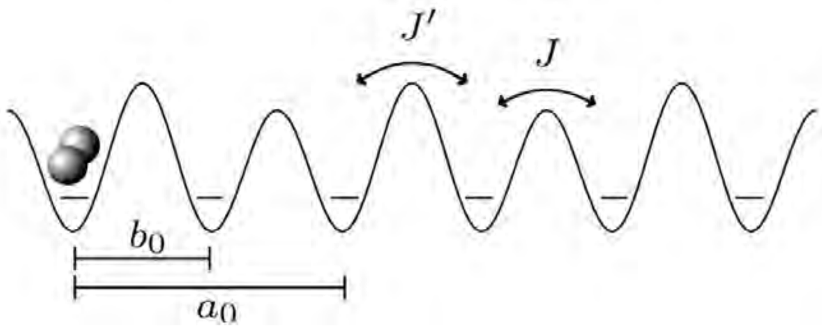

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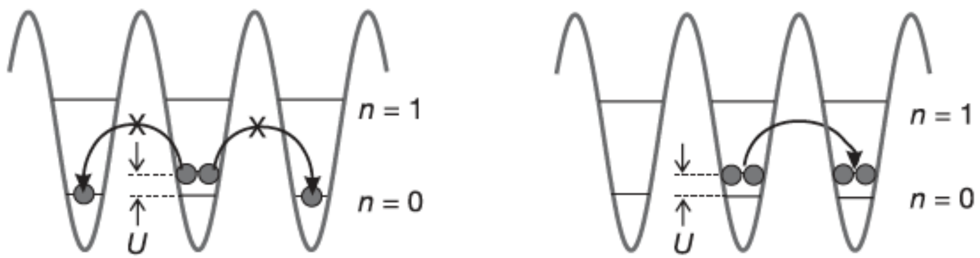


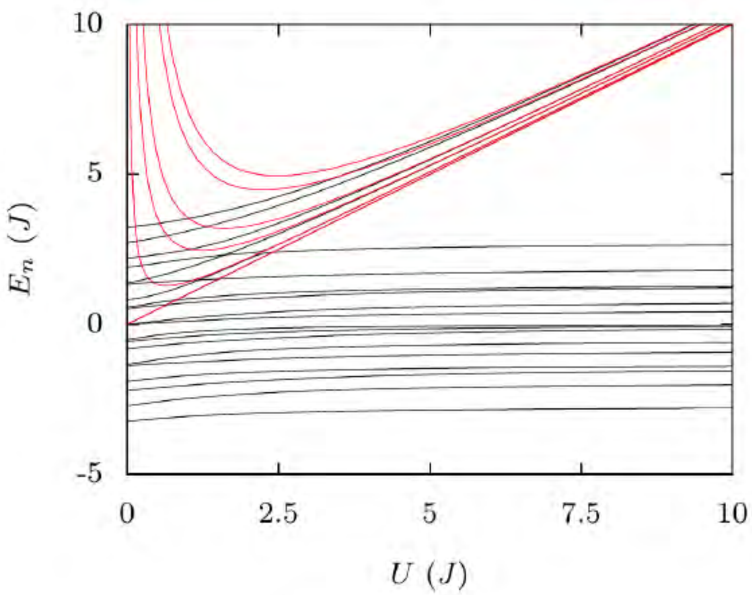
- Effective Hamiltonian for doublons?

- Unitary transformation that block-diagonalizes the Hamiltonian, perturbatively in powers of J/U up to first order.

$$H_{\text{eff}} = J'_{\text{eff}} \sum_{i=1}^{M} d^{\dagger}_{2i} d_{2i-1} + J_{\text{eff}} \sum_{i=1}^{M-1} d^{\dagger}_{2i+1} d_{2i} + H.c. + \sum_{i=1}^{2M} \mu_i n^d_i$$

$$d^{\dagger}_i = c^{\dagger}_{i\uparrow} c^{\dagger}_{i\downarrow} \qquad n^d_i = d^{\dagger}_i d_i$$

F. Hofmann et al., PRB, 85,205127 (2012), A. H. MacDonald et al.,PRB, 37, 9753 (1988)



Doublon's energy spectrum

Effective Hamiltonian

Single occupacy spectrum

M. Bello et al. , Scientific Rep. 6, 22562 (2016).

$$H_{\text{eff}} = \underbrace{J'_{\text{eff}} \sum_{i=1}^{M} d^{\dagger}_{2i} d_{2i-1} + J_{\text{eff}} \sum_{i=1}^{M-1} d^{\dagger}_{2i+1} d_{2i}}_{\text{dimer tight-binding}} + H.c. + \underbrace{\sum_{i=1}^{2M} \mu_i n^d_i}_{\text{effective chemical potential}}$$

$$J'_{eff} = 2J'^2/U \qquad J_{eff} = 2J^2/U$$

$$\mu_i = U + \sum_{\langle i,j \rangle} J^{\text{eff}}_{ij}$$ Depends on number of neighbours

For a finite lattice:

$$\mu_i = \begin{cases} \mu_{\text{bulk}} = J'_{\text{eff}} + J_{\text{eff}} + U & \text{if} \quad 1 < i < 2M \\ \mu_{\text{edge}} = J'_{\text{eff}} + U & \text{if} \quad i \in \{1, 2M\} \end{cases}$$

$$H_{\text{eff}} = J'_{\text{eff}} \sum_{i=1}^{M} d_{2i}^{\dagger} d_{2i-1} + J_{\text{eff}} \sum_{i=1}^{M-1} d_{2i+1}^{\dagger} d_{2i} + H.c. + \sum_{i=1}^{2M} \mu_i n_i^d$$

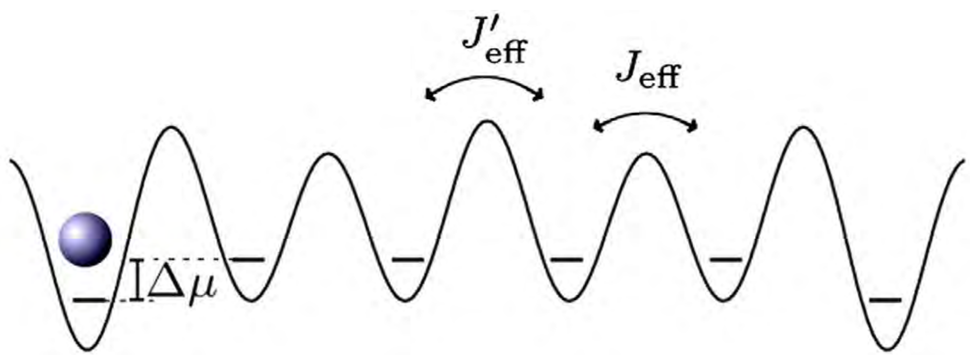
dimer tight-binding

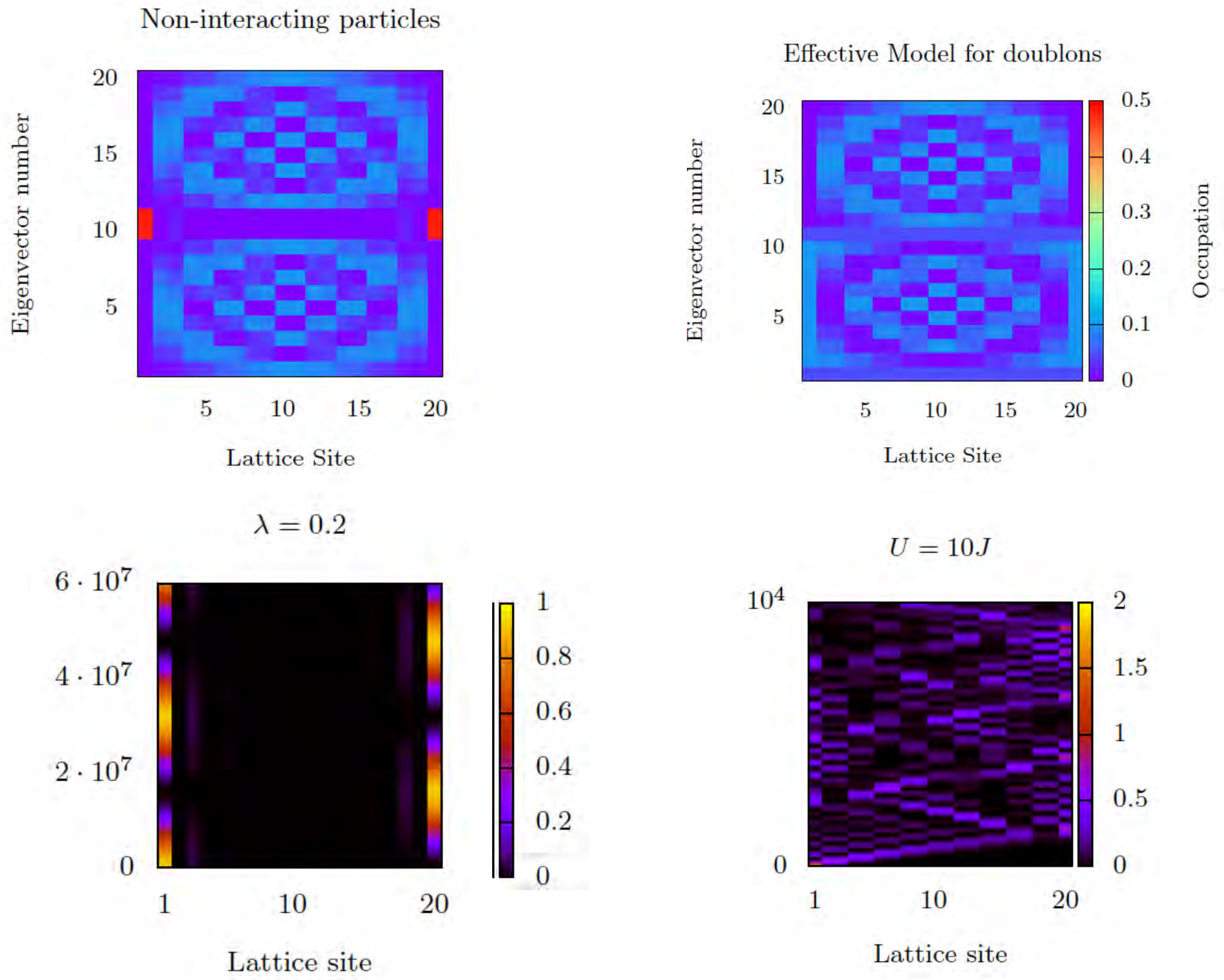
effective chemical potential

$$J'_{eff} = 2J'^2/U \qquad J_{eff} = 2J^2/U$$

$$\mu_i = U + \sum_{\langle i,j \rangle} J_{ij}^{\text{eff}}$$ Depends on number of neighbours

This forbids the presence of edge states for doublons



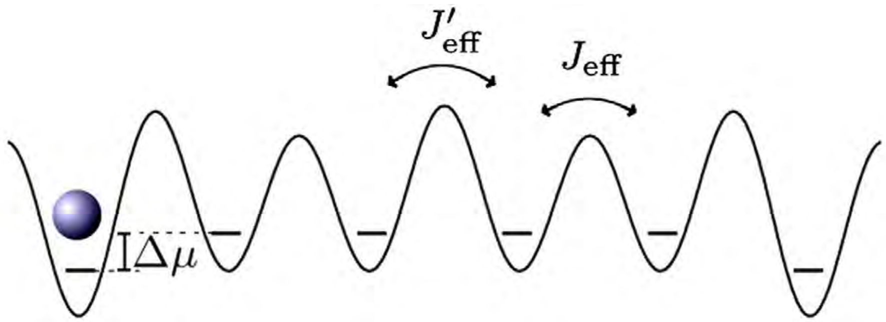


Non-interacting particles
Eigenvector number
Lattice Site
Effective Model for doublons
Eigenvector number
Lattice Site
Occupation
$\lambda = 0.2$
Lattice site
$U = 10J$
Lattice site

Conclusions

- Long-range transfer of particles can be produced in a dimer chain thanks to the presence of edge states

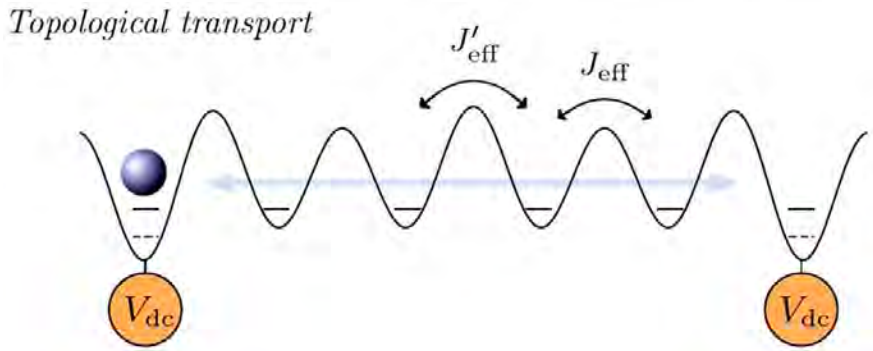
Doublons edge states do not occur naturally in the dimer chain.



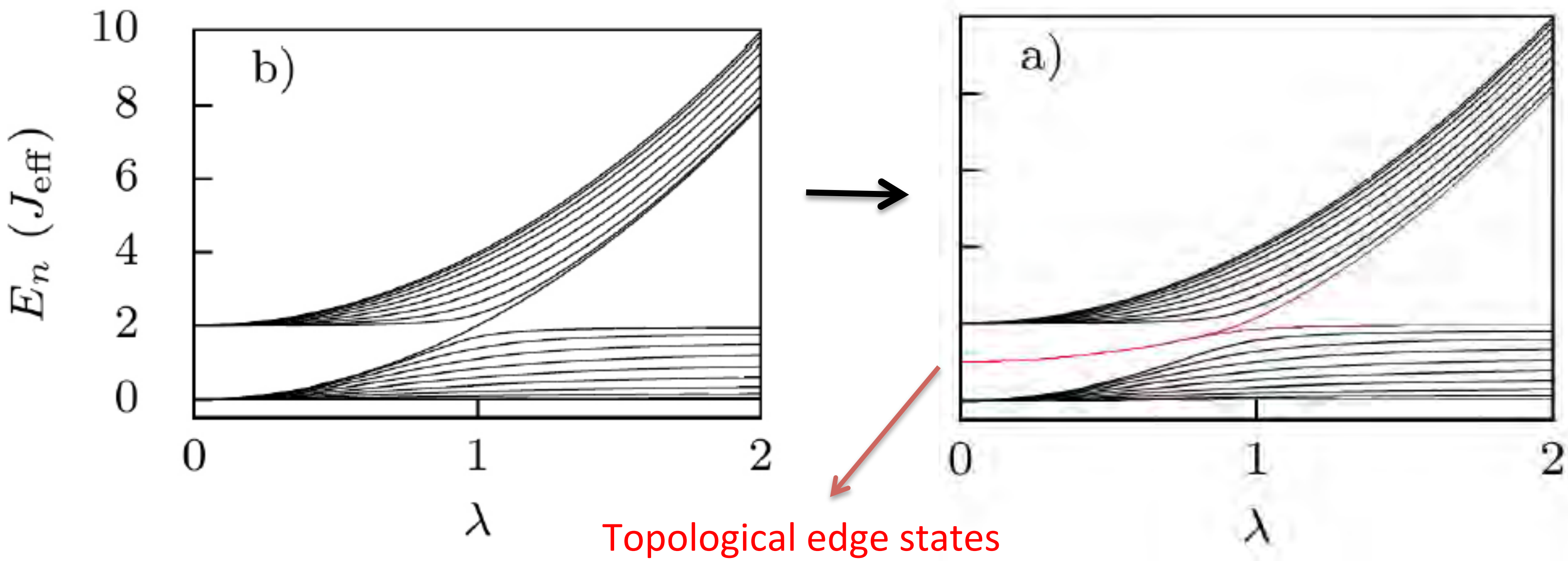
However they can be induced by different means:

1)

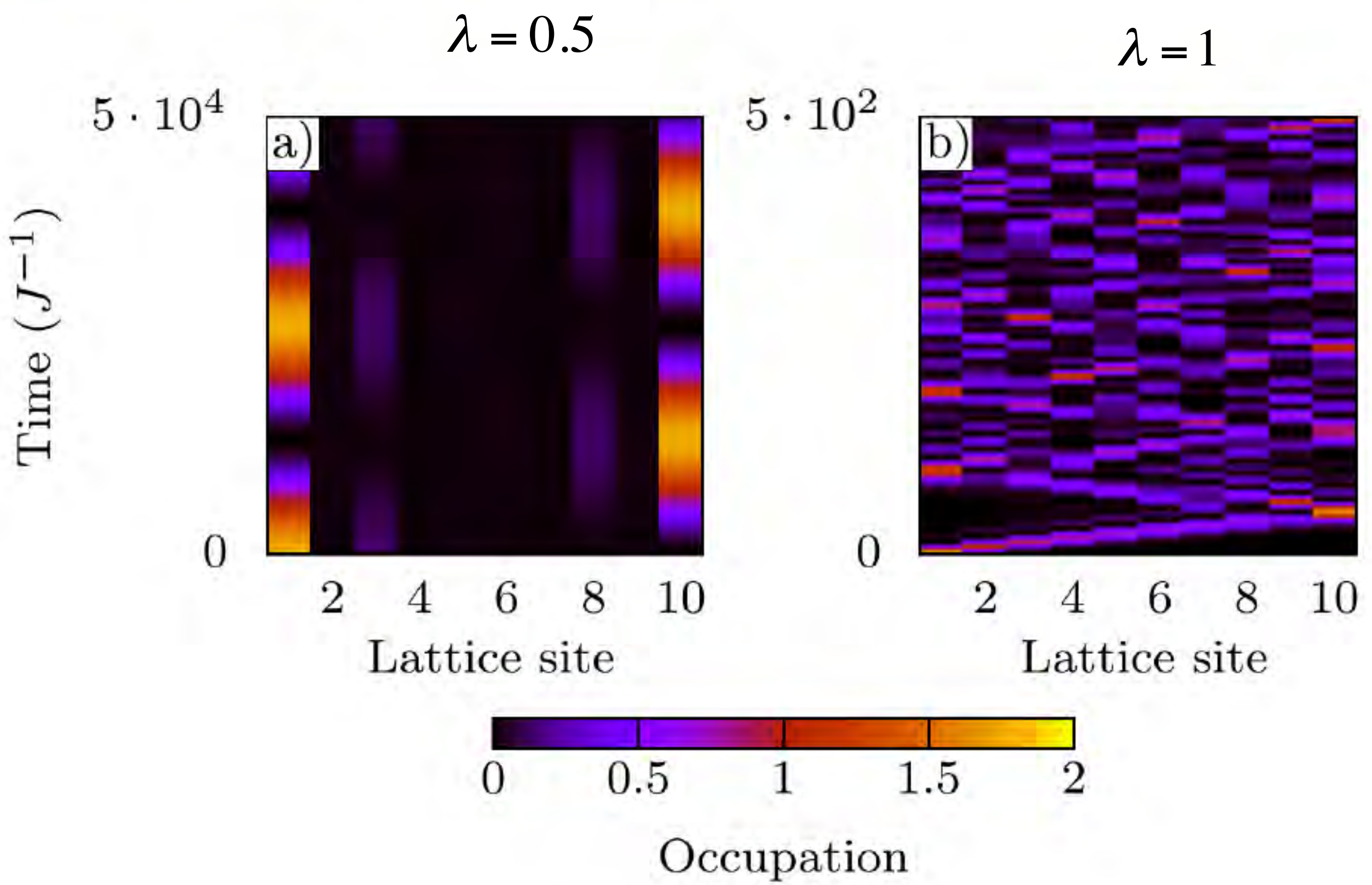
If we add a gate potential at the ends of the chain to compensate for the chemical potential difference, we recover the SSH model for doublons



Topological Direct Transfer



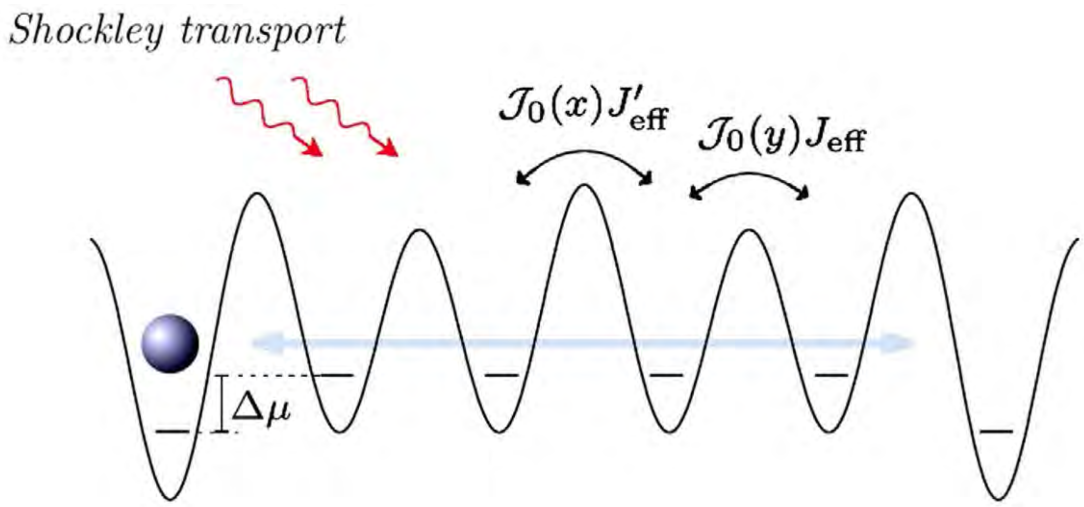
Topological Direct Transfer



$U = 16J$; a) $\lambda = 0.5$, b) $\lambda = 1$

2)

With AC driving: Shockley transfer:



Floquet theory and HFE

N. Goldman et al., PRX, 4, 031027
M. Bukov et al., Adv. Phys. 64,139

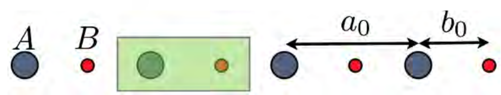
$$H(t) = H_{hopp} + H_U + E\cos(\omega t)\sum_{i=1}^{2M} x_i(n_{i\uparrow} + n_{i\downarrow})$$

Effective Hamiltonian, regime $U \gg \omega > J, J'$

Only the hopping parameters become renormalized by the ac field:

$$J'_{eff} \longrightarrow \mathcal{J}_0\left(\frac{2Eb_0}{\omega}\right) J'_{eff}$$

$$J_{eff} \longrightarrow \mathcal{J}_0\left(\frac{2E(a_0 - b_0)}{\omega}\right) J_{eff}$$



Floquet theory and HFE

N. Goldman et al., PRX, 4, 031027
M. Bukov et al., Adv. Phys. 64,139

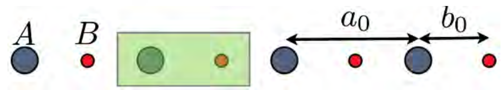
$$H(t) = H_{hopp} + H_U + E\cos(\omega t)\sum_{i=1}^{2M} x_i(n_{i\uparrow} + n_{i\downarrow})$$

Effective Hamiltonian, regime $U \gg \omega > J, J'$

Only the hopping parameters become renormalized by the ac field:

$$J'_{eff} \longrightarrow \mathcal{J}_0\left(\frac{2Eb_0}{\omega}\right) J'_{eff}$$

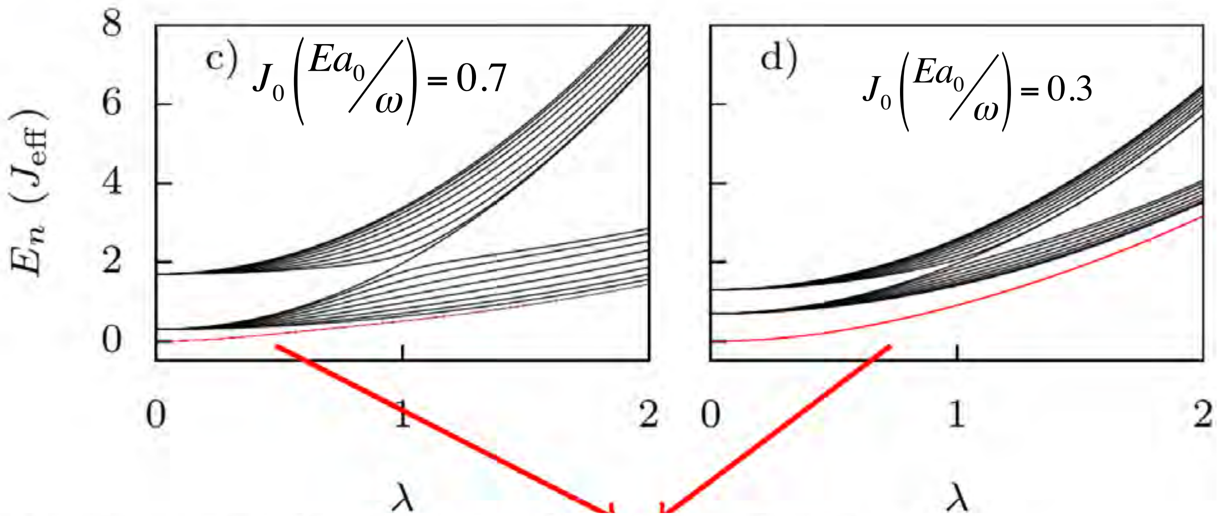
$$J_{eff} \longrightarrow \mathcal{J}_0\left(\frac{2E(a_0 - b_0)}{\omega}\right) J_{eff}$$



$$H_{\text{eff}} = \mathcal{J}_0(x) J'_{\text{eff}} \sum_{i=1}^{M} d^\dagger_{2i} d_{2i-1} + \mathcal{J}_0(y) J_{\text{eff}} \sum_{i=1}^{M-1} d^\dagger_{2i+1} d_{2i} + h.c. + \sum_{i=1}^{2M} \mu_i n_i^d \quad x = \frac{2Eb_0}{\omega} \quad y = \frac{2E(a_0 - b_0)}{\omega}$$

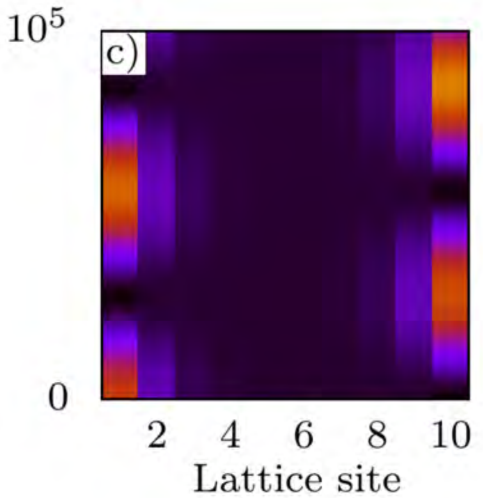
The ac field allows to tune the ratio between the hoppings and $\Delta\mu$

Inducing Shockley-like edge states

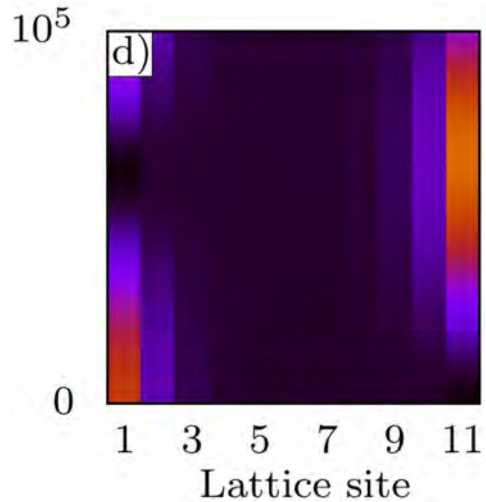


These edge states also form a non-local two level system

Odd number of sites

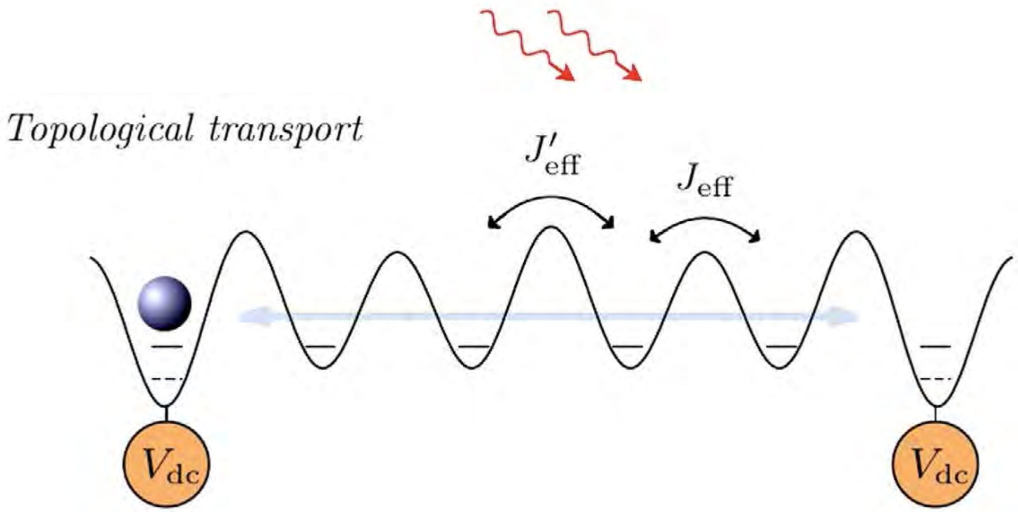


Shockley Direct Transfer



3)

Combination of both: AC induced topological transfer



AC fields + gate potentials

SSH model for doublons with tunable hoppings:

$$H_{\text{eff}} = \mathcal{J}_0(x) J'_{\text{eff}} \sum_{i=1}^{M} d^\dagger_{2i} d_{2i-1} + \mathcal{J}_0(y) J_{\text{eff}} \sum_{i=1}^{M-1} d^\dagger_{2i+1} d_{2i} + H.c.$$

$x = \frac{2Eb_0}{\omega}$

$y = \frac{2E(a_0 - b_0)}{\omega}$

A. Gómez-León & G. Platero PRL **110**, 200403 (2013)

AC fields + gate potentials

SSH model for doublons with tunable hoppings:

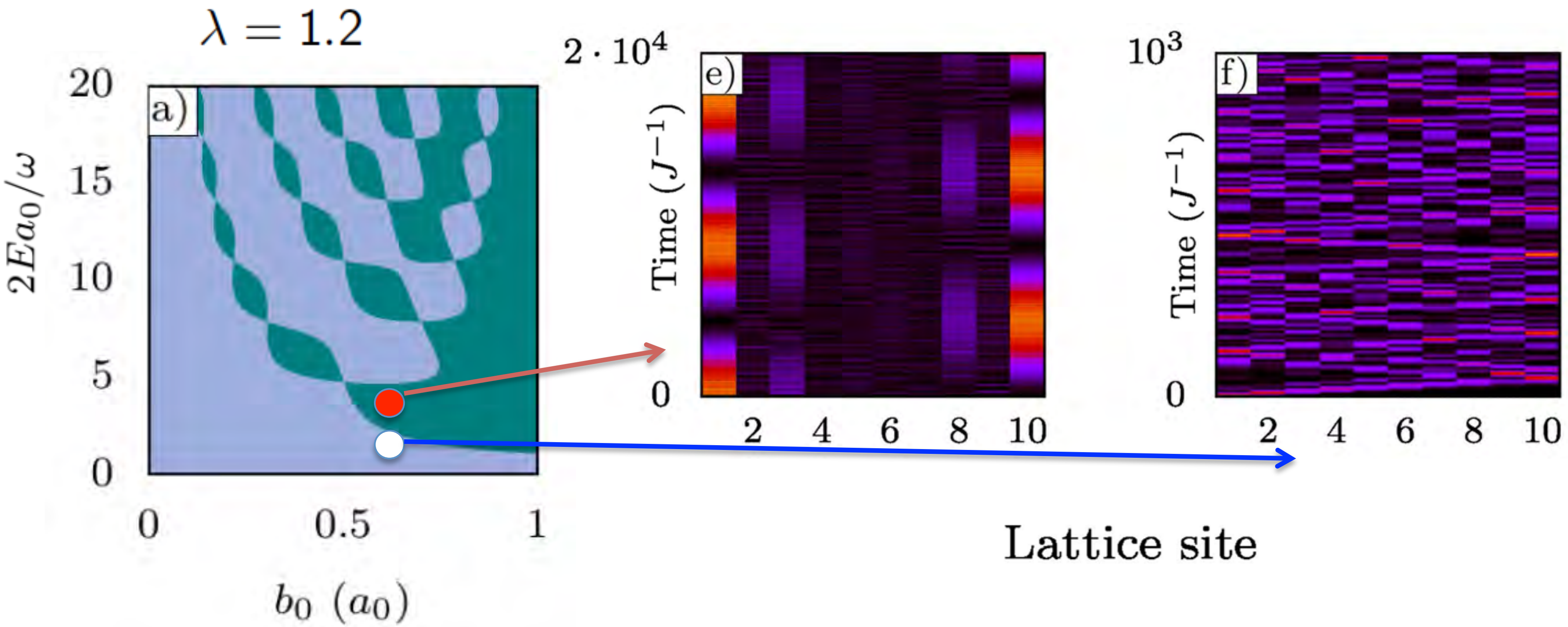
$\Longrightarrow$ Control over the topology of the system:

Z=π

$$\left| \frac{\lambda^2 \mathcal{J}_0\left(\frac{2E}{\omega} b_0\right)}{\mathcal{J}_0\left(\frac{2E}{\omega}(a_0 - b_0)\right)} \right| < 1$$

$$\lambda = \frac{J'}{J}$$

M. Bello, C. E. Creffield, and G. Platero, Scientific Rep. 6, 22562 (2016).



AC fields + gate potentials

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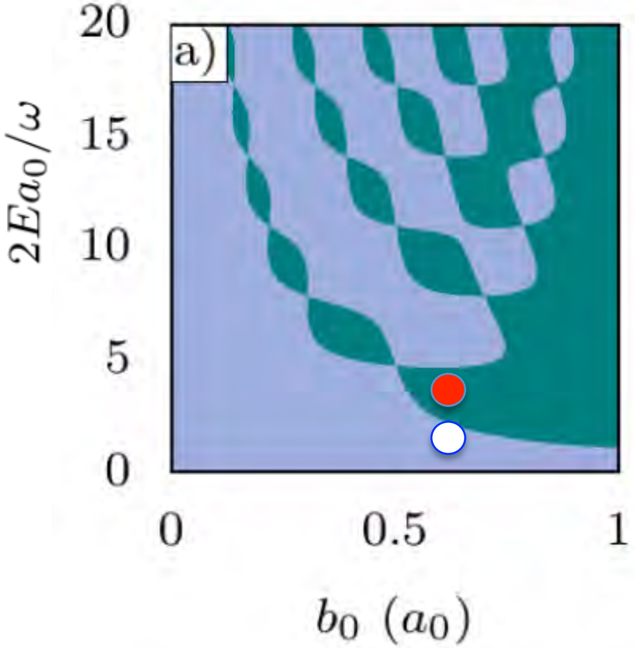
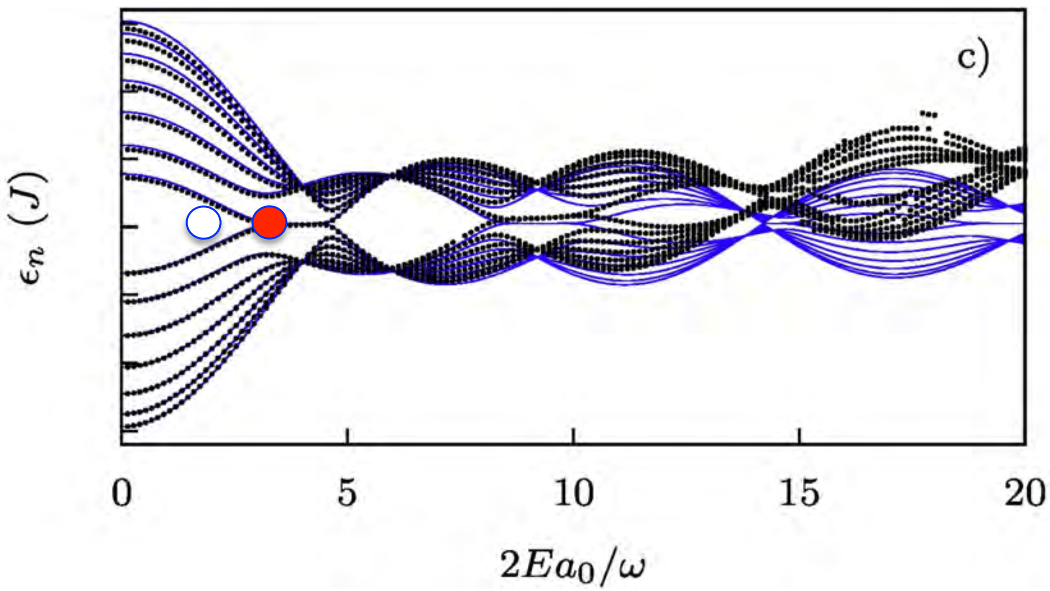
M. Bello, C. E. Creffield, and G. Platero, Scientific Rep. 6, 22562 (2016).

$\lambda = 1.2$





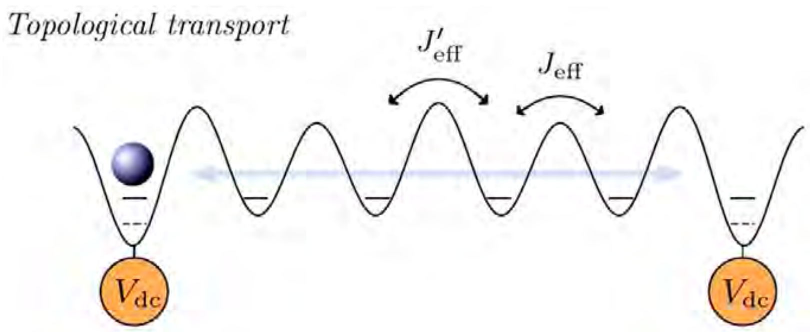
U = 16J, $b_0 = 0.6a_0$ and ω = 2J.

Conclusions

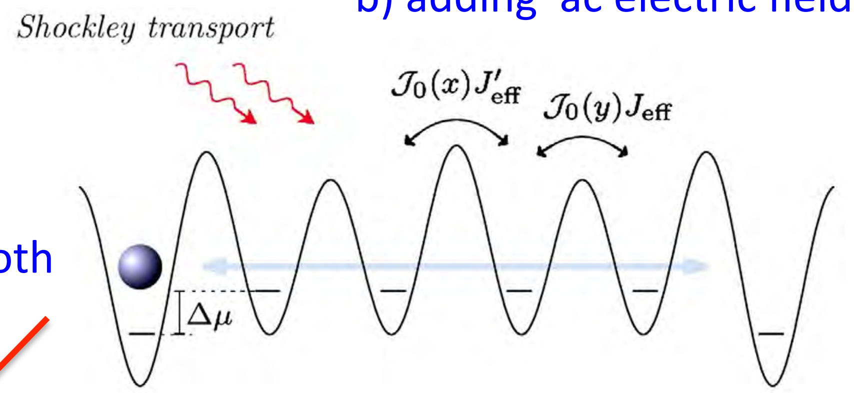
- Long-range transfer of particles can be produced in a dimer chain thanks to the presence of edge states

Doublons edge states do not occur naturally in the dimer chain, however they can be induced by different means:

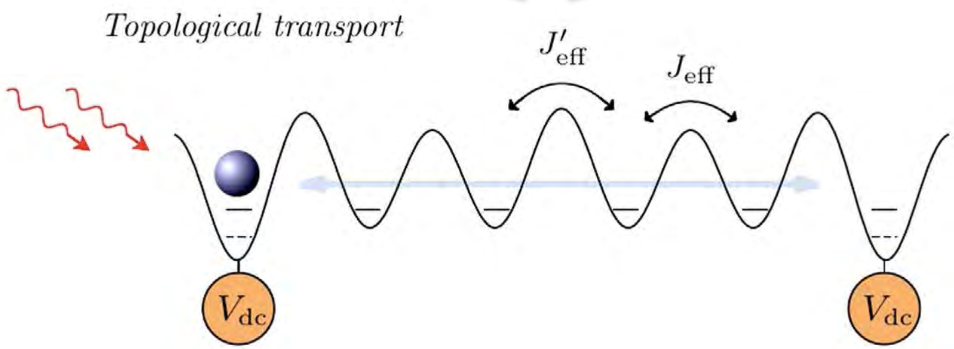
a) adding dc gate voltages



b) adding ac electric fields



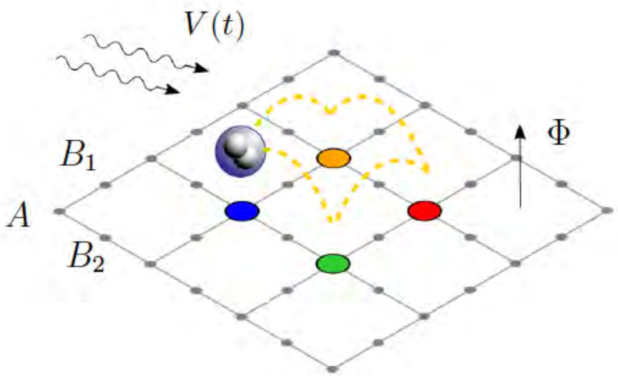
adding both



Doublons in 2D lattices driven with ac electric fields and static magnetic fields

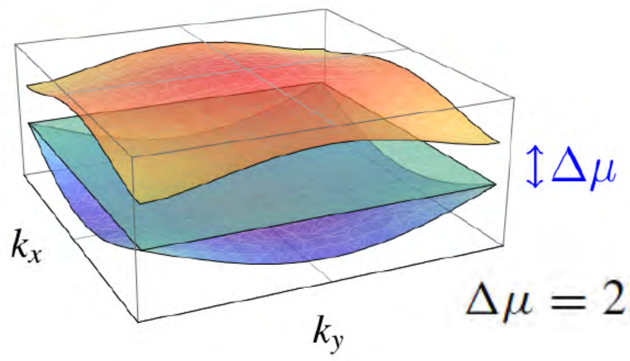
$$H(t) = -J \sum_{\langle i,j \rangle,\ \sigma} e^{i\phi_{ji}} c^{\dagger}_{j\sigma} c_{i\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} + \sum_i V_i(t)(n_{i\uparrow} + n_{i\downarrow})$$

Circular polarization $V_i(t) = x_i E \cos(\omega t) + y_i E \sin(\omega t)$



$$H_{\text{eff}} = \sum_{\langle i,j \rangle} J^{\text{eff}}_{ij} d^{\dagger}_i d_j + \sum_i \mu^{\text{eff}}_i d^{\dagger}_i d_i$$

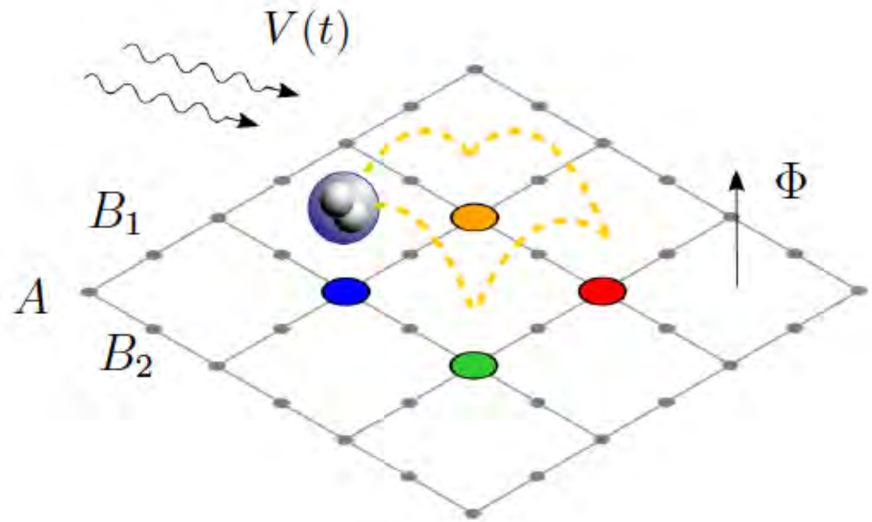
$$J^{\text{eff}}_{ij} = \frac{2J^2 e^{i2\phi_{ij}}}{U} \mathcal{J}_0 \left(\frac{2E\delta}{\omega} \right) \quad \mu^{\text{eff}}_i = \frac{2J^2 z_i}{U}$$



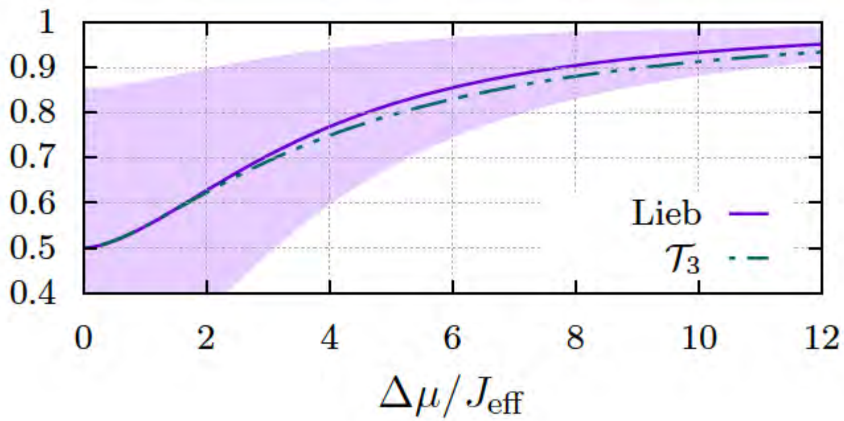
Sublattice dynamics

$\Phi = 0$

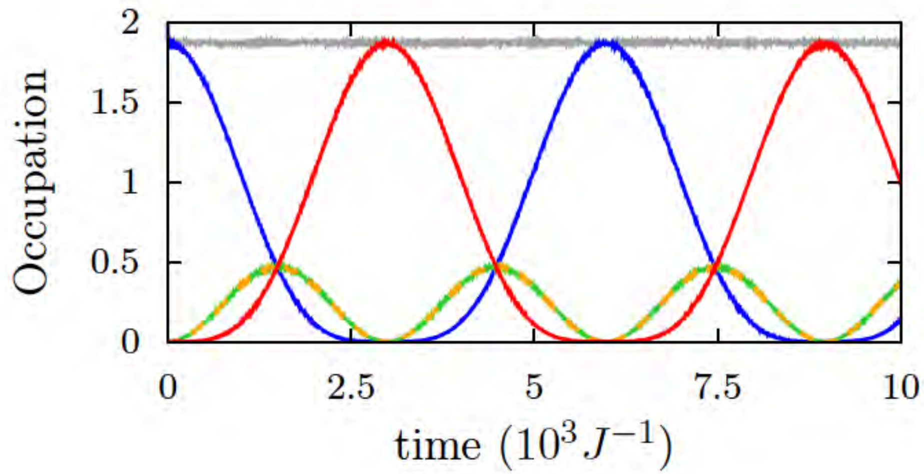
$$\Delta\mu = 2J^2(z_A - z_B)/U$$

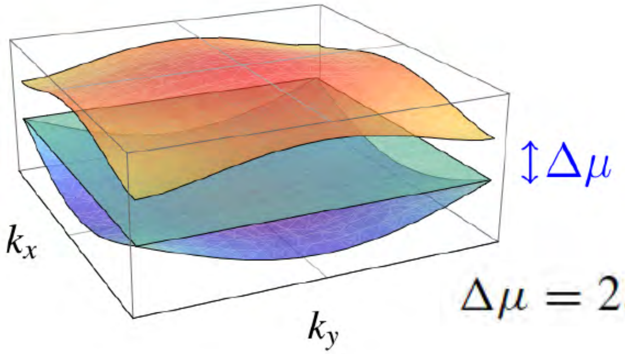


The ac field modifies the relative weight of the Bloch states on each sublattice



Time average probability for the doublon to remain in sublattice A





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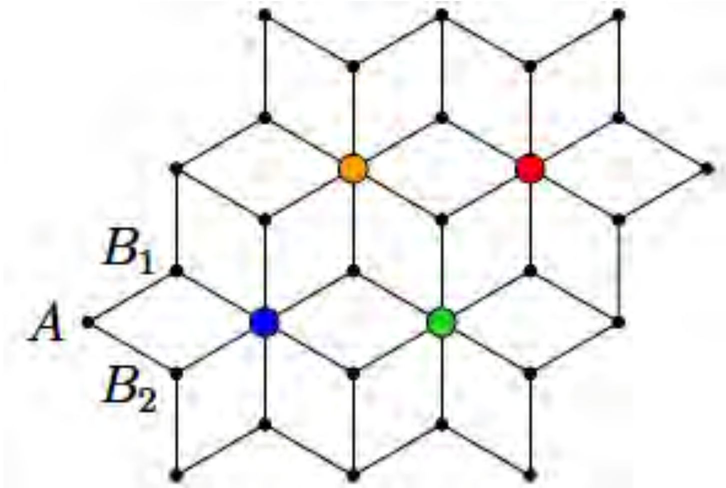

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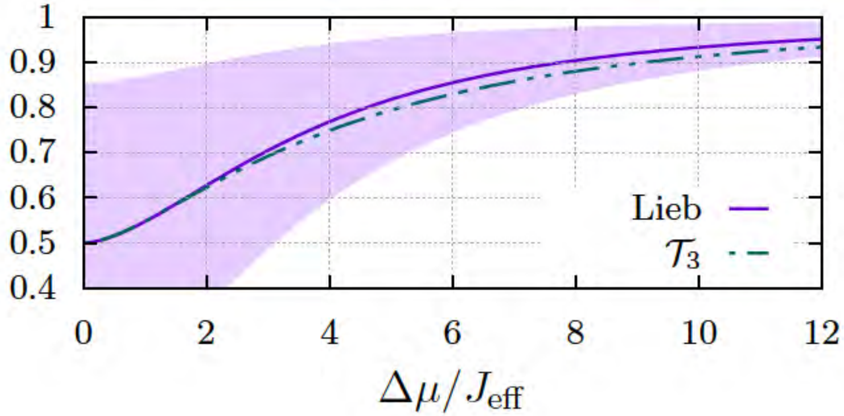
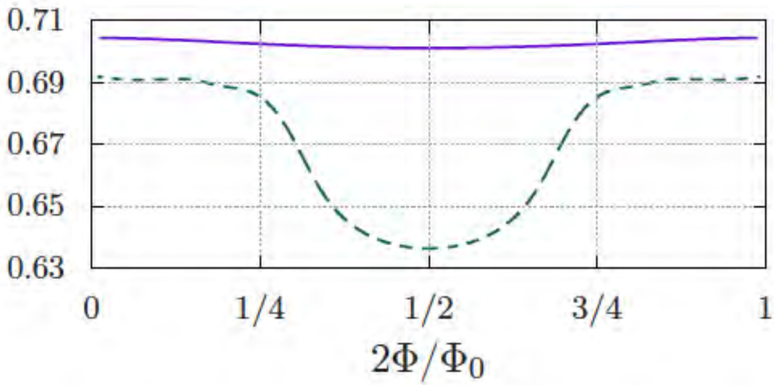
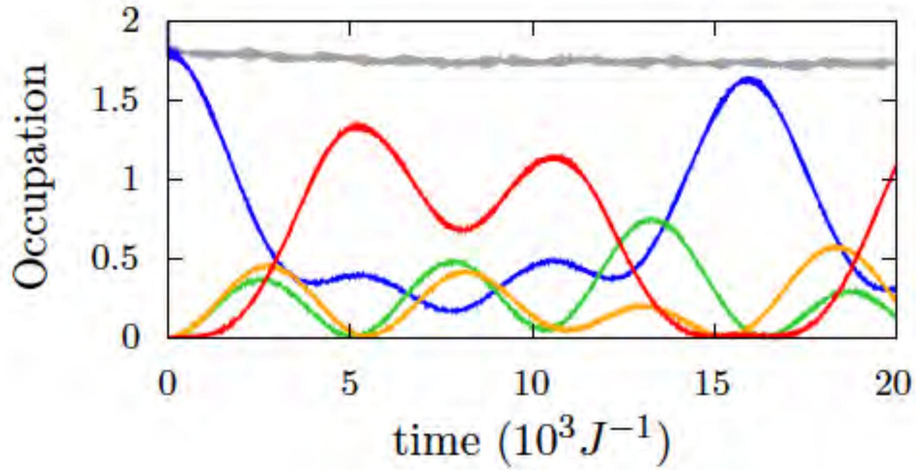
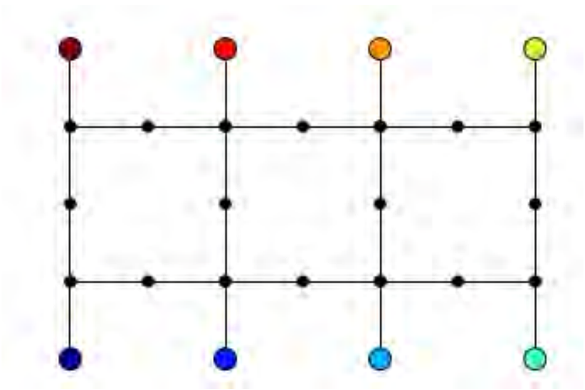


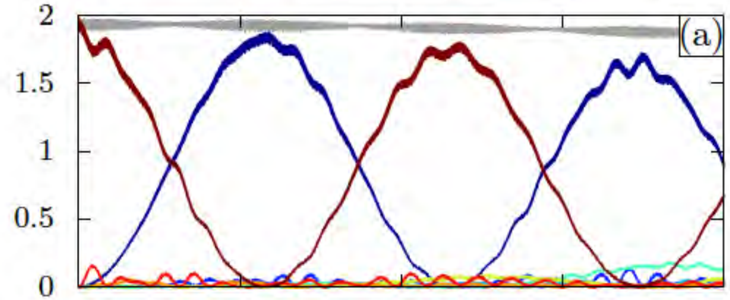
Vidal et al., PRL 1998 Aharonov-Bohm Cages

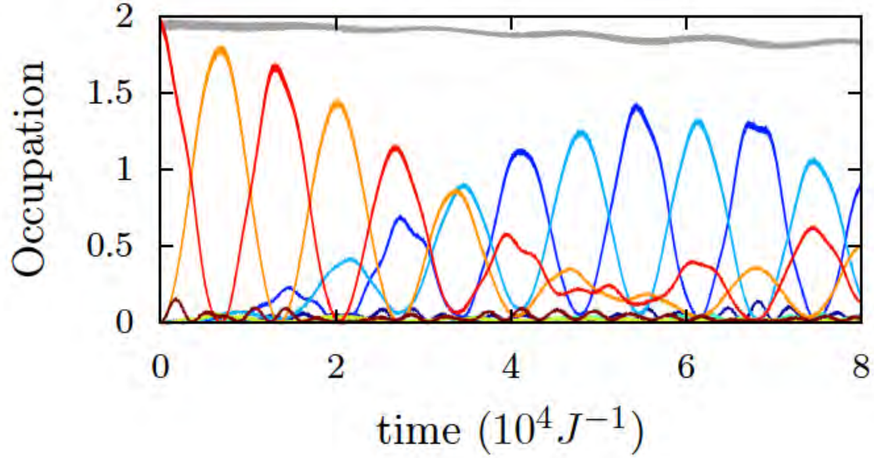


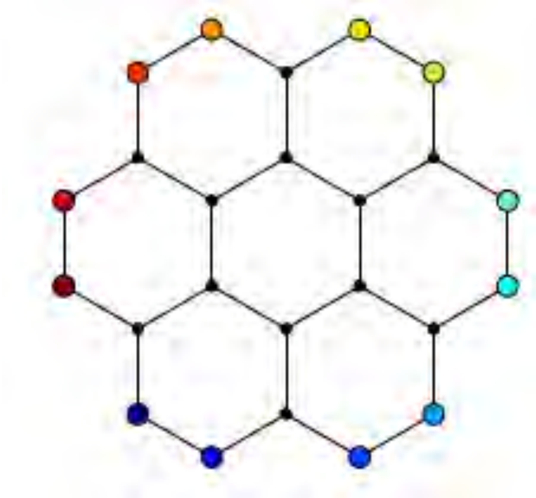


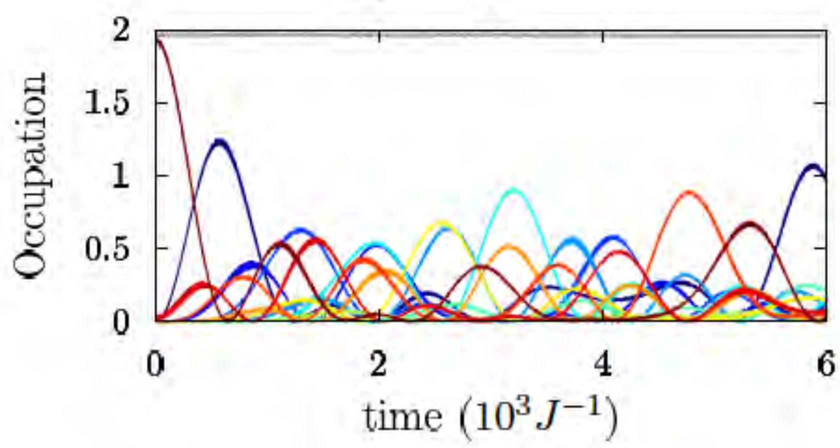
Edge dynamics and long range transfer of doublons $\Phi = 0$







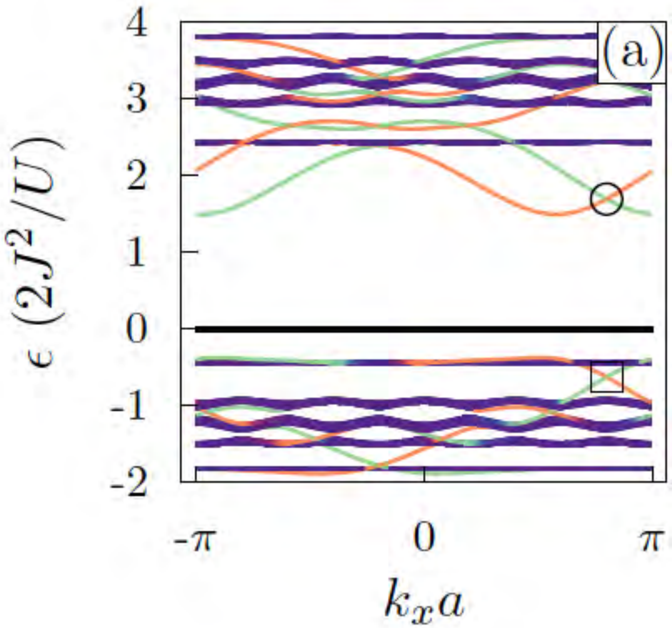


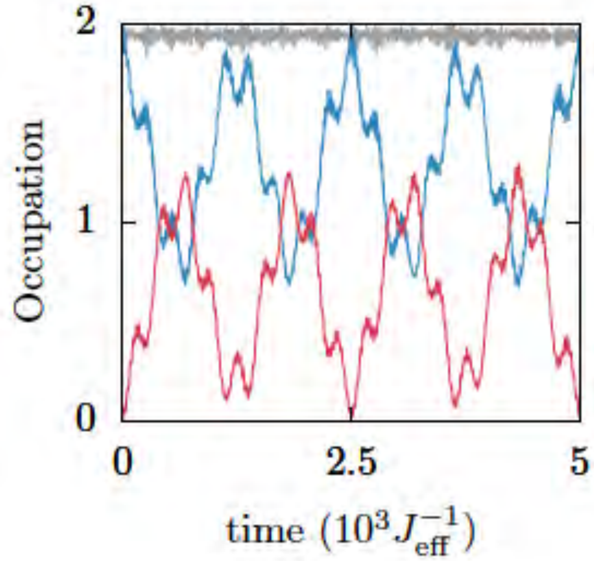


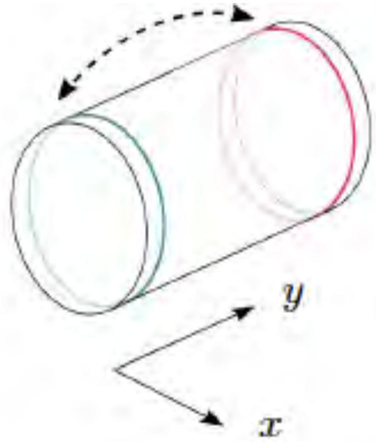
$$\Phi \neq 0$$

$$\Phi/\Phi_0 = 1/10$$

$$N_y = 100$$



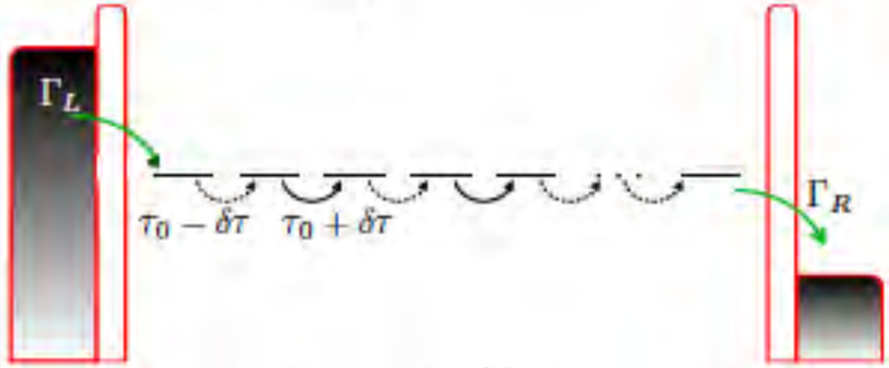




M. Bello, C.E. Creffield and G.Platero, PRB, 95, 094303 (2017)

Quantum transport in a dimer chain

- Transport from source to drain (voltage bias V)
- Low temperatures
- $|\tau_0 \pm \delta\tau| \ll eV \ll U_{\mathsf{d}} \rightarrow$ only single-electron states



$\tau_n = \tau_0 + (-1)^n \delta\tau$

- Master equation

$$\dot{\rho} = -\frac{i}{\hbar}[H_{\mathsf{SSH}}, \rho] + \Gamma_L \mathcal{D}(c_1^\dagger)\rho + \Gamma_R \mathcal{D}(c_N)\rho \Rightarrow$$

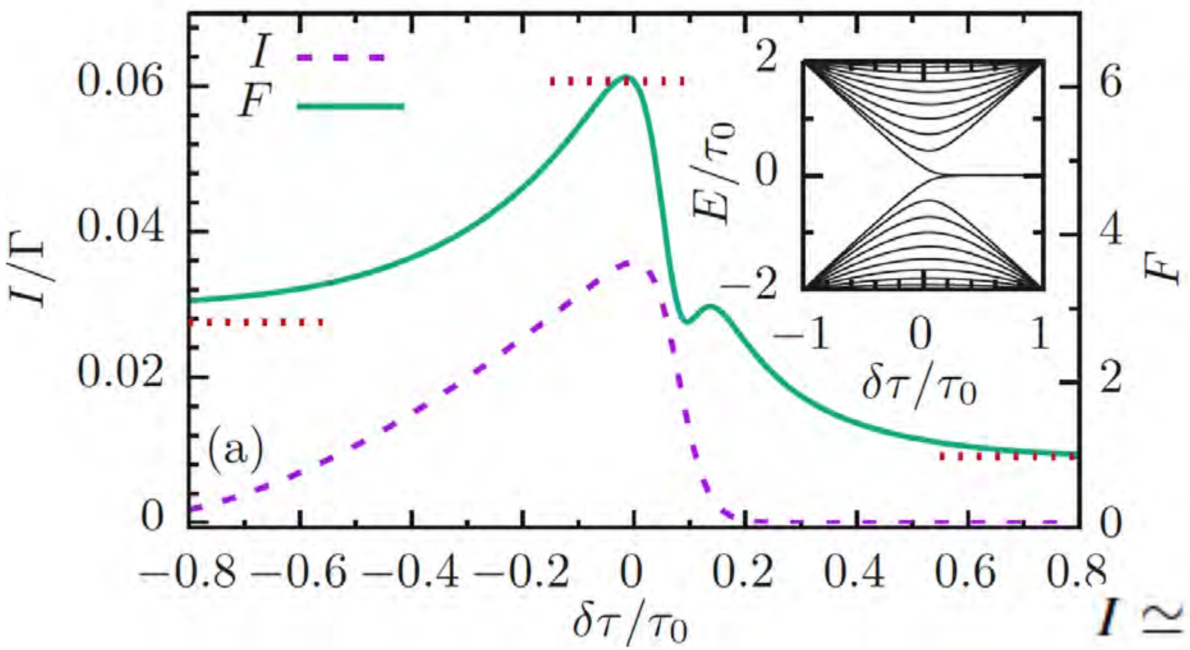
- steady state
- current

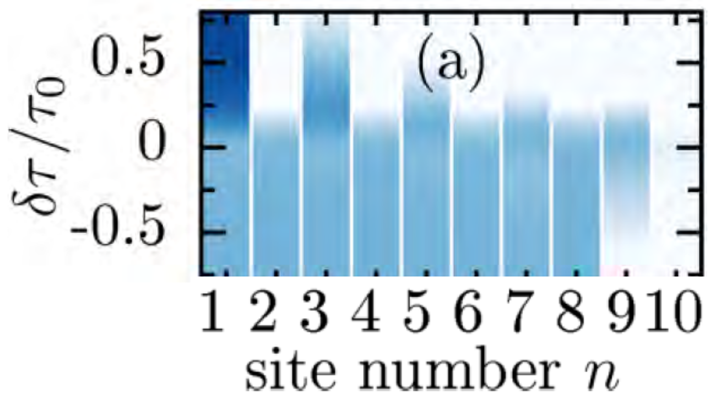
Lindblad operator: $\mathcal{D}(x)\rho = \left(2x\rho x^\dagger - x^\dagger x\rho - \rho x^\dagger x\right)/2$

- $\delta\tau < 0$ no edge states
- $\delta\tau > 0$ two edge states

N=20 atoms

$$\Delta \approx \tau_0 \exp(-N\delta\tau/\tau_0)$$



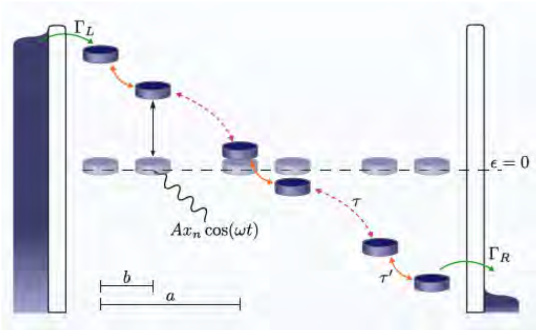


$$I \simeq \Delta^2/\Gamma$$

- Electron blocked at the source edge state
- Coulomb interaction avoids a second electron to enter
- edge state at the source + Coulomb interaction $\Rightarrow$ edge-state blockade

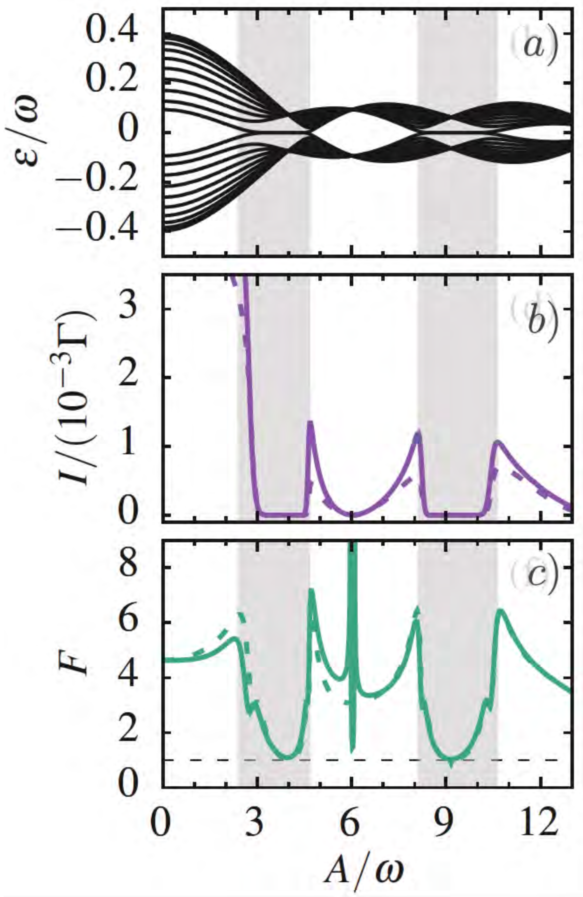
M. Benito, M. Niklas, G. Platero, S. Kohler, PRB, 93, 115432 (2016)

Dimer chain: AC driven transport to characterize the topology

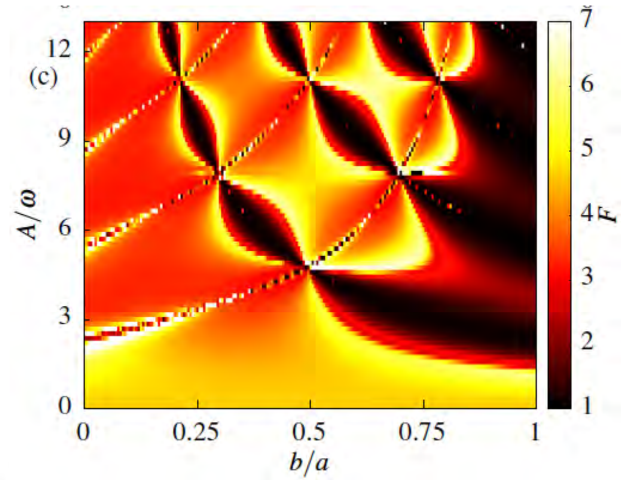


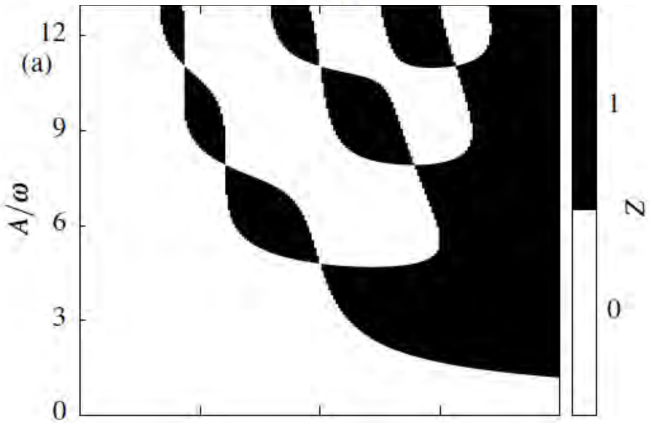
$$H(t) = H_{\mathrm{SSH}} + A \sum_{n=1}^{N} x_n c_n^\dagger c_n \cos(\omega t)$$

While the shape of the current suppression would be sufficient to identify edge-state blockade, the Fano factor exhibits clearler fingerprints of the topological phase diagram.



Shot noise





b_0/a_0

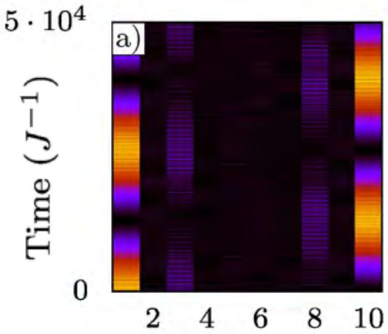
Zak phase

M. Niklas, M. Benito, S. Kohler and G. Platero, Nanotechnology, 2017

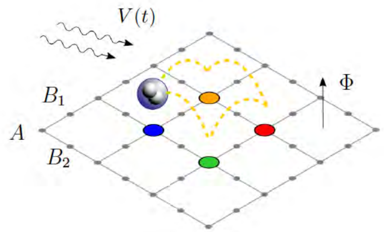
Summary

Long range transfer of particles in a dimer chain mediated by edge states

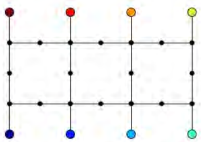
Doublons edge states in the dimer chain induced by dc voltages and ac electric fields: Long range transfer of doublons

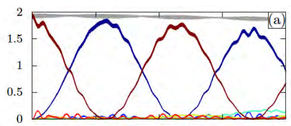


Sublattice Doublon dynamics in 2D lattices controlled by ac electric fields

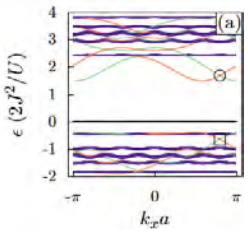


long range Doublon transfer





coexistence of Schockley and topological edge states



Current edge state blockade in a dimer chain:
ac transport: fingerprints of topology in the noise