CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
INSTITUTO DE CIENCIA DE MATERIALES DE MADRID (ICMM)

Long-Range Quantum Transfer in Semiconductor Quantum Dots Arrays

Gloria Platero

Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC)

“Novel trends in topological systems and quantum thermodynamics”

(i-Link)

Outline:

Semiconductor quantum dot arrays (artificial molecules) for…

- ❑ Long-range transfer of electron and hole spins
- ❑ Quantum simulation of lattices with non trivial topology by Floquet engineering

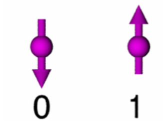
↓

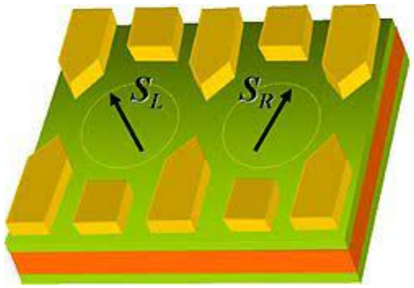
- ❑ Edge states for quantum information transfer

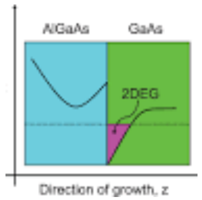
QDs as a Platform for a Quantum Computer

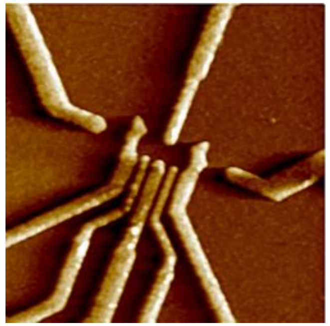
- From the Loss and Divicenzo proposal: **"Quantum computation with quantum dots " (**PRA 1998), more than 10 years devoted to double quantum dots to implement one qubit and two qubits operations

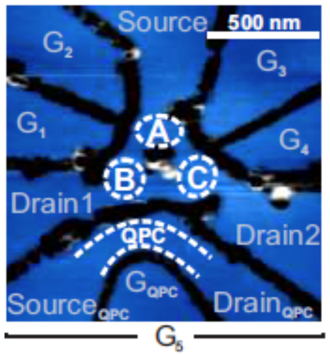
Spin Qubits



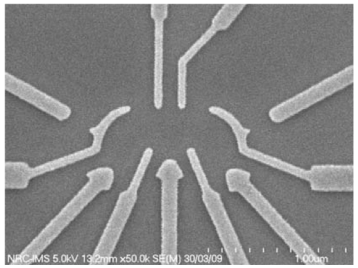




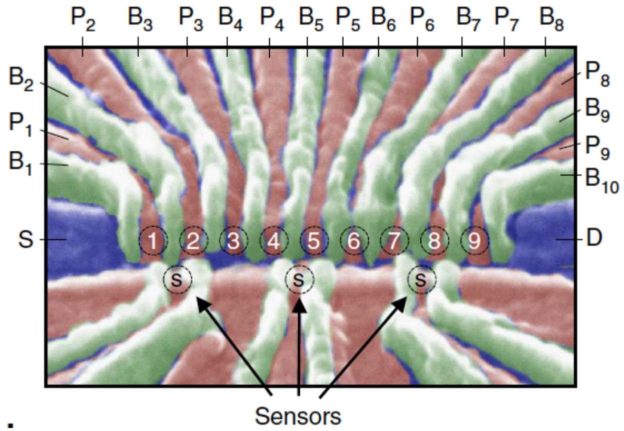




M.C. Rogge et al., PRB 2008



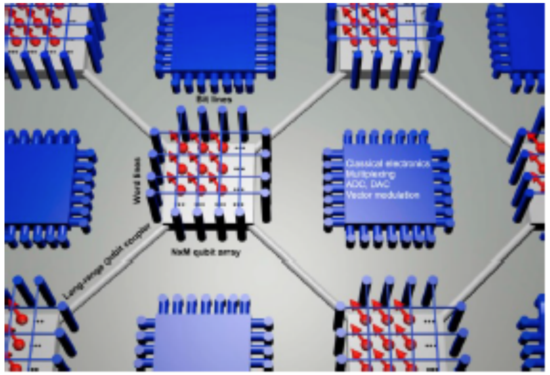
Granger et al., PRB 2010

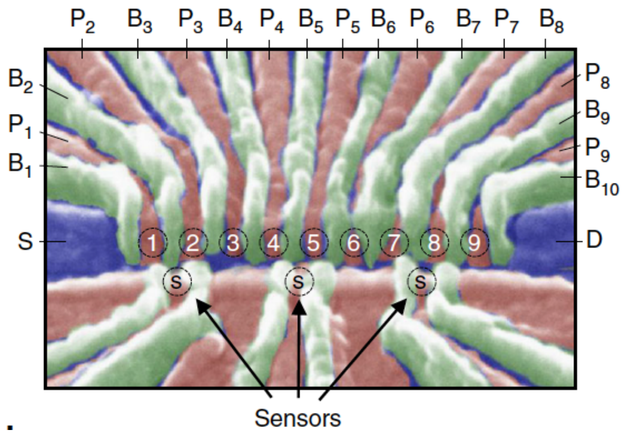


Zajac et at., Phys. Rev Appl. (2016)

QDs as a Platform for a Quantum Computer

Vandersypen, npj,
Quantum Info, 2017





Zajac et al.,
Phys. Rev Appl. 2016

Communication between distant sites in a quantum chip

Fast and High-fidelity transfer: robust against different noise sources

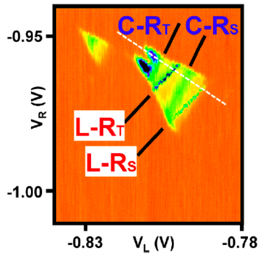
Experimentally feasible driving pulses

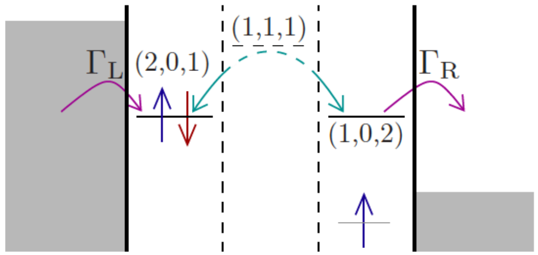
Distribution of entangled particles

Quantum State Transfer in QDs

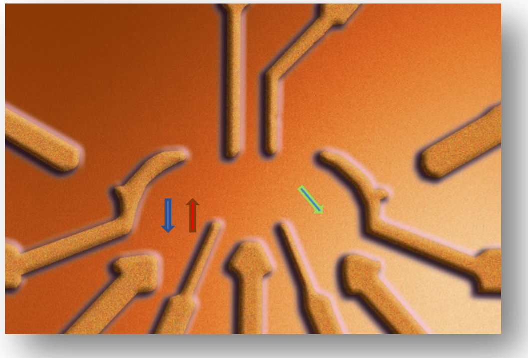
M. Busl et al., Nature Nanotech, 8, 262 (2013)

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





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



NRC, Ottawa
A. Sachrajda

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

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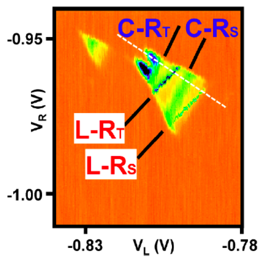

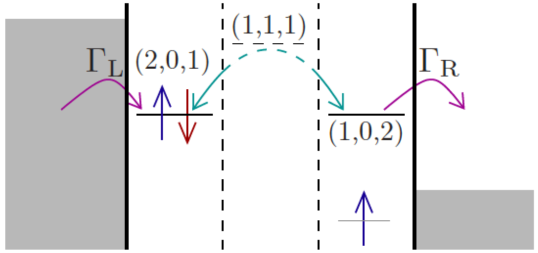

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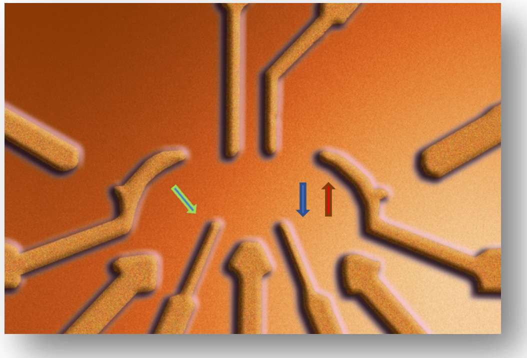

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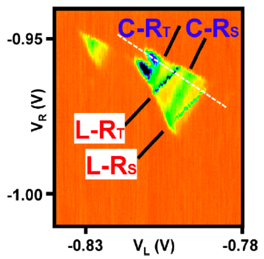

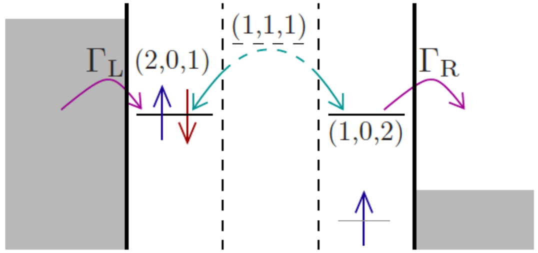

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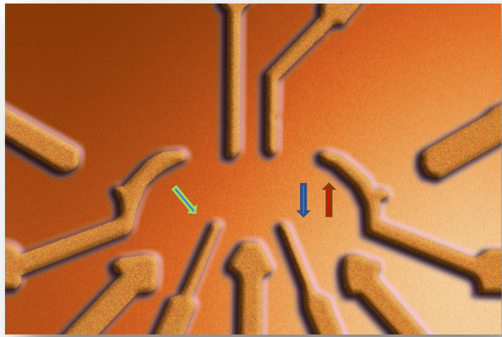

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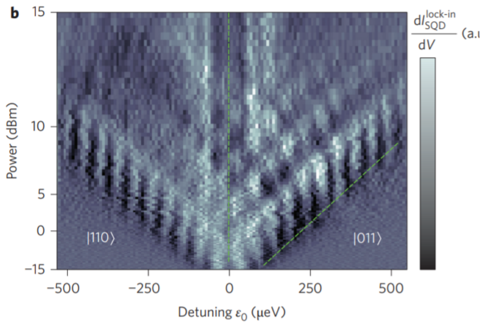
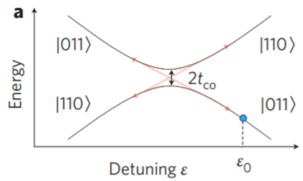
As an electron tunnels from one extreme to the other an arbitrary spin state ψ is transferred in the opposite direction

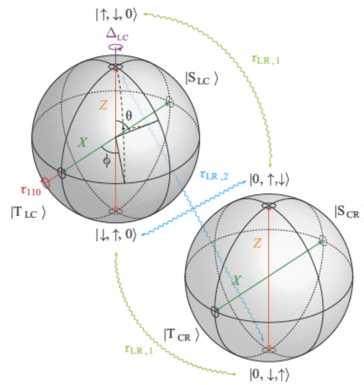
- Long range photo-assisted tunneling





F. Braakman et al.
Nature Nanotech
2013

J. Picó-Cortés, F. Gallego-Marcos and G. P., PRB, 99, 155421 (2019)
P. Stano et al., PRB 2015
F. Gallego et al., JAP 2015
F. Gallego et al., PRB 2017



$$|\Psi_L\rangle = \cos(\theta_L/2)\,|\uparrow,\downarrow,0\rangle + e^{i\phi_L}\sin(\theta_L/2)\,|\downarrow,\uparrow,0\rangle$$

Quantum State Transfer in QDs

CTAP A. Greentree et al., PRB, 70, 235317 (2004)

$$\Omega_{12}(t) = \Omega^{\max} \exp\left[-\left(t - \frac{t_{\max}+\sigma}{2}\right)^2 / (2\sigma^2)\right]$$

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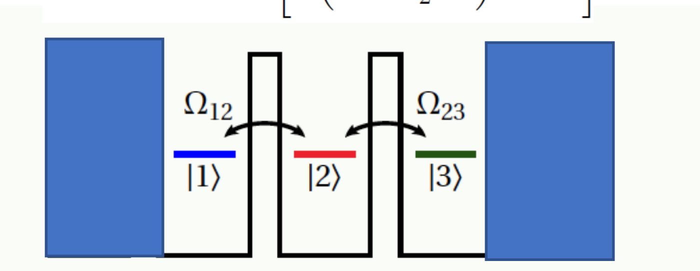
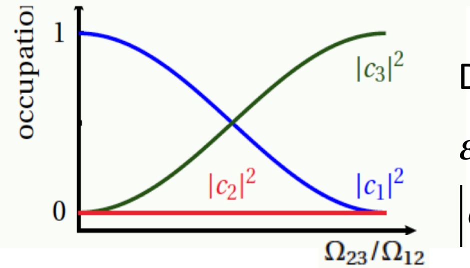




J. Huneke et al., PRL 110,036802 (2013)

Dark State

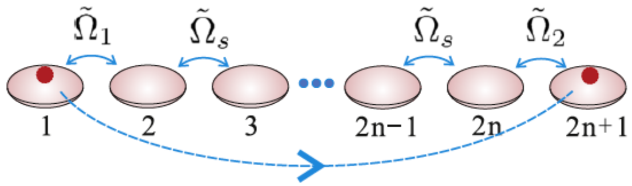
$$\varepsilon = 0$$

$$|\varphi\rangle = |D_0\rangle = \cos\theta|1\rangle - \sin\theta|3\rangle$$

$$\theta = \arctan(\Omega_{12}/\Omega_{23})$$

$$|\mathcal{E}_0 - \mathcal{E}_\pm| \gg |\langle\dot{\mathcal{D}}_0|\mathcal{D}_\pm\rangle|.$$

Longer arrays



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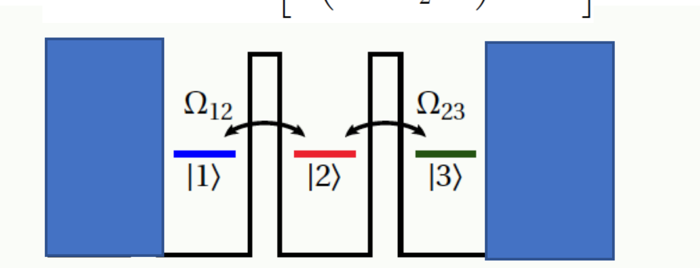

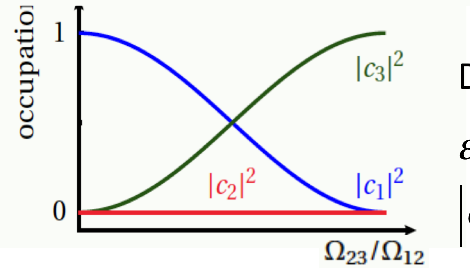

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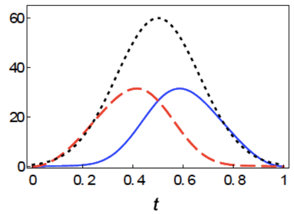

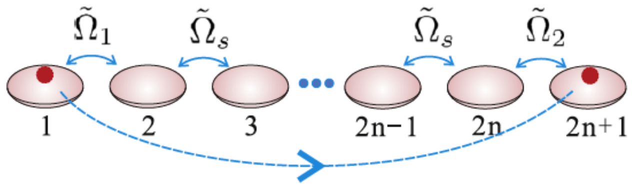

$|\phi_0\rangle = \cos\theta|1\rangle - (-1)^n \sin\theta|2n+1\rangle - X\left[\sum_{j=1}^{n}(-1)^{j+1}|2j-1\rangle\right], \qquad \tan\theta = \Omega_1/\Omega_2$

In the dark state, dots in the even order remain empty.

Undesirable population in the dots 3th, 5th, …, 2n − 1th can be effectively limited.

$X = \frac{\Omega_1\Omega_2}{\Omega_s\sqrt{\Omega_1^2+\Omega_2^2}} \ll 1, \qquad \Omega_{s0} >> \Omega_0$

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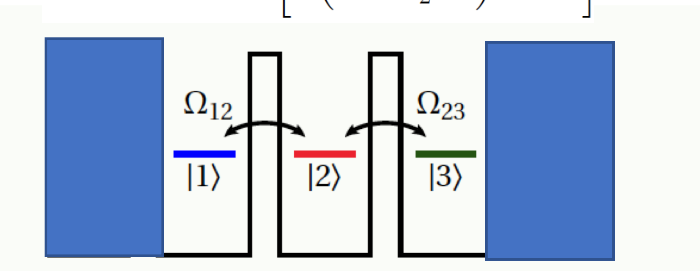

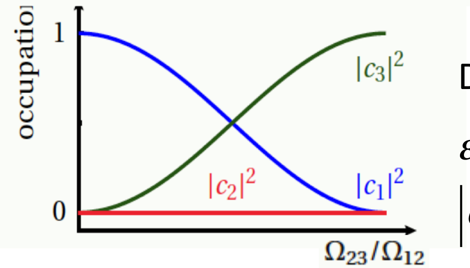

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Shortcuts to Adiabaticity (STA): versatil ways to speed up adiabatic passages.

(D. Guéry-Odelin et al., Rev. Modern Phys., 91, 045001, 2019)

Inverse Engineering: impose the desired evolution of the occupation and infer from it the time evolution of the parameters.

$$\tilde{H}(t) = \tilde{\Omega}_{12}(t) c_1^+ c_2 + \tilde{\Omega}_{23}(t) c_2^+ c_3 + h.c$$

$$|\Psi(t)\rangle = \cos\chi \cos\eta |1\rangle - i \sin\eta |2\rangle - \sin\chi \cos\eta |3\rangle$$

Boundary conditions $\chi(0) = 0,\ \chi(t_f) = \pi/2,\ \eta(0) = 0 \quad \eta(t_f) = 0$

+ Ansatz for $\chi,\ \eta$

$$i\hbar \partial_t \Psi(t) = \tilde{H}(t)\Psi(t) \longrightarrow \tilde{\Omega}_{12}(t), \tilde{\Omega}_{23}(t)$$

Y. Ban, et al., Nanotechnology, 29, 505201 (2018)

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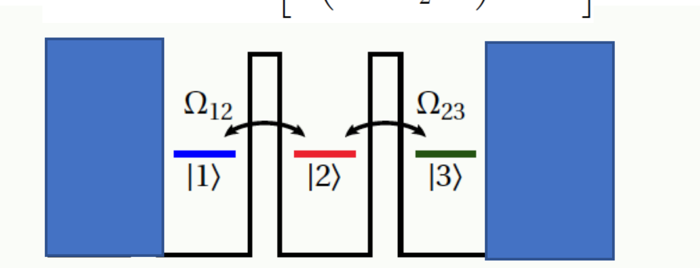

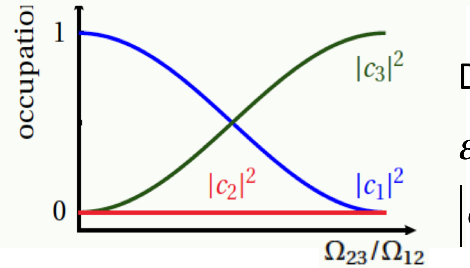

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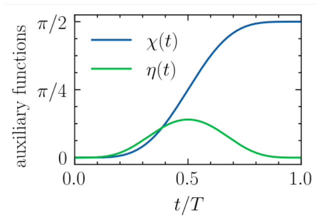
+ Ansatz for $\chi,\ \eta$

$$\chi(t) = \pi\frac{t}{2T} - \frac{1}{3}\sin\left(\frac{2\pi t}{T}\right) + \frac{1}{24}\sin\left(\frac{4\pi t}{T}\right)$$
$$\eta(t) = \arctan(\dot{\chi}/\alpha)$$



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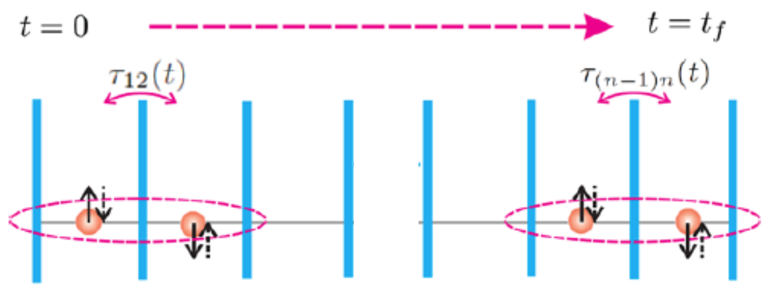
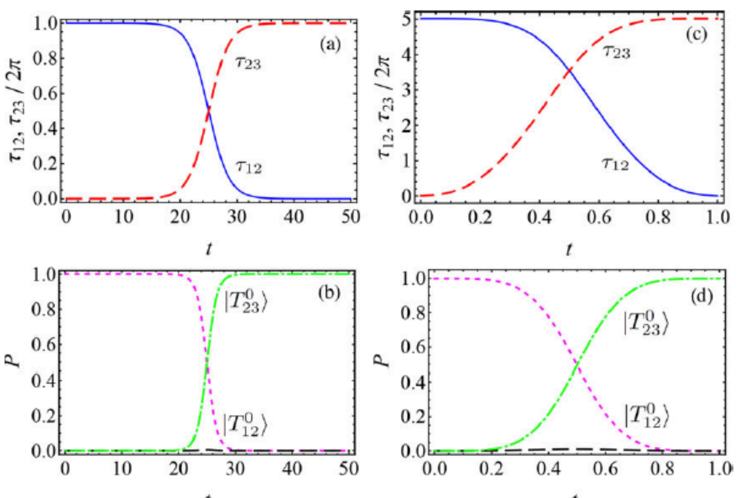
Quantum State Transfer in QDs

$$H=\sum_i \varepsilon_i n_i + U\sum_i n_{i\uparrow}n_{i\downarrow} + E_Z\sum_i (n_{i\uparrow}-n_{i\downarrow}) - \sum_{i,\sigma}\left(\tau_{N,i}c^{\dagger}_{i\sigma}c_{i+1\sigma} + \mathrm{h.\,c.}\right)$$

Spin-conserving tunneling rate



$$|T^0_{ij}\rangle = (|\uparrow_i\downarrow_j\rangle + |\downarrow_i\uparrow_j\rangle)/\sqrt{2}$$



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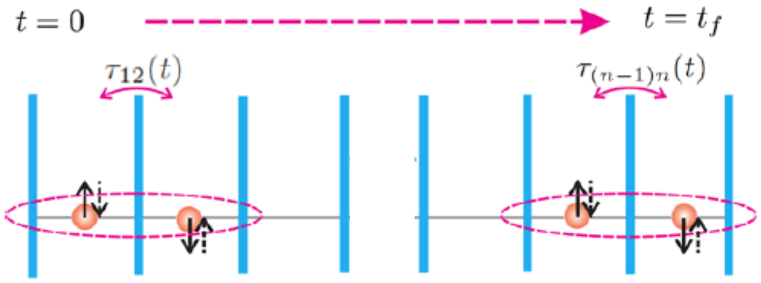

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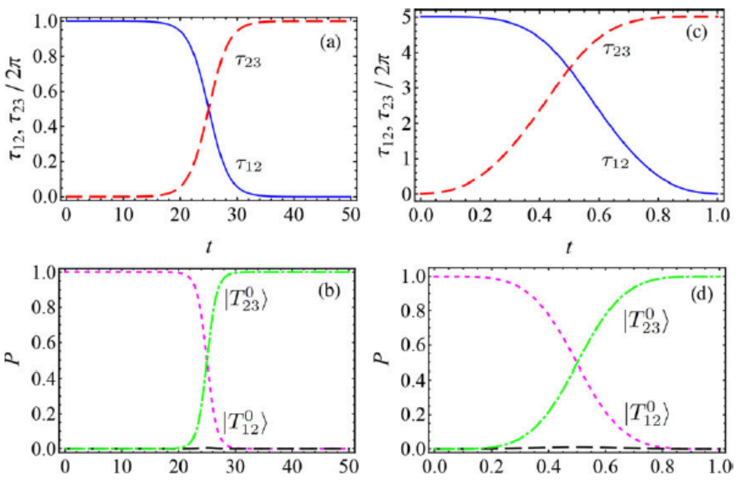

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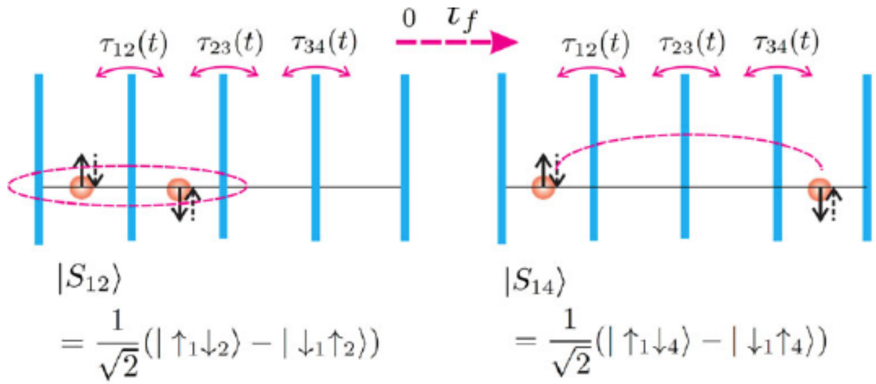
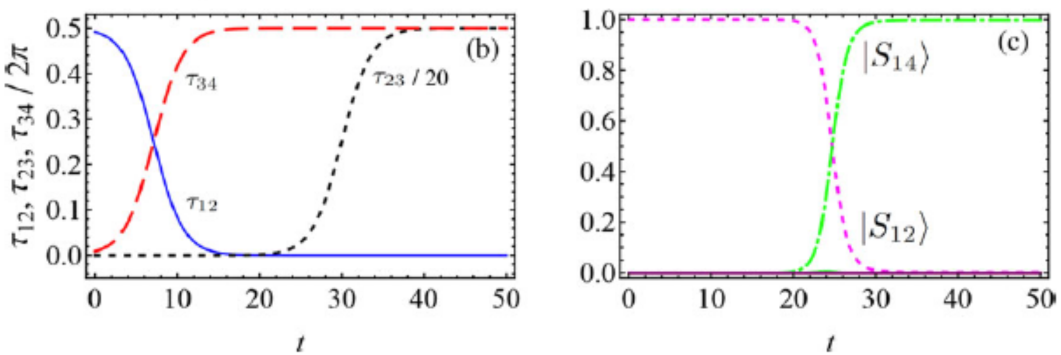
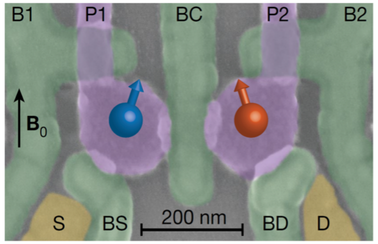




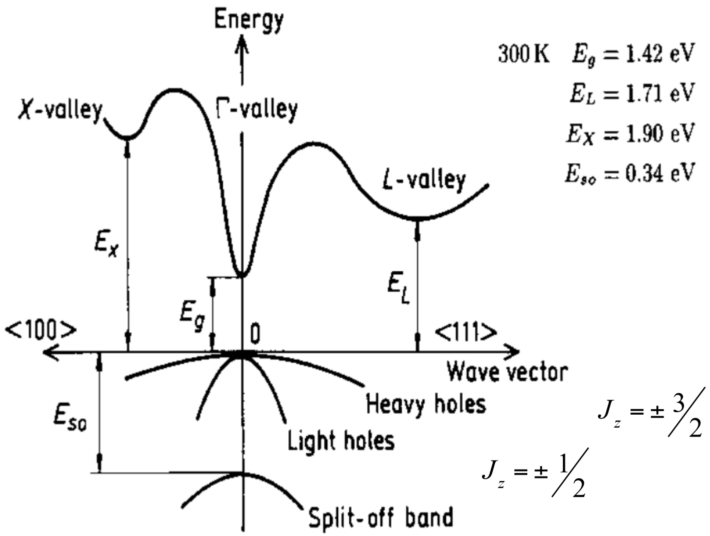
Y. Ban, et al.,Advanced Quantum Tech., 1900048 (2019).

Hole Spin Qubits

- **Weak Hyperfine Interaction**
- **Long spin decoherence and relaxation times**
- **Strong Spin-Orbit interaction**
- **Fast quantum operations (EDSR)**
- **High fidelity in the one and two quantum bits operations**

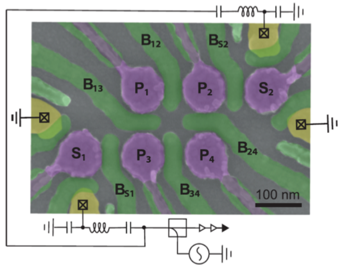


N.W. Hendrickx et al., Nature, 2020

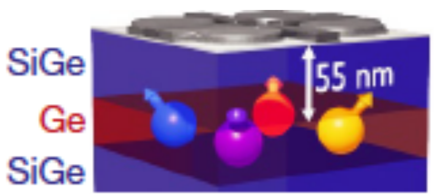


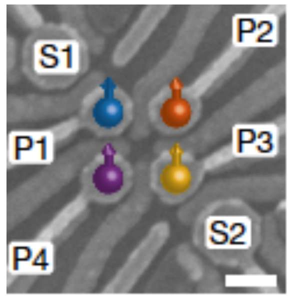
Recent advances in hole-spin qubits

Yinan Fang et al 2023
Mater. Quantum. Technol.



M. Veldhorst, et. al.
Appl. Phys. Lett. **118**, 2021





N. W. Hendrickx et al., Nature 2021

long-range hole spin transfer

Spin-Orbit interaction

$$H = \sum_i \varepsilon_i n_i + U \sum_i n_{i\uparrow} n_{i\downarrow} + E_Z \sum_i (n_{i\uparrow} - n_{i\downarrow}) - \sum_{i,\sigma} \left(\tau_{N,i} c^\dagger_{i\sigma} c_{i+1\sigma} + \mathrm{h.\,c.} \right) + \sum_i \left[-\tau_{F,i} \left(c^\dagger_{i\uparrow} c_{i+1\downarrow} - c^\dagger_{i\downarrow} c_{i+1\uparrow} \right) + \mathrm{h.\,c.} \right]$$

Spin-conserving tunneling rate

Spin-flip tunneling rate

$$H_{\mathrm{SOC}} = i\alpha E_\perp \left(\sigma_+ p_-^3 - \sigma_- p_+^3 \right) - \beta \left(\sigma_+ p_- p_+ p_- + \sigma_- p_+ p_- p_+ \right)$$

Rashba (structure inversion asymmetry) **Dresselhaus** (bulk inversion asymmetry)

Burkard, Phys. Rev. Res. 2021

$$H_{\mathrm{SOC}} = \sum_{i \neq j} \sum_{\sigma \neq \sigma'} \left(t_{F,ij} e^{i\vartheta_{ij}} \hat{c}^\dagger_{i\sigma} \hat{c}_{j\sigma'} + \mathrm{H.c.} \right)$$

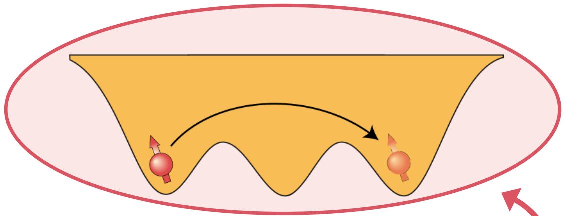
Due to spin-orbit coupling there is an effective spin-flip tunneling rate

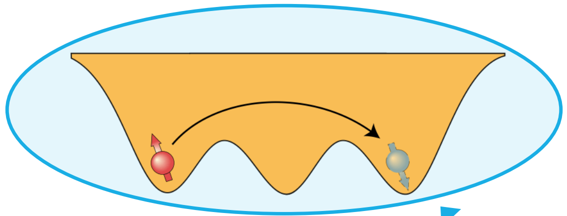
Dark State TQD

Triple Quantum Dot

All levels in resonance: $E_Z = 0$ $\varepsilon_i = 0$

- Proportional **spin-flip** and **spin-conserving** tunneling rates $\tau_{F,i}(t)/\tau_{N,i}(t) = x_{\mathrm{SOC}}$





$\tan\theta \equiv \tau_{N,2}/\tau_{N,1}$

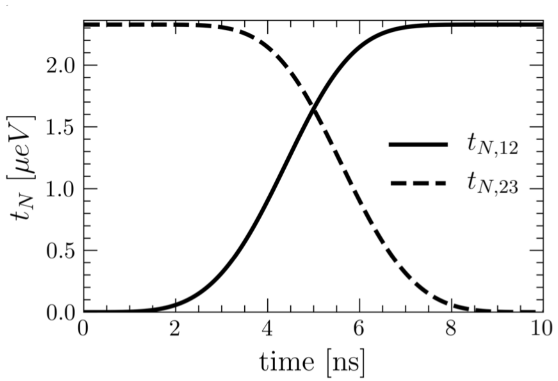
$$|\mathrm{DS}_1\rangle = -\sin\theta|\uparrow,0,0\rangle + \frac{\cos\theta}{x_{\mathrm{SOC}}^2+1}\left[(x_{\mathrm{SOC}}^2-1)\,|0,0,\uparrow\rangle + 2x_{\mathrm{SOC}}\,|0,0,\downarrow\rangle\right]$$

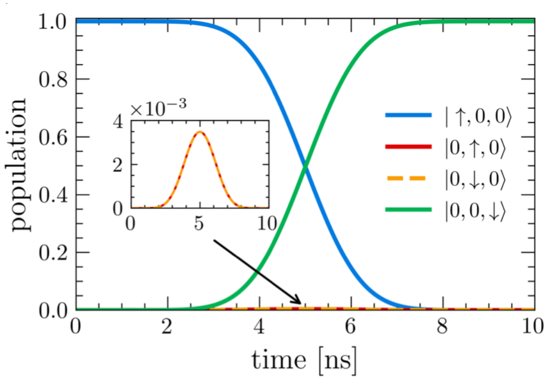
- Using the dark state, we connect **distant sites with minimal population in the middle site**
- The final **spin projection is controlled via the SOC**

long-range hole spin transfer

STA

1 Hole spin transfer in a TQD

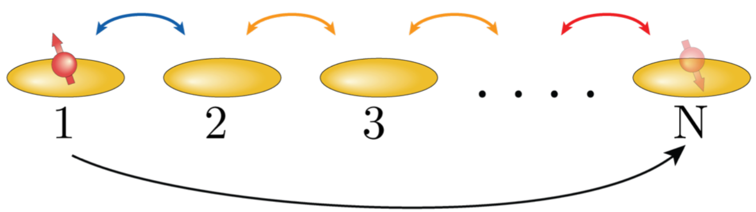


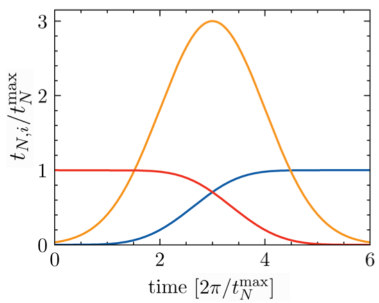


$X_{SOC}=1$

1 Hole spin transfer in N QDs Arrays

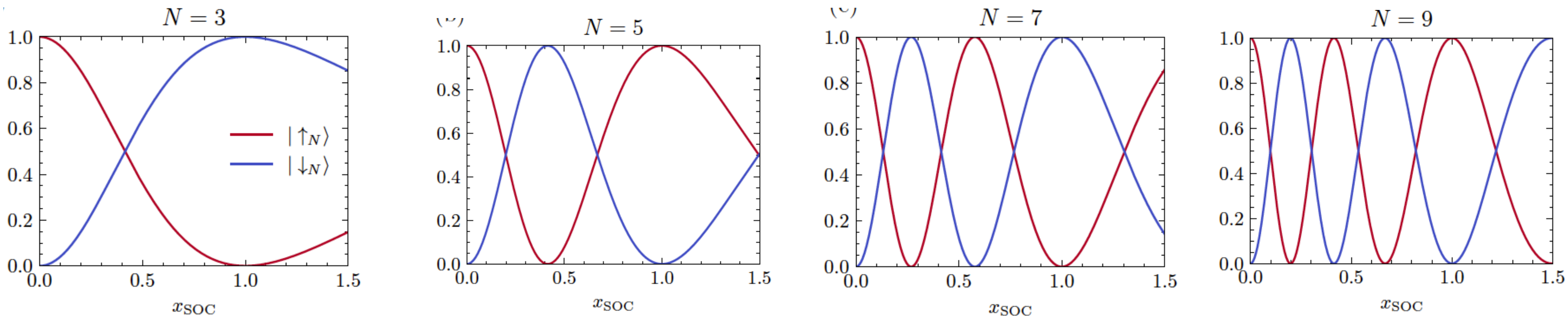
N-dots arrays (N>3)





long-range hole spin transfer

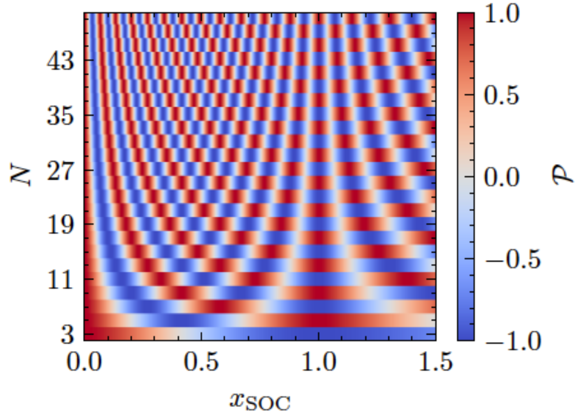
1 Hole spin transfer in N QDs Arrays (STA)

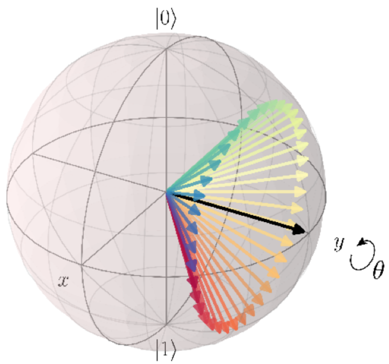


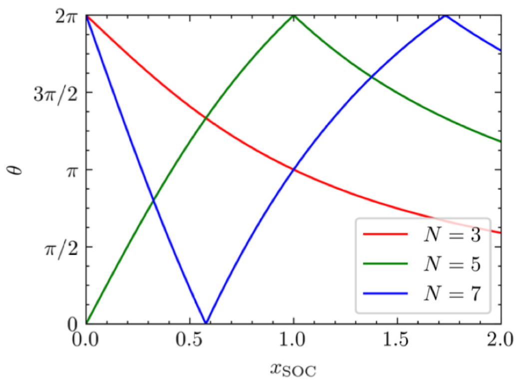
Intial state: | ↑ $_1$ >

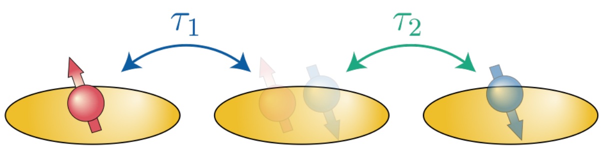
Tuning $x_{SOC} = \tau_{F,i}/\tau_{N,i}$

Control of the spin polarization



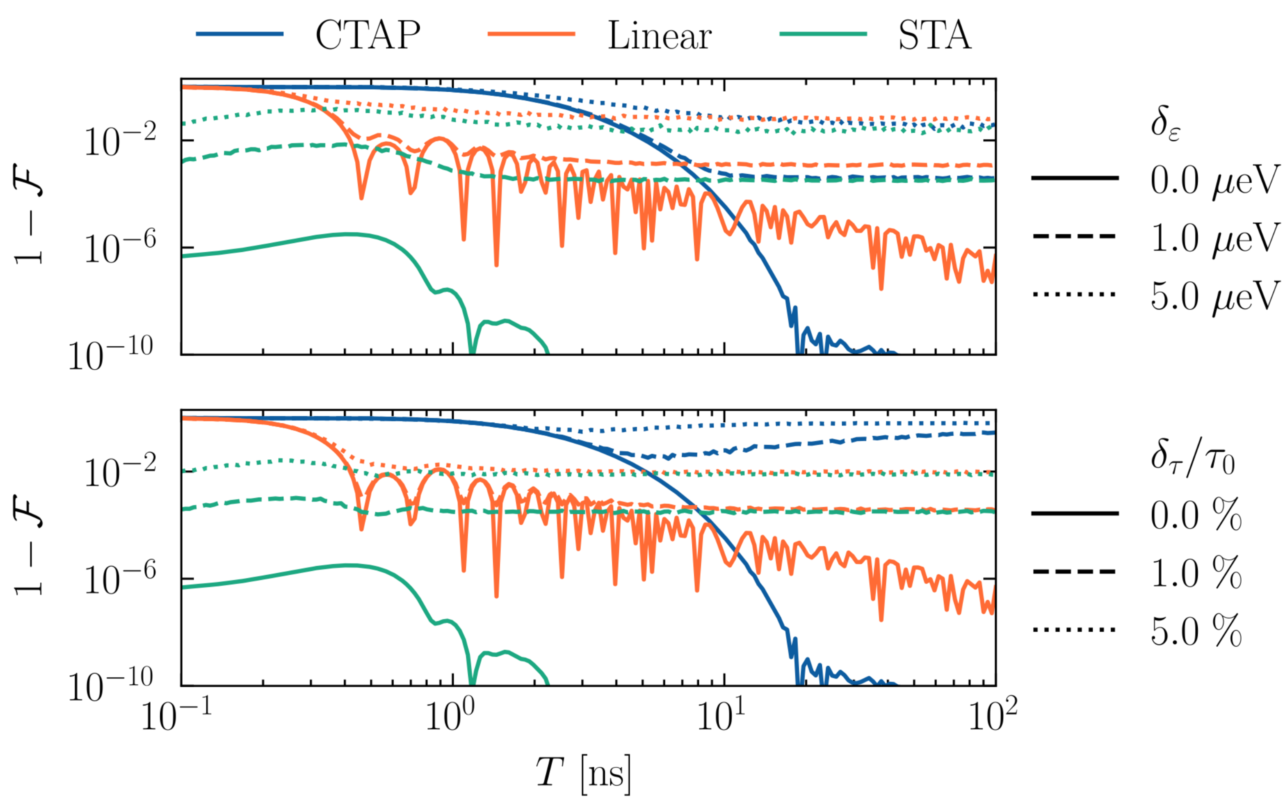






Noisy transfer

- Transfer fidelity defined as: $\mathcal{F} \equiv |\langle 0,0,\downarrow | \Psi(T)\rangle|^2$



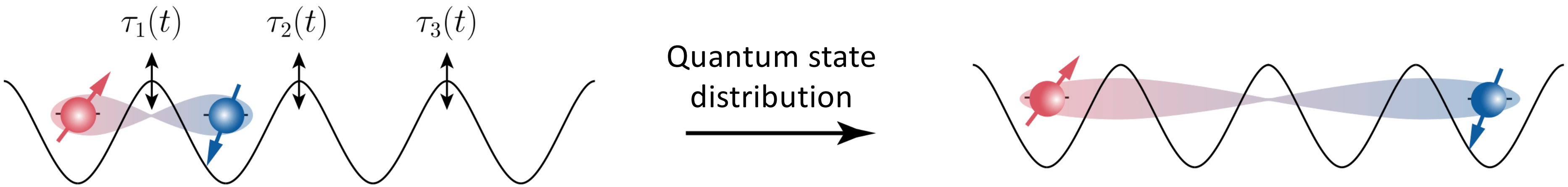
Parameters
$x_{SOC} = 1$
$\sigma = T/6$
$f_{min} = 0.16$ mHz
$f_{max} = 0.1$ MHz
$\tau_0 = 10$ μeV

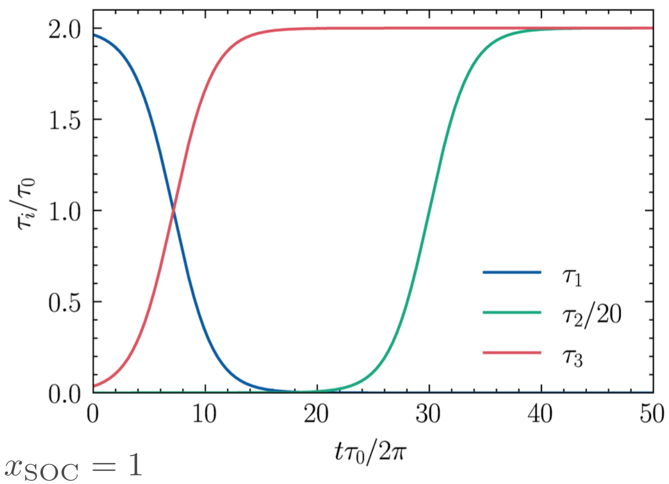
- **CTAP** highly sensitive to error in the tunneling rates
- **Linear** pulse obtain good results if the transfer time is large enough
- **STA** is the best among all the protocols for low transfer times

Quantum State Distribution

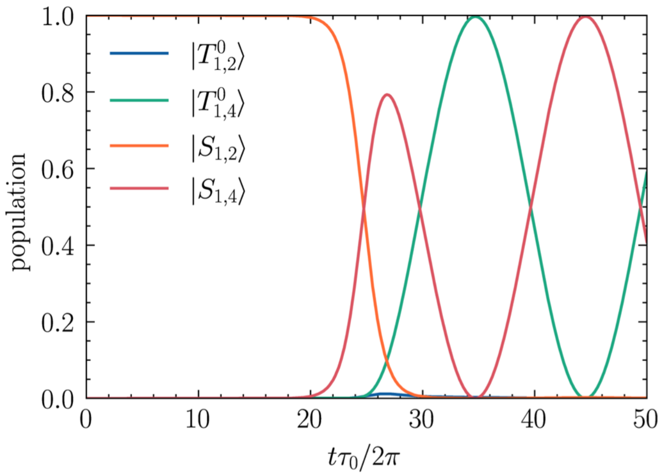
4 dots

- To communicate between distant quantum processors, we must be able to distribute entangled pairs (Yue Ban, et al., Adv. Quant. Tech. **2**, 1900048 (2019))





$x_{\mathrm{SOC}} = 1$
$E_Z = 10^3 \times \tau_0$



- **By tunning the total transfer time, the final spin state can be modified**

Quantum State Distribution

Initial state $|S_{1,2}>$

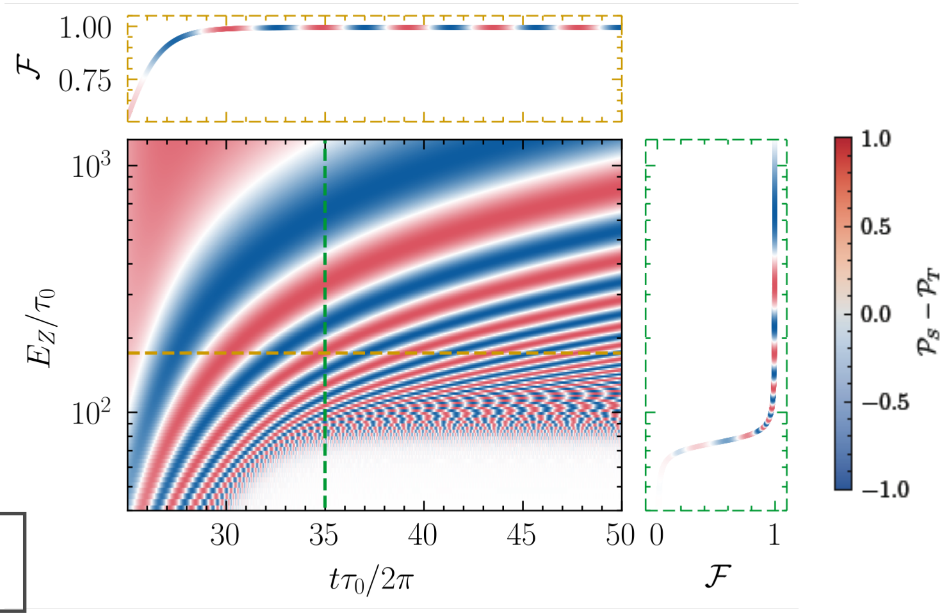
$$\mathcal{P}_S(t) \equiv |\langle S_{1,4}|\Psi(t)\rangle|^2$$

$$\mathcal{P}_T(t) \equiv |\langle T^0_{1,4}|\Psi(t)\rangle|^2$$

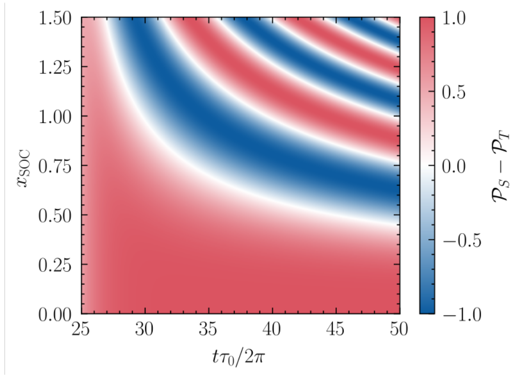
- **Spin polarization** between ends of the QD chain

$$\mathcal{F} \equiv \mathcal{P}_S(T) + \mathcal{P}_T(T)$$

- **Transfer fidelity**



<u>Parameters</u>
$x_{\rm SOC} = 1$

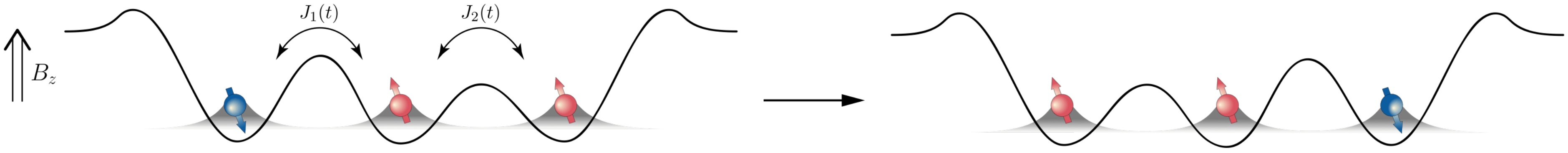


<u>Parameters</u>
$E_Z = 10^3 \times \tau_0$

Electric and magnetic control for the final spin projection of the entangled pair

Triple QD: HH half filling

- We can transfer quantum information by **moving the spin**, and not the charge

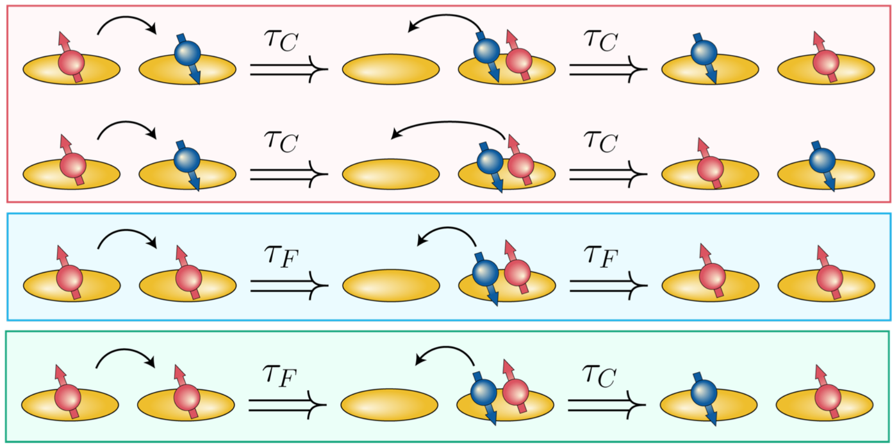


$$H_{\text{eff}} = E_Z \sum_i^N \sigma_z^i + \sum_i^{N-1} \Big[J_i^{NN} (\sigma_x^i \sigma_x^{i+1} + \sigma_y^i \sigma_y^{i+1} + \sigma_z^i \sigma_z^{i+1} - 1/4)$$

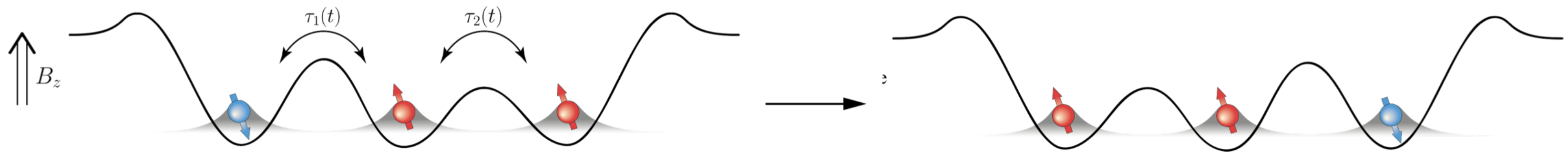
$$+ J_i^{FF} (-\sigma_x^i \sigma_x^{i+1} + \sigma_y^i \sigma_y^{i+1} - \sigma_z^i \sigma_z^{i+1} - 1/4)$$

$$+ 2 J_i^{NF} (\sigma_x^i \sigma_z^{i+1} - \sigma_z^i \sigma_x^{i+1}) \Big]$$

$$J_i^{ab} \equiv \tau_i^a \tau_i^b / U$$



Triple QD: HH half filling



For $E_Z \gg J^{ab}$ the subspaces with a total fixed spin projection are far apart in energy

$$E_Z/J_0 = 100 \quad S_z = +1/2$$

$$H_{\text{eff}} = \begin{pmatrix} -J_1^{NN} - J_2^{FF} & J_1^{NN} & 0 \\ J_1^{NN} & -J_1^{NN} - J_2^{NN} & J_2^{NN} \\ 0 & J_2^{NN} & -J_2^{NN} - J_1^{FF} \end{pmatrix}$$

$$J^{ab} \equiv \tau_a \tau_b / U \quad a,b = \{N,F\}$$

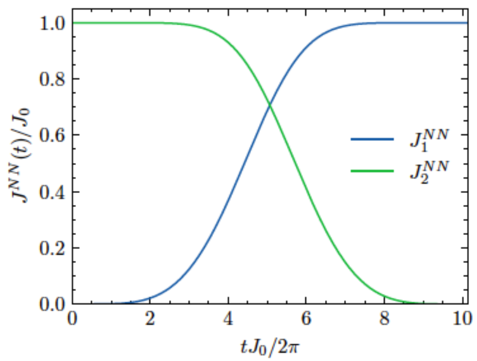
$$J_0 \equiv \max(J_1(t), J_2(t))$$

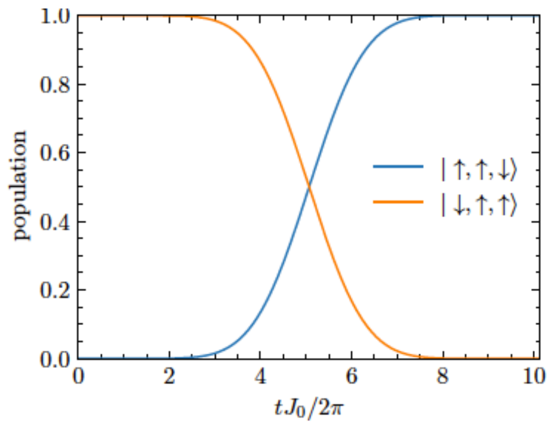
$$J_i^{NN} = J_i^{FF} = J_i$$

$$|\text{DS}\rangle = \sin\theta\,|\downarrow,\uparrow,\uparrow\rangle - \cos\theta\,|\uparrow,\uparrow,\downarrow\rangle$$

$$\tan\theta \equiv J_2/J_1$$

STA



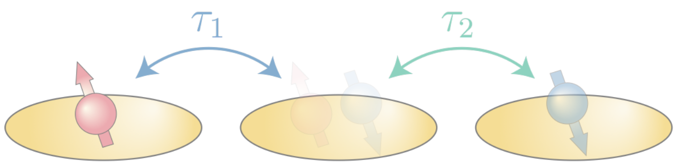


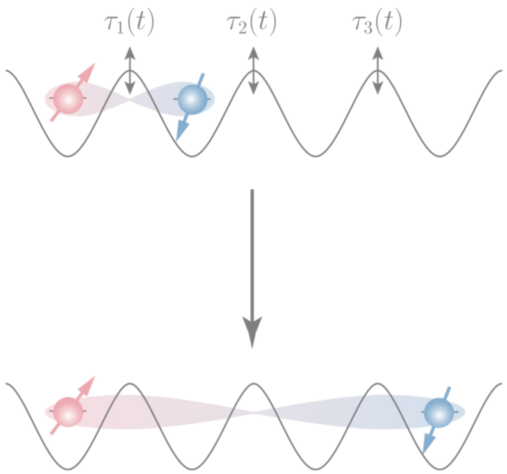
D. Fernández et al., in progress

Summary

- We have applied **STA** techniques to **hole spin qubits**, with **strong SOC**

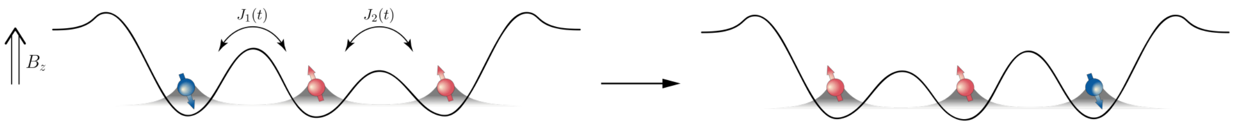
- **SOC** provides a **new control parameter** for the long-range **quantum information transfer**



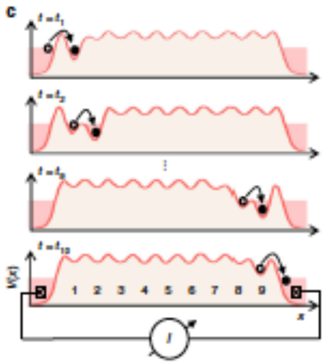


- We can perform a **one-qubit gate in parallel** to the state transfer
- Strong SOC also allows for **quantum state distribution** in large arrays

- Long-range **spin swapping**

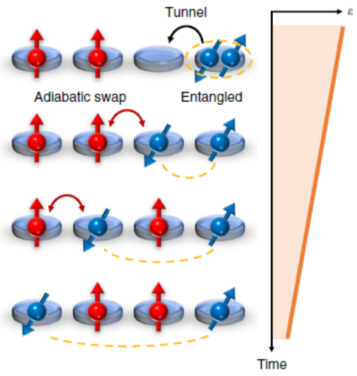


Quantum State Transfer in QD arrays



A.R. Mills e. al, Nature Comm, 2019

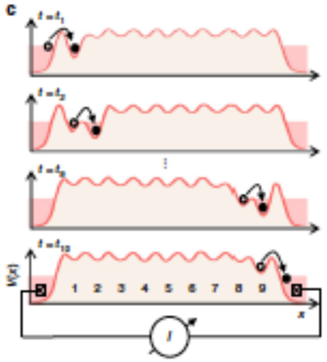
Nakajima et. al.,
Nat. Comm. 2018



Adiabatic quantum state transfer in a semiconductor quantum-dot spin chain, Y. P. Kandel et al., Nature Comm. 2021

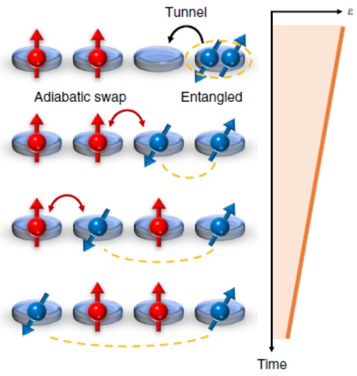
Coherent transport of spin by adiabatic passage in quantum dot arrays, MJ Gullans, J. Petta, PRB 2020

Quantum State Transfer in QD arrays



Nakajima et. al.,
Nat. Comm. 2018

A.R. Mills e. al, Nature Comm, 2019



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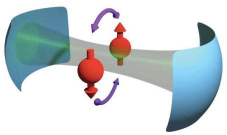
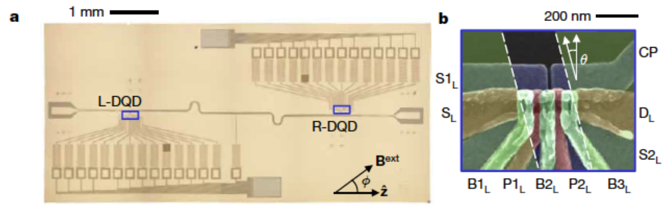
A Coherent Spin-Photon Interface in Silicon



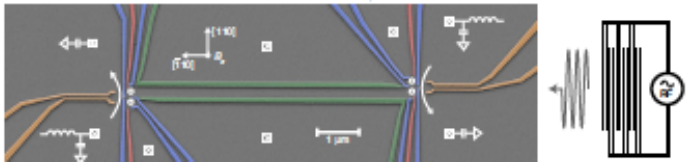
X. Mi et al., Nature, 2018

Strong coupling between a photon and a hole spin in silicon, CX Yu et al, 2022

Towards cavity mediated spin-spin coupling F. Borjans et al., Nature, 2020



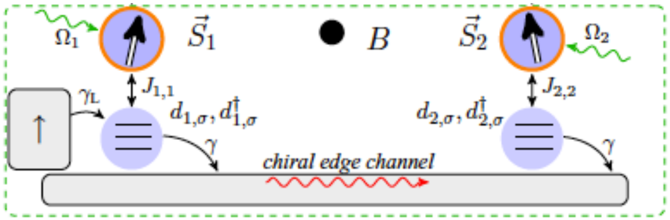
QDs and SAW: Distant spin entanglement via fast and coherent electron shuttling,
Jadot et al., , Nature Nanotech, 2021



Quantum state transfer by topological edge states

Mesoscopic One-Way Channels for Quantum State Transfer via the Quantum Hall Effect

Stace et al., PRL, 2004



Long-distance entanglement of spin qubits via quantum Hall edge states, G. Yang et al., PRB 2016

Long-range entanglement generation between electronic spins, M. Benito et al., PRB 2016

Entangling Nuclear Spins in Distant Quantum Dots via an Electron Bus, M. Bello et al., Phys. Rev. Applied, 2022.

Simulation of a 1D topological insulator in a driven quantum dot array

B. Pérez-González et al., PRL 2019

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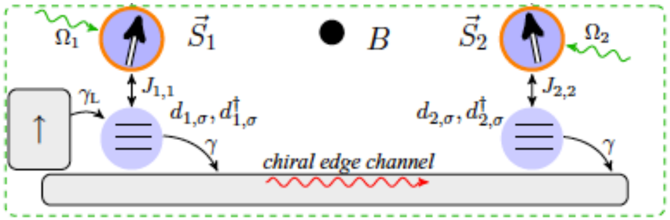

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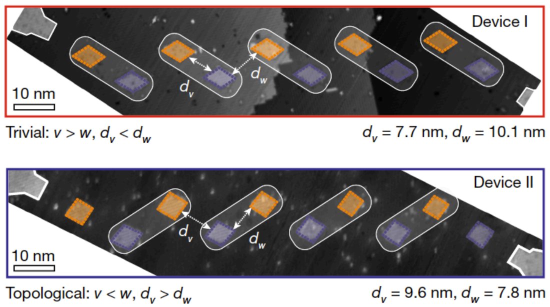
B. Pérez-González et al., PRL 2019

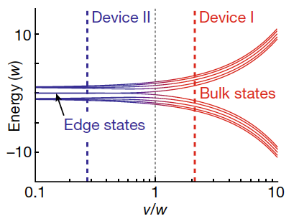
Floquet theory:
see M. Grifoni and P. Hanggi,
Phys. Reports, **304** (1998) 229—354

A dimer chain

Engineering topological states in atom-based semiconductor quantum dots

M. Kiczynski et al.
Nature, June 2022





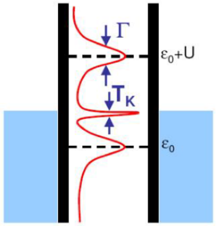
QDs as Quantum Simulators

Quantum Simulation of Antiferromagnetic Heisenberg Chain with Gate defined QDs, PRX, C.J. van Diepen et al., 2021

Quantum Simulation of the Fermi-Hubbard model using QD arrays, T. Henggens et al., Nature, 2017

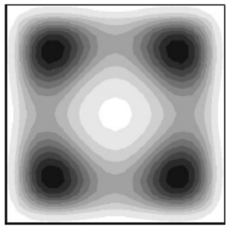
A Tunable Kondo Effect in Quantum Dot
S. Cronnenwelt et al., Science 98

Kondo effect and SO coupling in Graphene QDs,
A. Kurzman et al., Nat. Comm., 2021

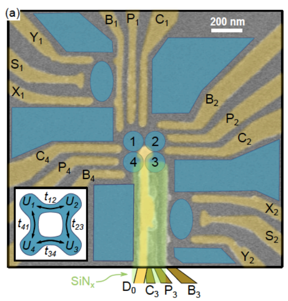


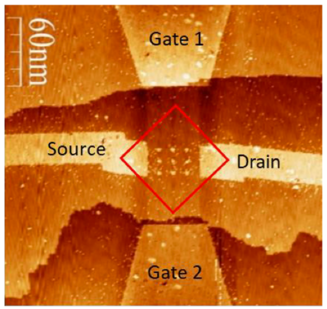
Dynamical control of correlated states in a square quantum dot

C. Crefield and GP, PRB 2002



Nagaoka ferromagnetism observed in a QD plaquette, JP Dehollais et al., Nature 2020

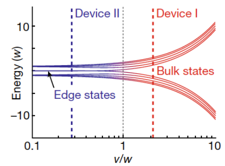


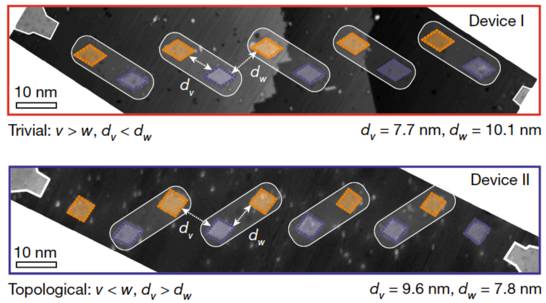


Quantum Simulation of an Extended Fermi-Hubbard Model Using a 2D Lattice of Dopant-based Quantum Dots ,
X. Huang et al., arXiv: 2110.08982.

Engineering topological states in atom-based semiconductor quantum dots

M. Kiczynski et al.
Nature, June 2022

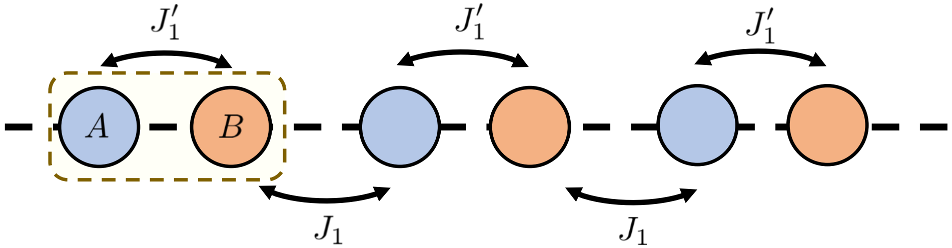




Topology

The level splitting decays exponentially
with the number of atoms

Dimer chain (SSH model)

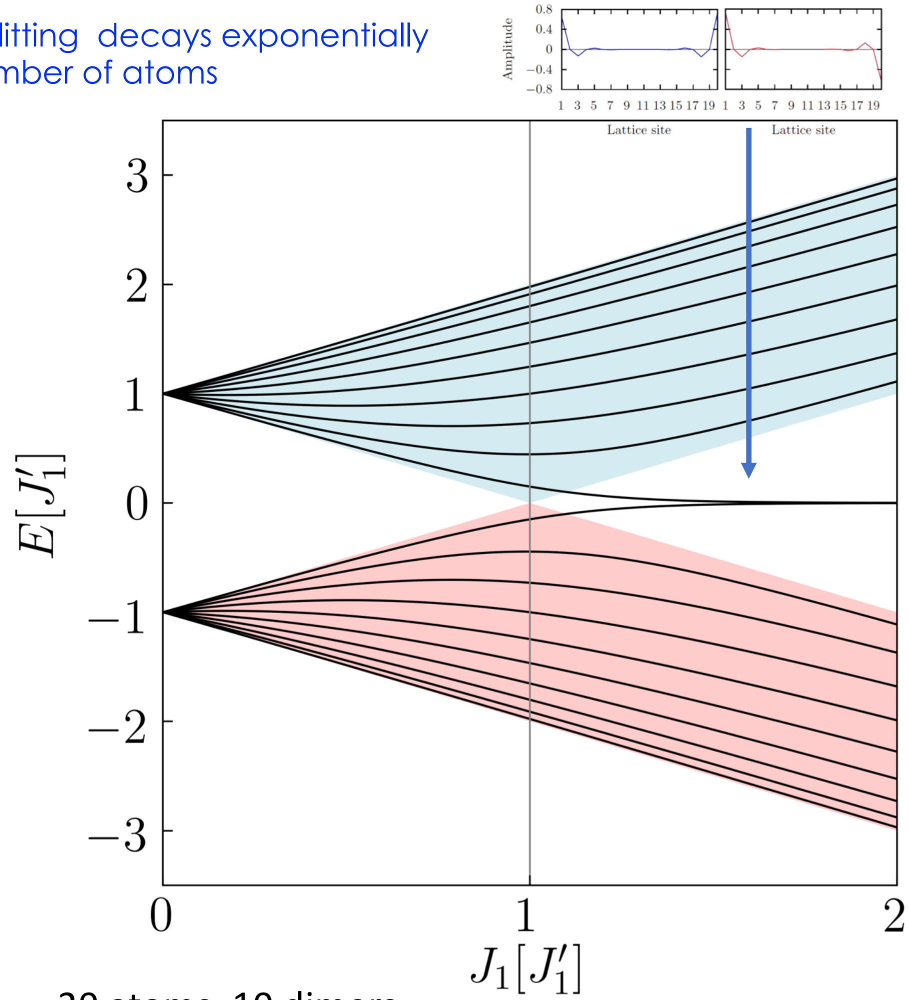


$$H = -J_1' \sum_{i=1,\sigma}^{M} c^{\dagger}_{2i\sigma} c_{2i-1\sigma} - J_1 \sum_{i=1,\sigma}^{M-1} c^{\dagger}_{2i+1\sigma} c_{2i\sigma} + \text{h.c.}$$

$$\left(\frac{J_1'}{J_1}\right)_c = 1 - \frac{1}{M+1}$$

$$N_{\text{bulk}} = 2M \qquad \frac{J_1'}{J_1} > \left(\frac{J_1'}{J_1}\right)_c$$

$$N_{\text{bulk}} = 2(M-1) \qquad \frac{J_1'}{J_1} < \left(\frac{J_1'}{J_1}\right)_c$$



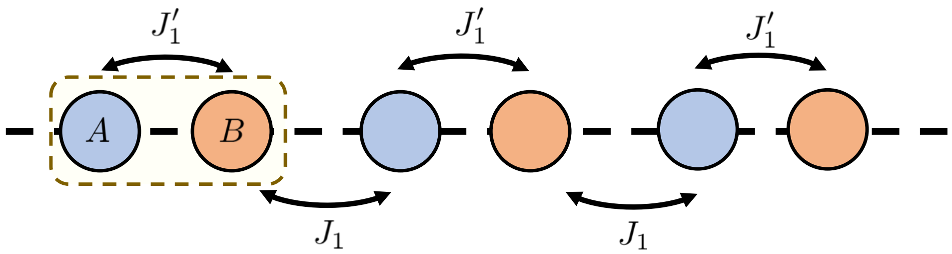
20 atoms, 10 dimers

“A short Course of Topological Insulators”, J.K. Asboth et al., Springer

BDI class in the Altland-Zirnbauer classification

20 atoms, 10 dimers

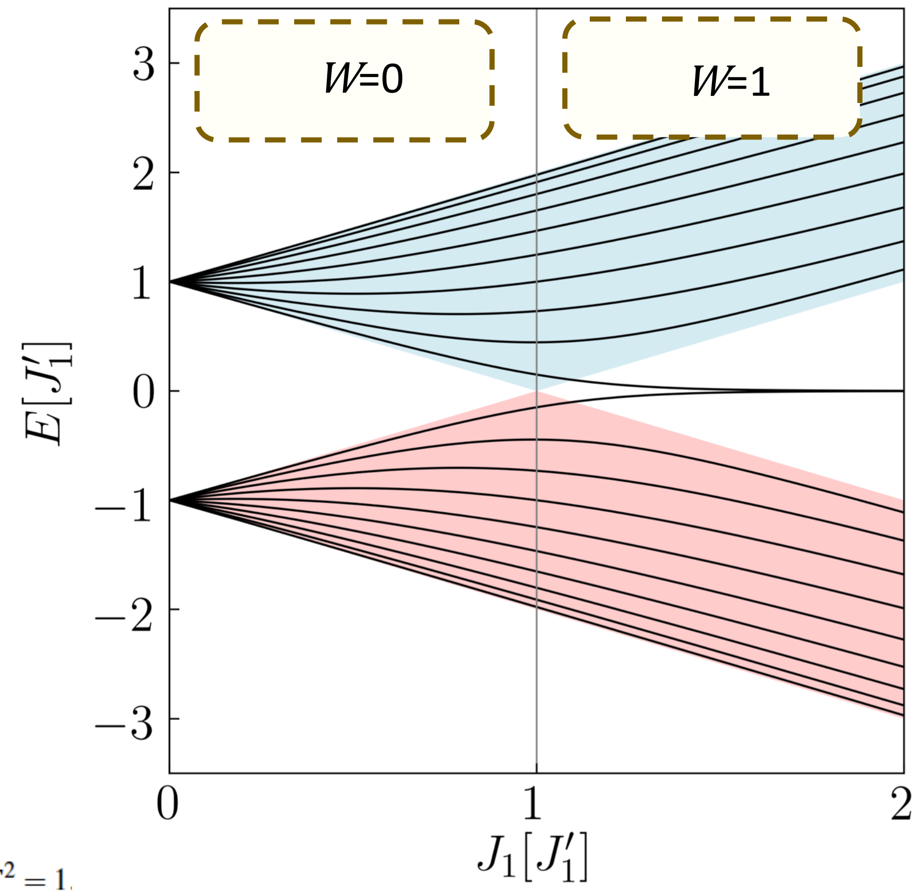
Dimer chain (SSH model)



$$\mathcal{W} = \frac{1}{2\pi} \int \langle u_{\alpha,k} | i\partial_k | u_{\alpha,k} \rangle dk$$

Berry's phase picked up by a particle moving accross the Brillouin zone.

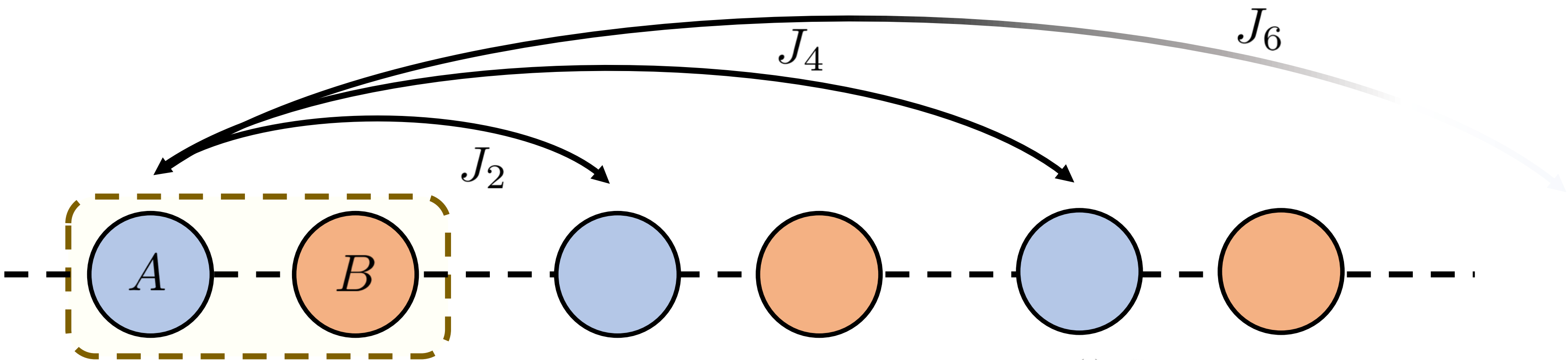
Measured in cold atoms by I. Bloch and coworkers: Nature Physics, M.Atala et al. 2013



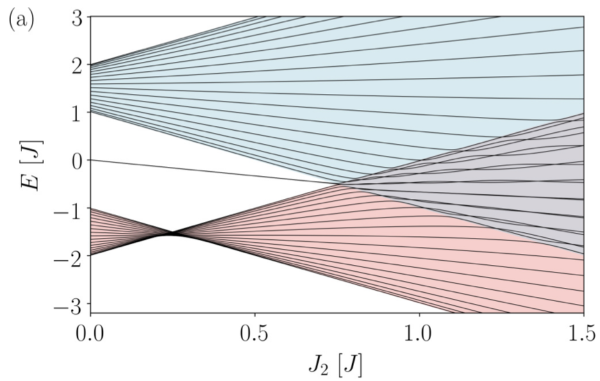
$\hat{\Gamma}\hat{H}\hat{\Gamma}^\dagger = -\hat{H}$ $\quad \hat{\Gamma}^\dagger\hat{\Gamma} = \hat{\Gamma}^2 = 1.$

Extended SSH model

even-neighbor hoppings



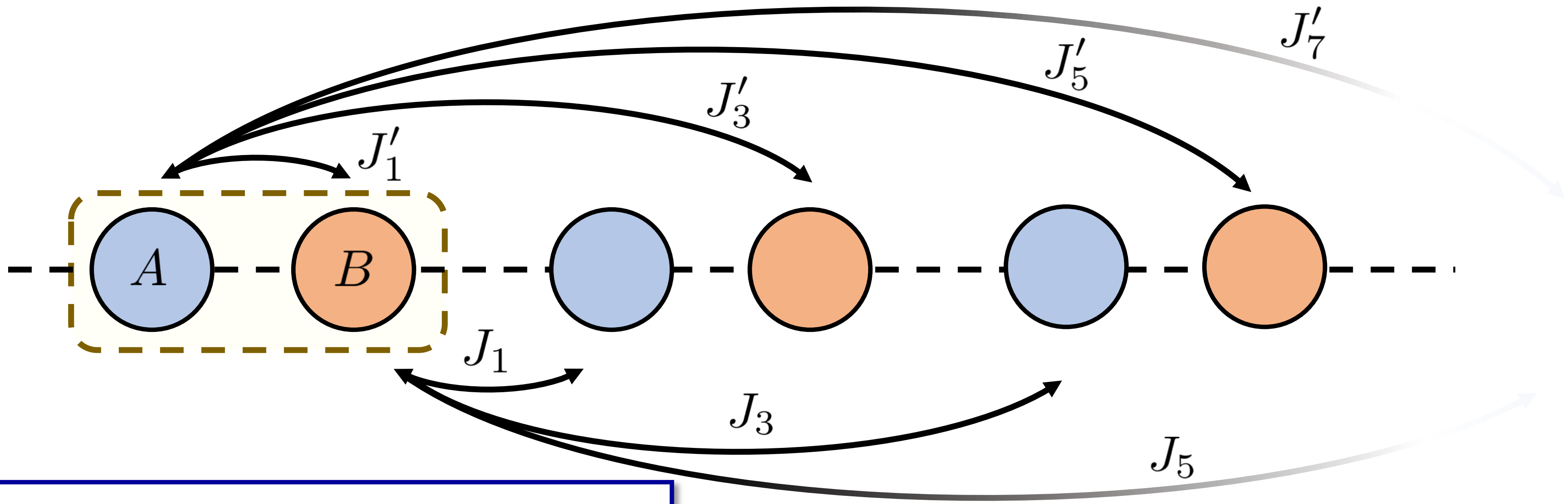
broken chiral symmetry



B. Pérez-González et al., Phys. Rev. B, **99**, 035146 (2019).

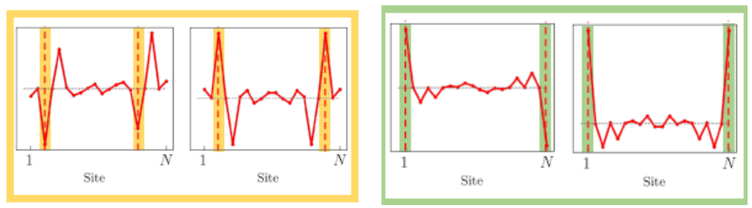
Extended SSH model

odd-neighbor hoppings



✓ chiral symmetry $\mathcal{W} = 0, 1, 2, 3, \ldots$

first and third neighbors



What is a Floquet System?

- Exhibits discrete time translation symmetry:

$$H(t+T) = H(t)$$

- For such a system, the Floquet theorem must hold

Floquet Theorem:

$$H(t+T) = H(t) \implies \Psi_\lambda(\mathbf{r},t) = e^{-i\omega_\lambda t} u_\lambda(\mathbf{r},t),$$

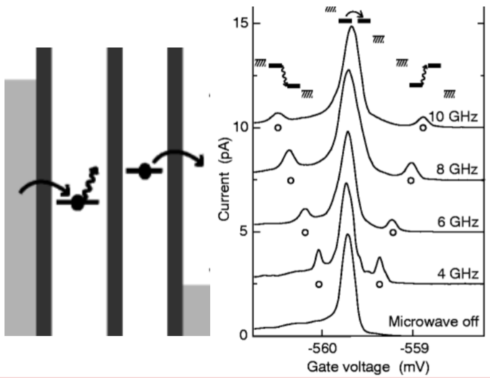
$$u_\lambda(\mathbf{r},t+T) = u_\lambda(\mathbf{r},t)$$

Energy → Quasienergy $\hbar\omega_\lambda \in \left[-\frac{\pi\hbar}{T}, \frac{\pi\hbar}{T}\right]$

(Note: totally analogous to Bloch's theorem!)

Driving with periodic AC fields ➡ $H_{ac}(t)$: Floquet Engineering

- Photoassisted Tunneling (PAT) in quantum dots



Coherent destruction
of tunnel,
P. Hänggi, PRL, 1991

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

Driving with periodic AC fields ➡ $H_{ac}(t)$: Floquet Engineering

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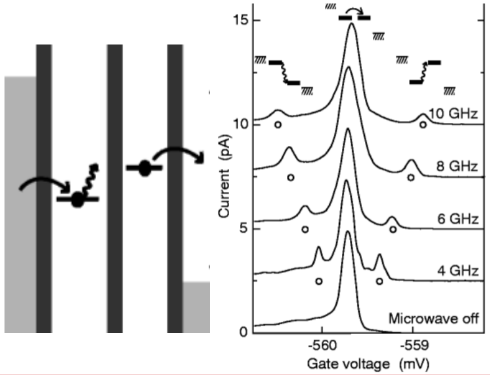
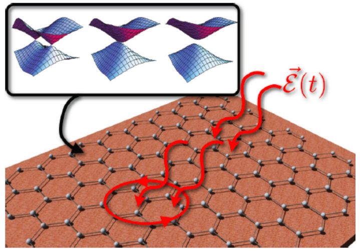


T. H. Oosterkamp et al., Nature 395, 873-876, 1998

Coherent destruction of tunnel, P. Hänggi, PRL, 1991

Bonds renormalization

❑ Tuning electronic and topological properties in driven systems



P. Delplace, A. Gómez León, GP PRB 88, 245, 2013

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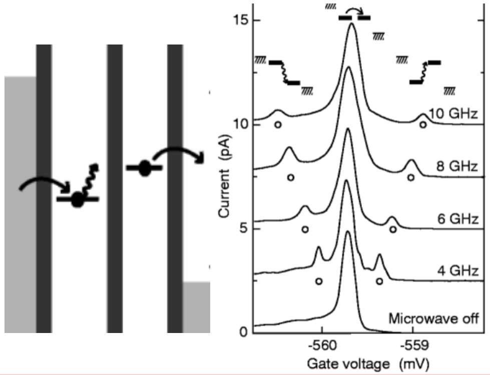

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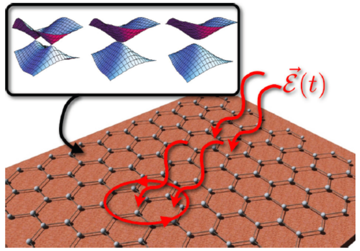

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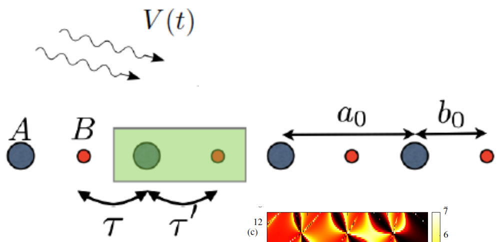
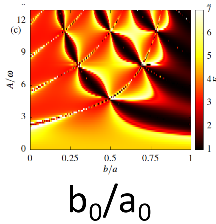
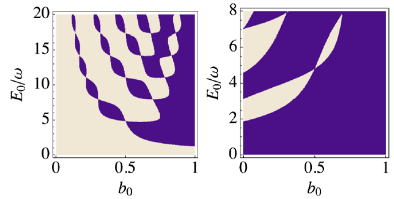


A. Gómez León and GP,
B. PRL,110, 200403, 2013





M. Niklas et al., Nanotech., 2017

M. Bello, C.E. Creffield, GP, Scientific Rep, 6, 22562, 2016

Driving with periodic AC fields ➡ $H_{ac}(t)$: Floquet Engineering

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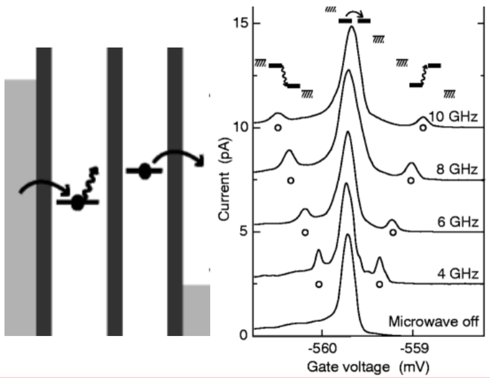

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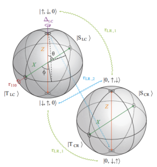
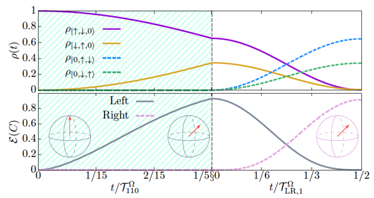
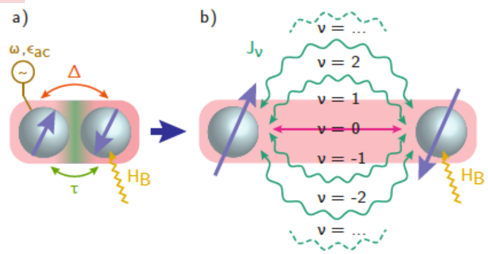


$$\cos\left(\frac{\theta_L}{2}\right)|\uparrow,\downarrow,0\rangle + \sin\left(\frac{\theta_L}{2}\right)e^{i\phi_L}|\downarrow,\uparrow,0\rangle$$

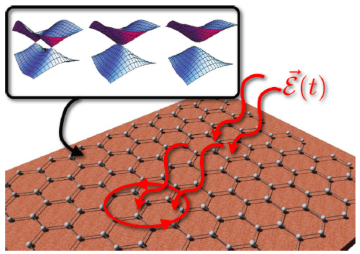


J. Picó-Cortés et al., PRB 2019



J. Picó-Cortés, G.P., Quantum 5,607, 2021

- ❑ Tuning electronic and topological properties in driven systems



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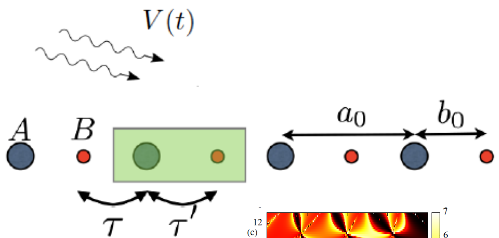
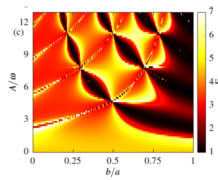
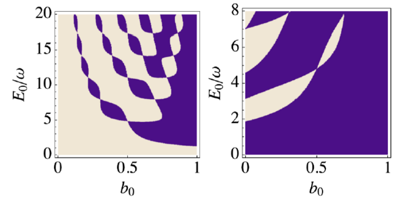


A. Gómez León and GP, B. PRL,110, 200403, 2013



b_0/a_0

M. Niklas et al., Nanotech., 2017



M. Bello, C.E. Creffield, GP, Scientific Rep, 6, 22562, 2016

Model

$$H(t) = \sum_{|i-j|<R} J_{ij} c_i^\dagger c_j + \sum_i A_i f(t) c_i^\dagger c_i \qquad f(t) = \begin{cases} 1 & \text{if} \quad 0 \le t < T/2 \\ -1 & \text{if} \quad T/2 \le t < T \end{cases}$$

$$\omega \gg J_{ij}$$

$$H_{\text{eff}} = \sum_{|i-j|<R} \tilde{J}_{ij} c_i^\dagger c_j$$

renormalized hopping amplitudes in terms of the field parameters

$$\tilde{J}_{ij} = J_{ij} \frac{i\omega}{\pi(A_i - A_j)} \left[e^{-i\pi \frac{A_i - A_j}{\omega}} - 1 \right]$$

- periodically spaced zeroes, located at

$$A_i - A_j = 2\omega q \qquad (q = 0, 1, 2 \ldots)$$

- functions of the difference between on-site potentials

Simulation of the extended SSH model

our driving protocol:

- creates a dimerized structure
- suppresses all even hoppings

$$\tilde{J}_{ij} = J_{ij}\frac{i\omega}{\pi(A_i - A_j)}\left[e^{-i\pi\frac{A_i - A_j}{\omega}} - 1\right]$$

$A_j - A_i = \alpha + \beta$

$|i - j| = 2n$

$n = 1,2\ldots$

$\alpha + \beta = 2\omega q$

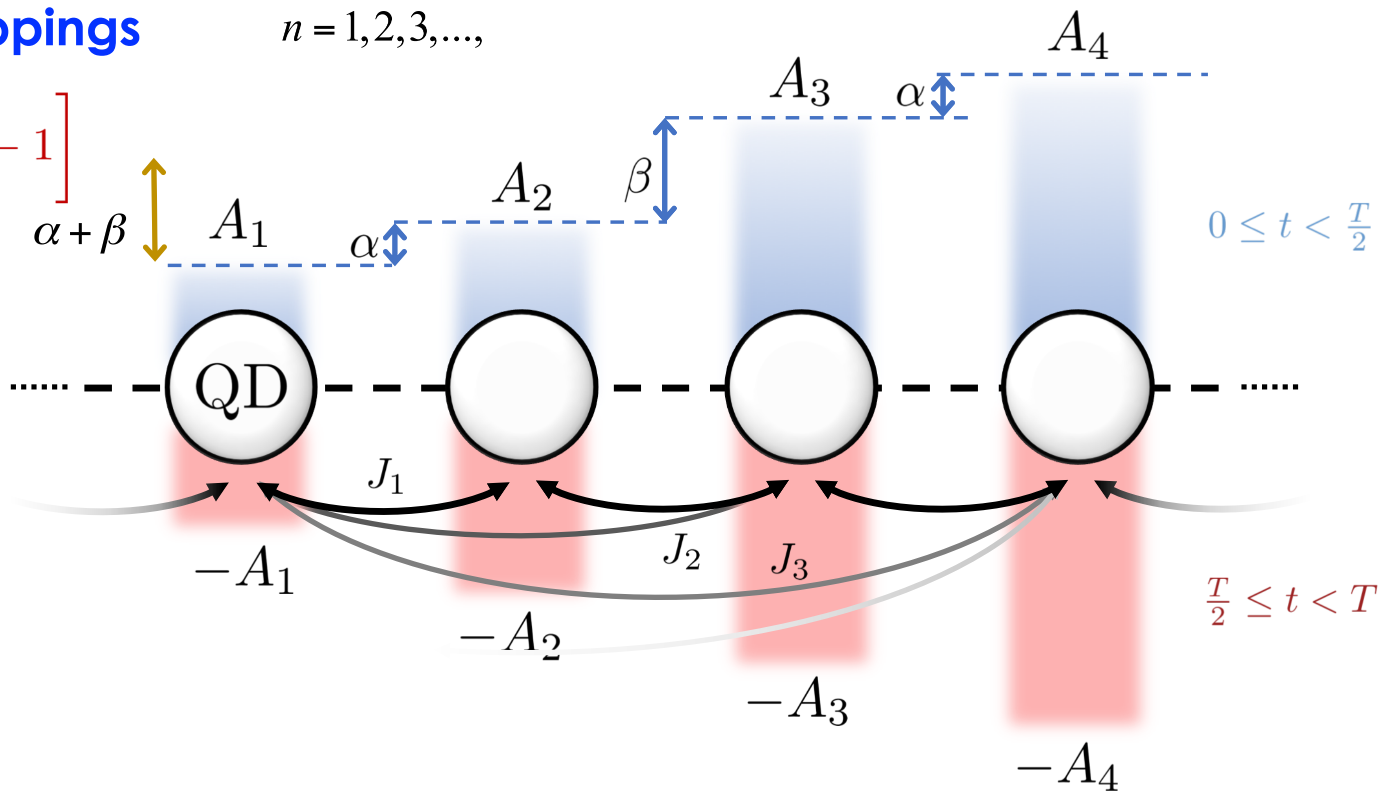
$J_{i,i+2n} = 0$

$A_{2n} = n(\alpha+\beta)$

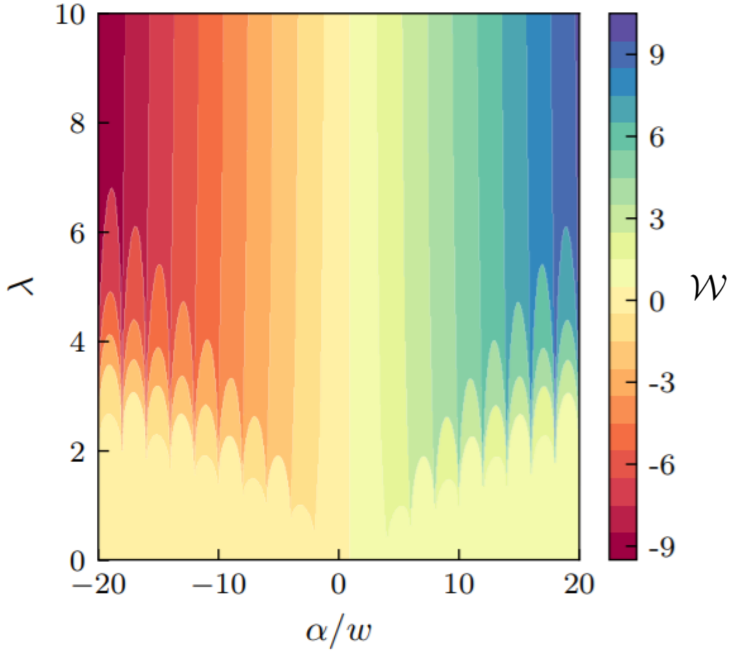
$A_{2n-1} = n(\alpha+\beta) - \alpha$

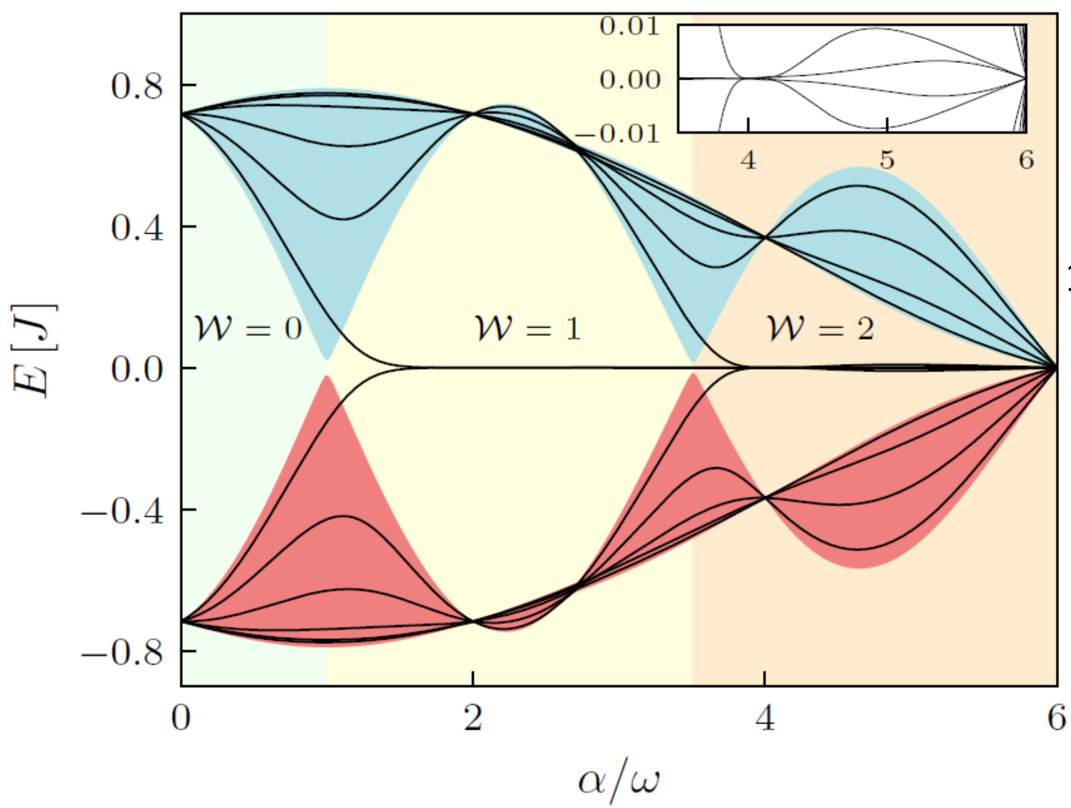
$n = 1,2,3,\ldots,$

$\alpha \to$ effective field amplitude



Simulation of the extended SSH model





12 QDs

- exponential decay with distance

$$J_{ij} = Je^{-d_{ij}/\lambda}$$

- R defined as a function of λ

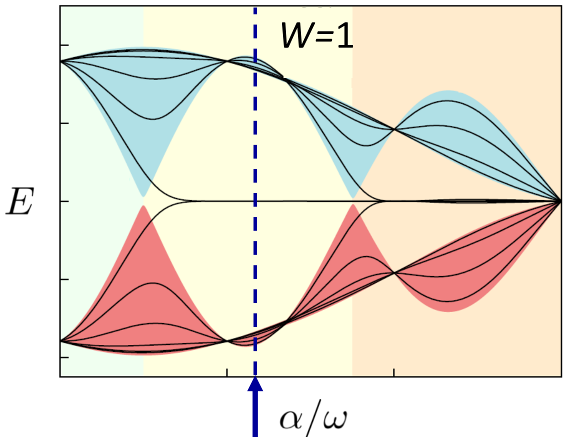
$$\frac{J_{\text{longest}}}{J_{\text{shortest}}} = 10^{-8}$$

$$\lambda = 1.5$$

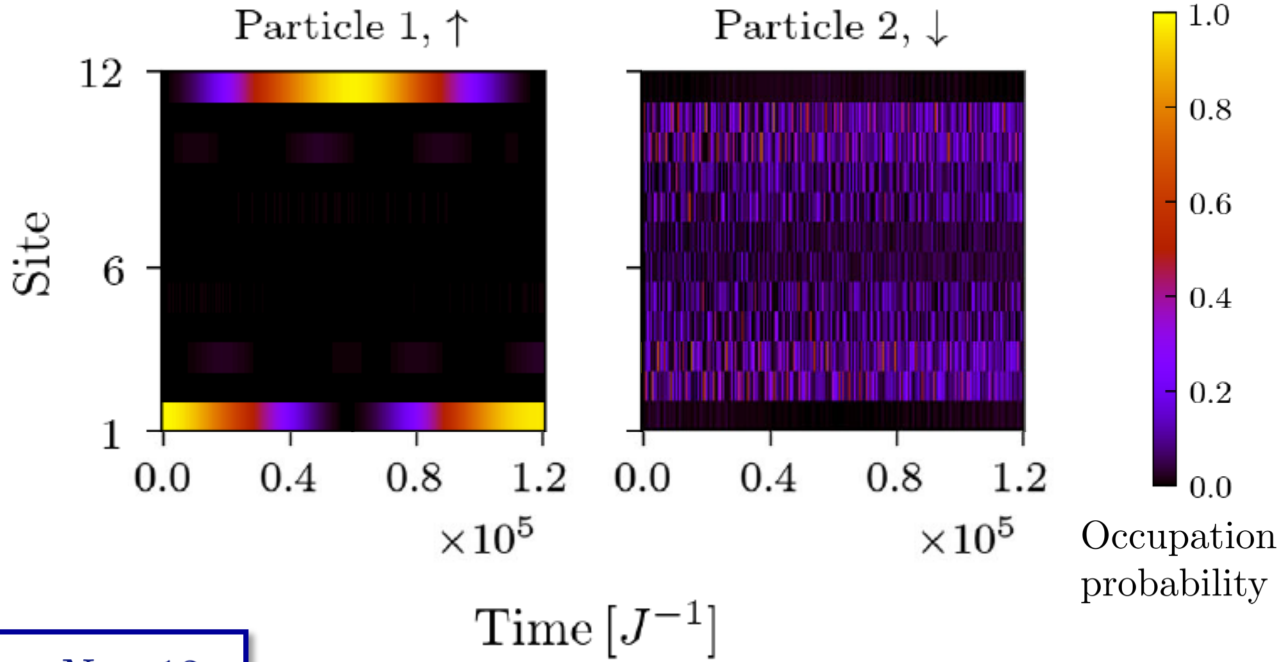
Simulation of the extended SSH model

dynamics of two interacting particles with opposite spin loaded into the system as $|\uparrow_1 \downarrow_3\rangle$

- $U = 0$



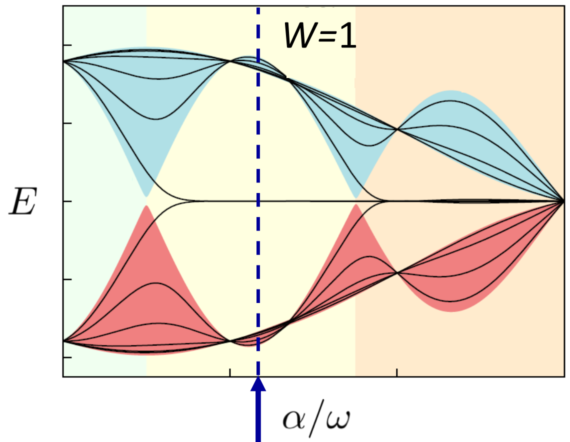
$\omega = 100 \quad \alpha = 230 \quad \lambda = 1.5 \quad N = 12$

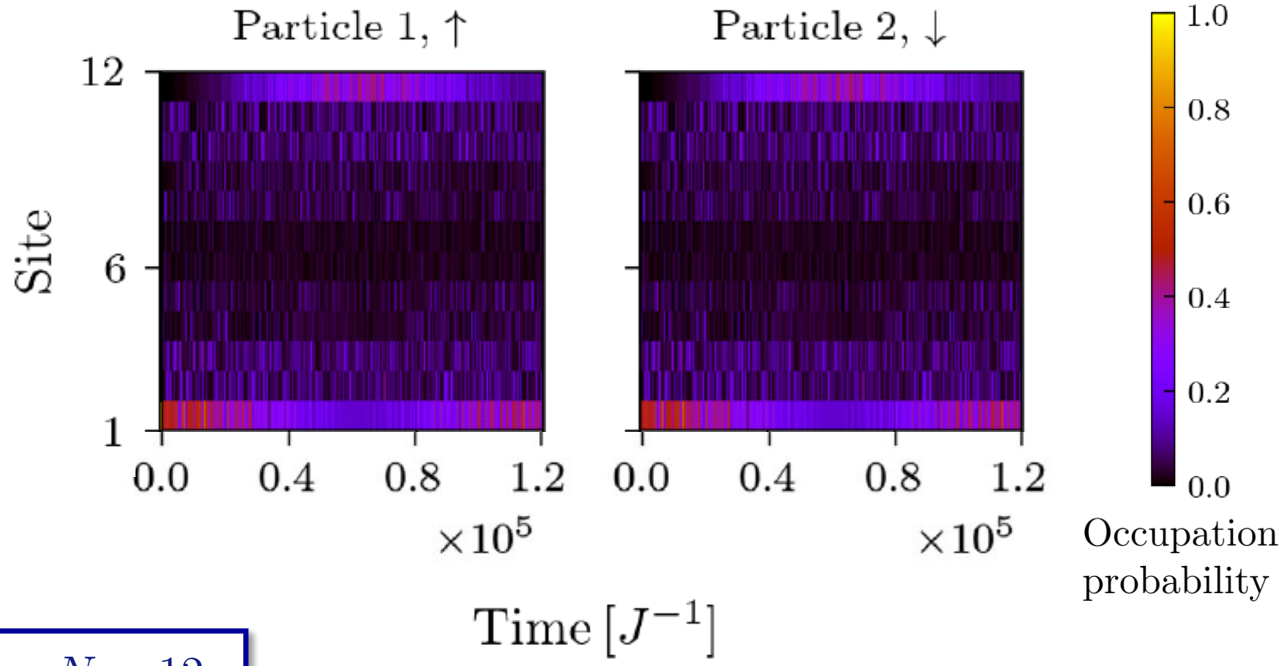


Simulation of the extended SSH model

dynamics of two interacting particles with opposite spin loaded into the system as $|\uparrow_1\downarrow_3\rangle$

- $U = 5J$





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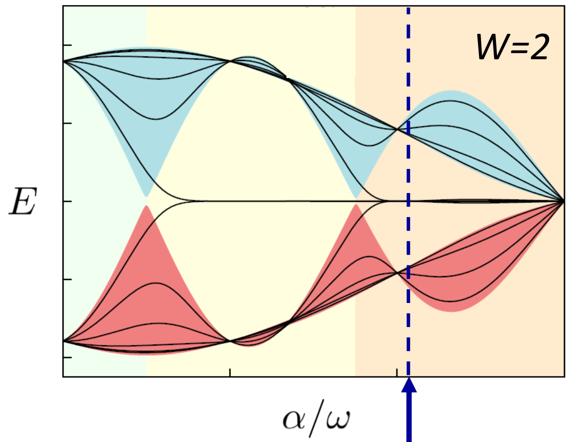

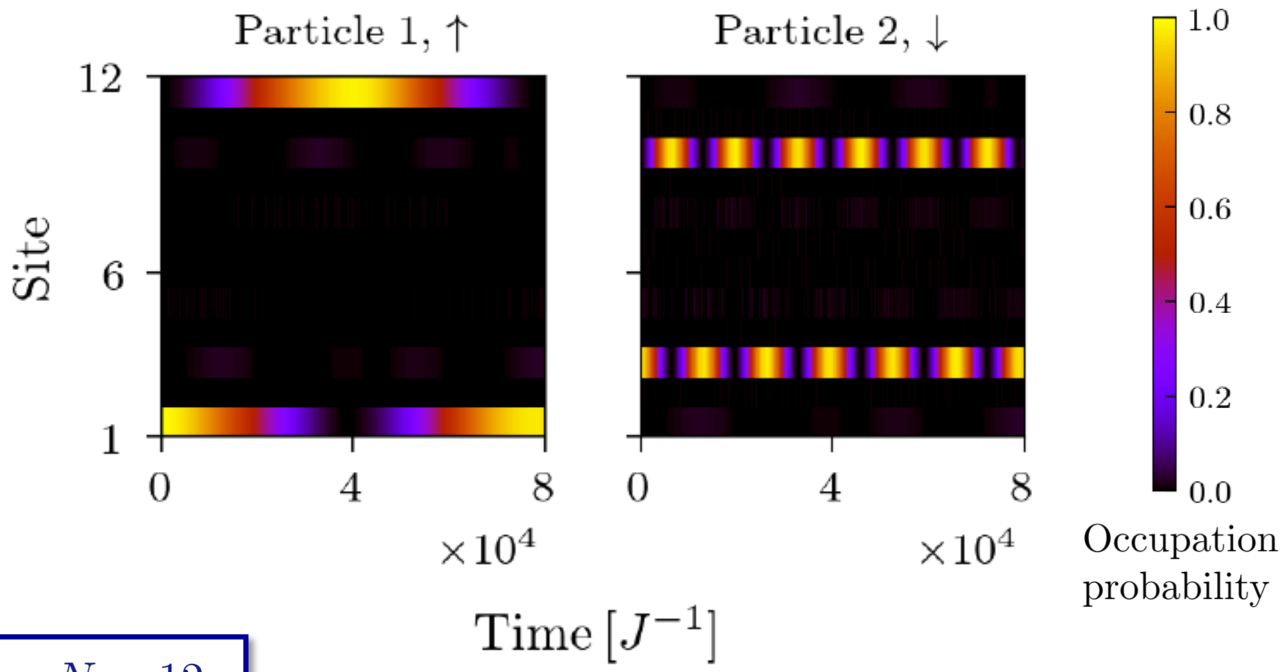

$\omega = 100 \quad \alpha = 410 \quad \lambda = 1.5 \quad N = 12$

Simulation of the extended SSH model

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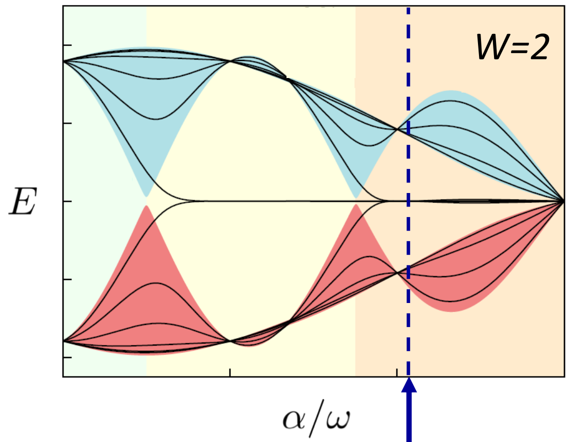
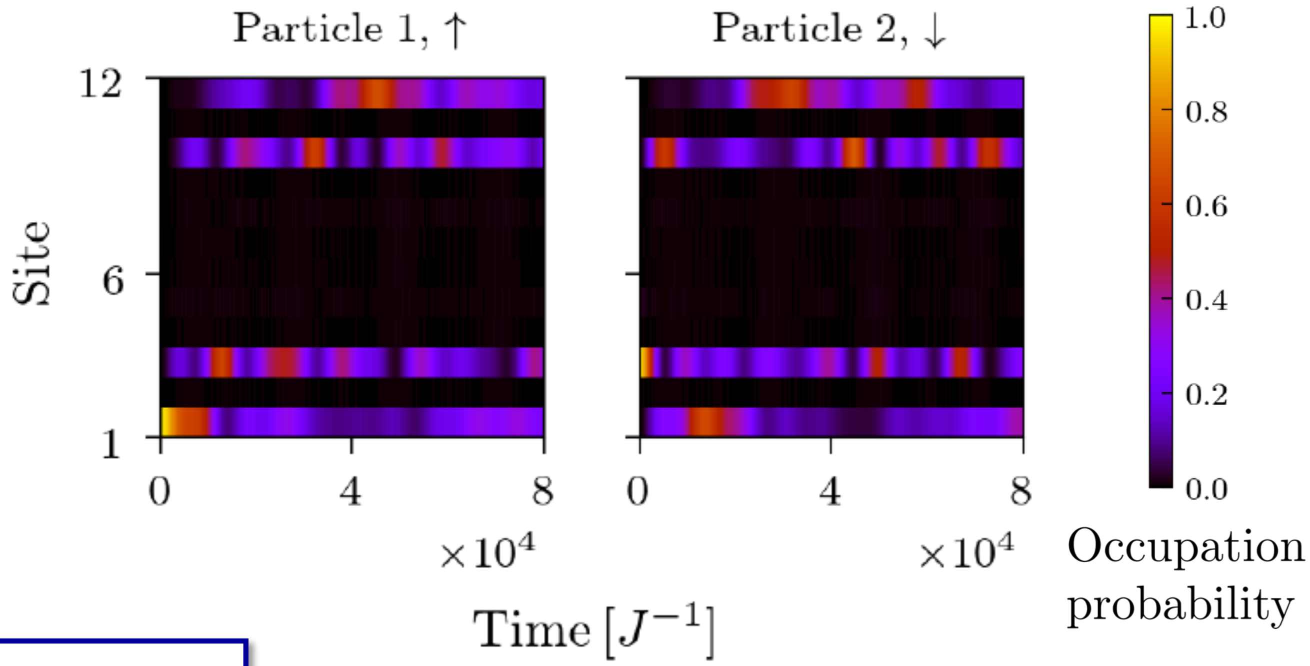




$\omega = 100 \quad \alpha = 410 \quad \lambda = 1.5 \quad N = 12$

B. Pérez-González et al., PRL,123,126401 (2019)

Summary

Quantum dot networks: solid state platform for quantum state transfer and quantum simulation: Hole spin qubits

ac driven protocol to simulate the extended SSH in a QD array with new topological phases and edge states

Summary

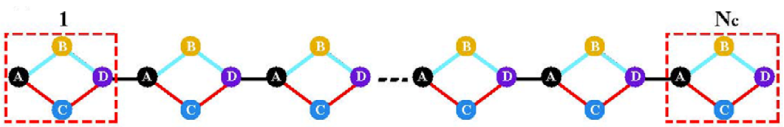
Quantum dot networks: solid state platform for quantum state transfer and quantum simulation: Hole spin qubits

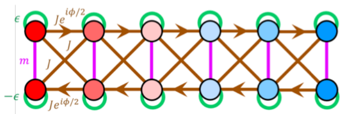
ac driven protocol to simulate the extended SSH in a QD array with new topological phases and edge states

Outlook

Topological domain walls as quantum amplifiers (J. Zurita et al., arXiv:2208.00797)

Investigate other quasi-1D hamiltonians for transfering Information mediated by edge states





J. Zurita, et al., Advances Quantum Tech., 3, 1900105 (2020).

J. Zurita et al., Quantum 5, 591 (2021)

Acknowledge to my collaborators

David Fernández
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Charles Creffield UCM

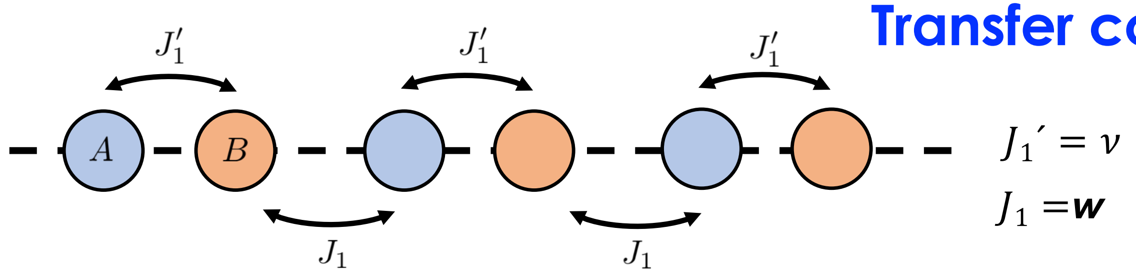
Beatriz Pérez
ICMM (CSIC)

Miguel Bello
MPI, Garching

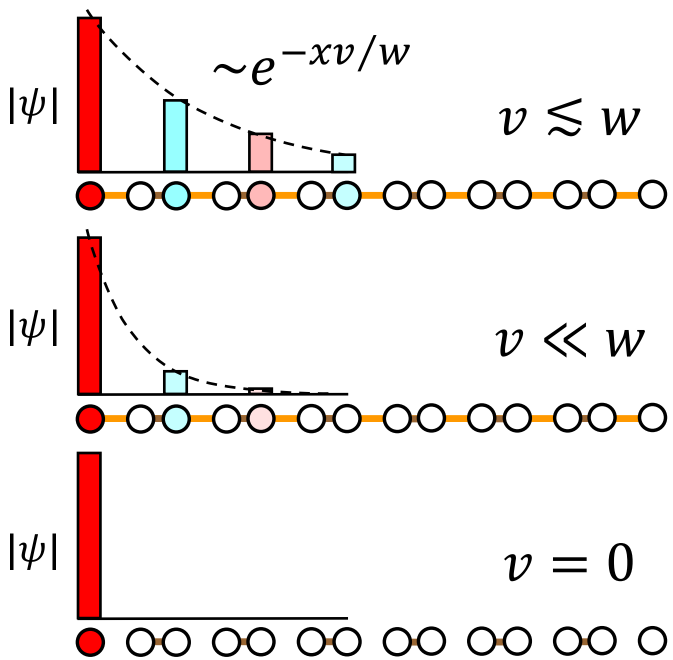
Álvaro Gómez Léon
IFF (CSIC)

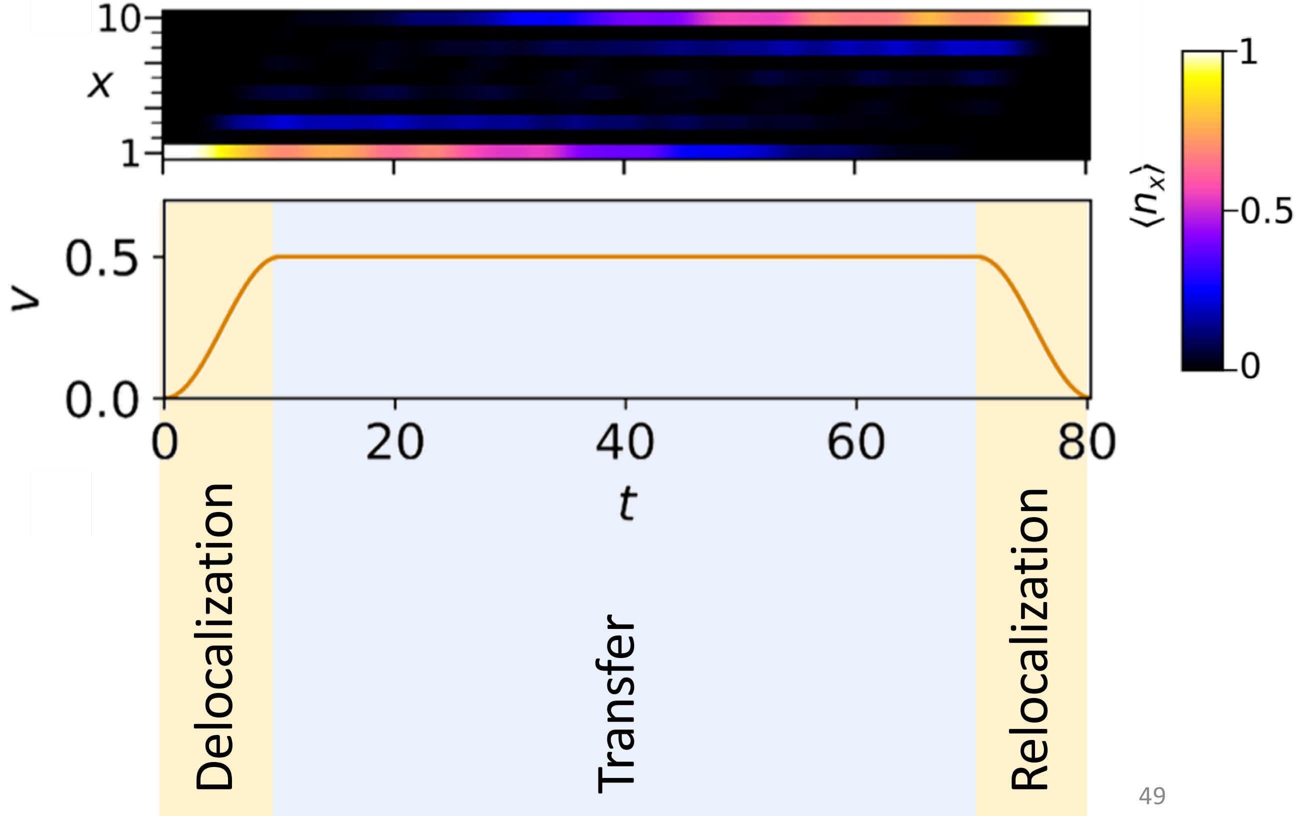
… thank you for your attention!

Transfer control in a dimer molecule (SSH)

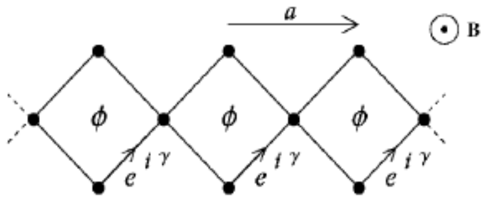


Decay length $\propto v/w$



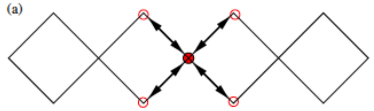


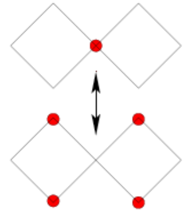
Aharonov-Bohm caging

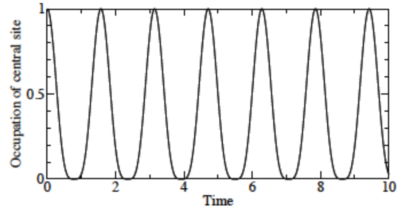


† Vidal et al, PRL 81, 5888 (1998)

When $\phi = \pi$, interference cancels the tunneling



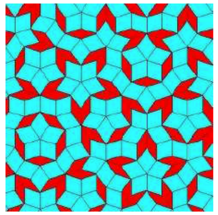


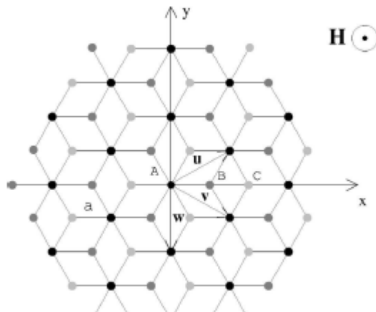


CEC & GP, PRL 105, 086804 (2010)

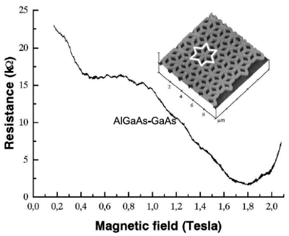
AB-caging does not occur on every lattice –

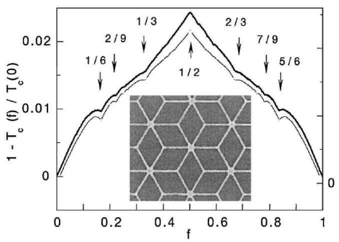
- square, triangular, honeycomb – no caging
- Penrose, octagonal, $\mathcal{T}_3$ – caging possible

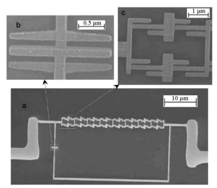




AB caging has been observed in a variety of systems

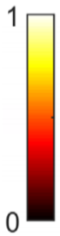


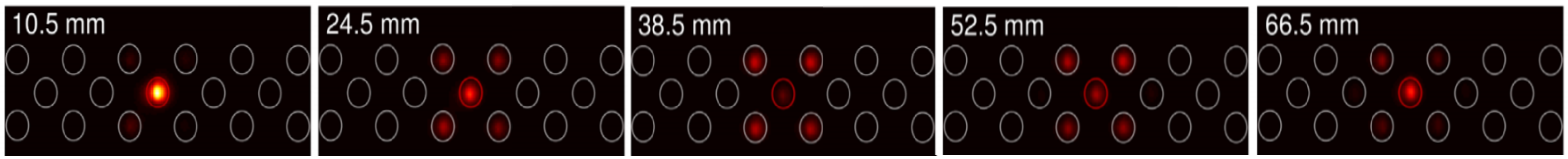




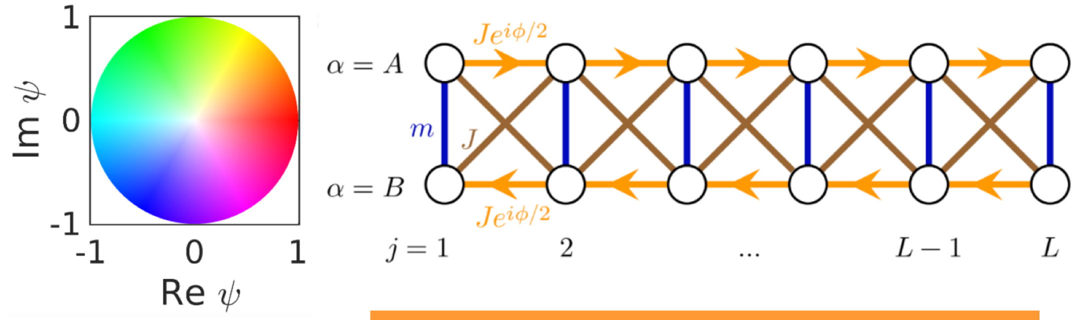
S. Mukherjee et al. PRL (2018)

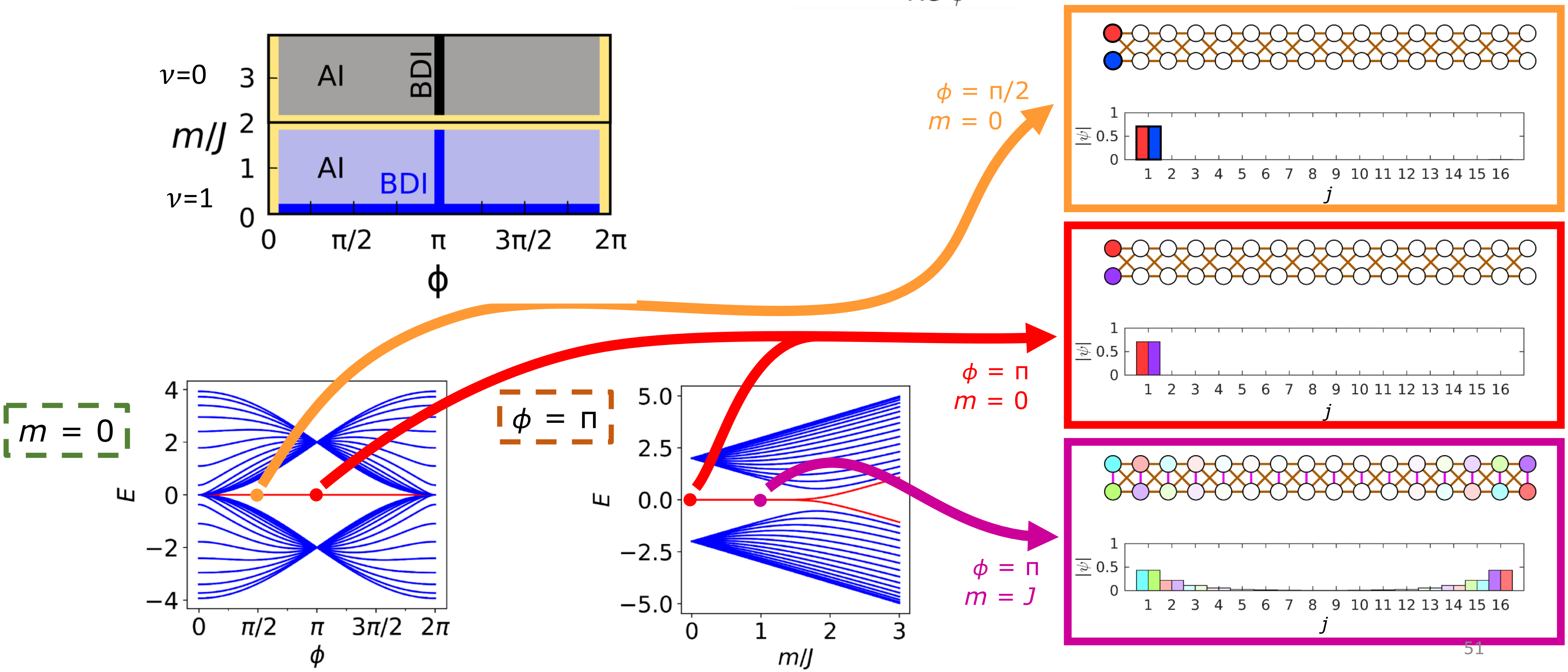
AB caging in a photonic lattice (rhombus chain):



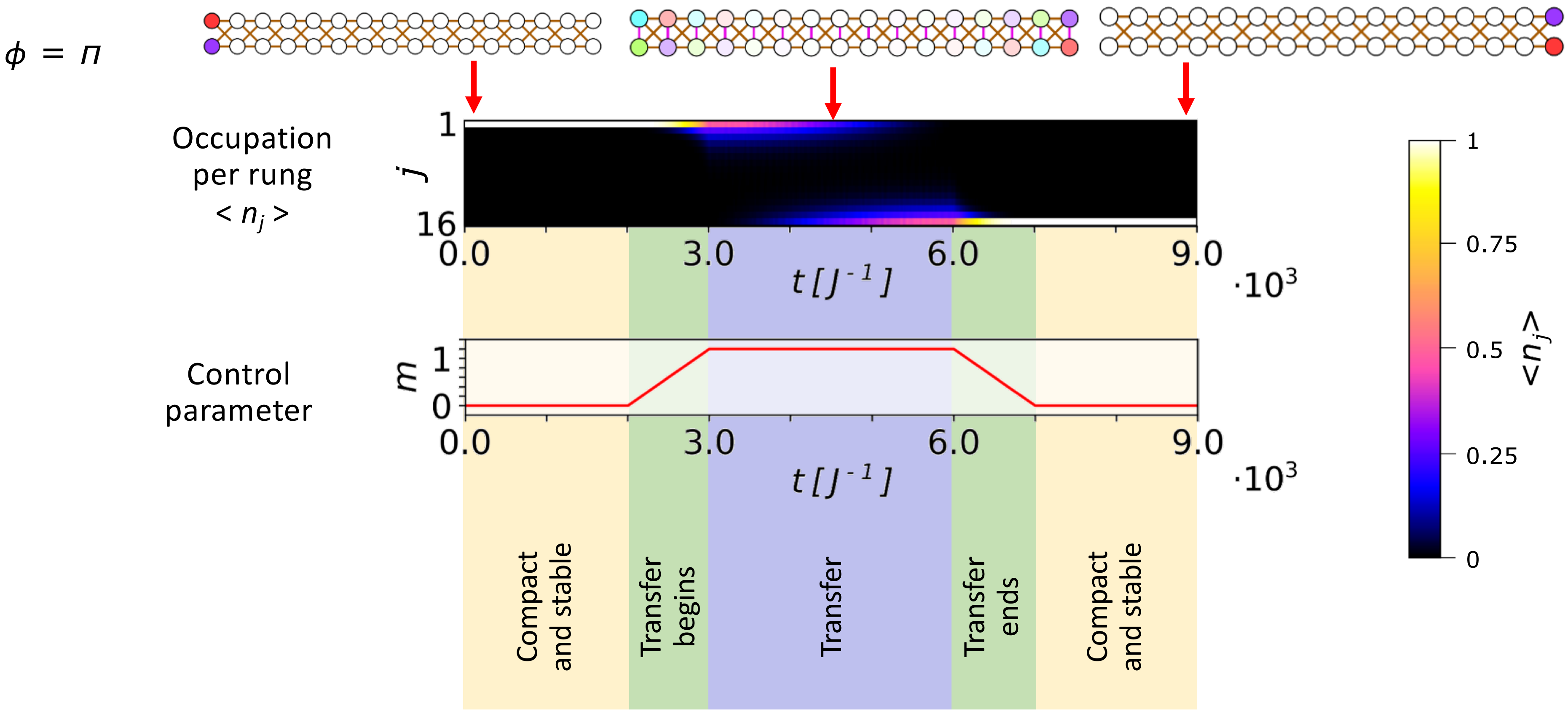


Topological phases

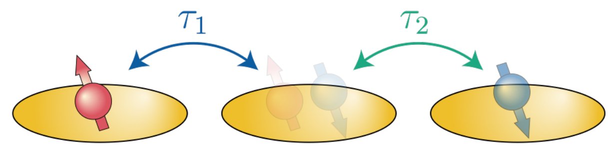




Topological quantum state transfer



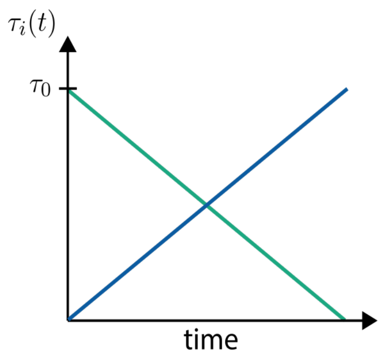
J. A. Zurita et al., arXiv:2208.00797



5. Transfer protocols

- The **driving parameters** are the tunneling rates
- There exists multiple **adiabatic transfer protocols**, some of the most known ones are

Linear ramp

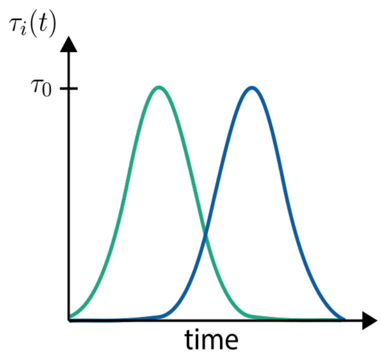


- Easy to implement in experimental device
- Analytical results based on LZ passage
- **Robust** against error in the tunneling

CTAP

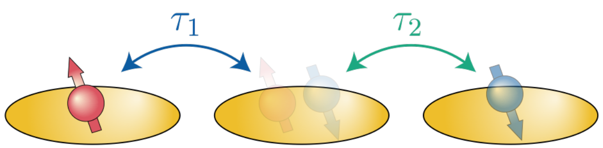
Coherent **T**ransfer by **A**diabatic **P**assage

A. D. Greentree, et al., PRB **70**, 235317 (2004)



- **Smooth** pulses
- **Robust** against error in the detuning
- High expressivity

8. Noise model

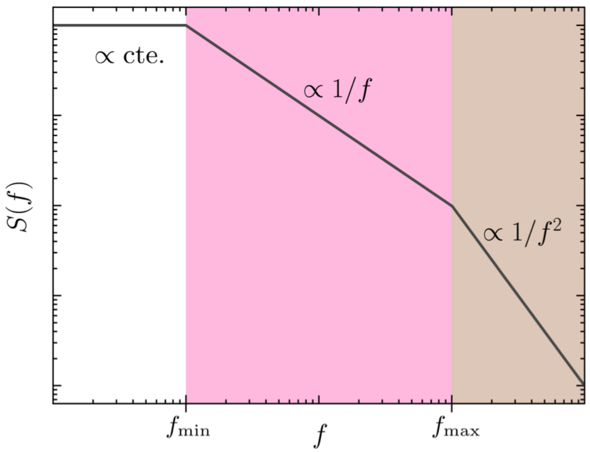


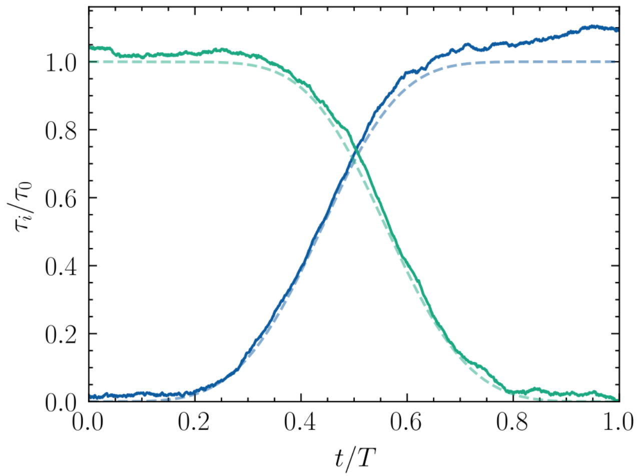
- Noise in the **detuning** as $\varepsilon_i^n(t) = \varepsilon_i + \delta_\epsilon \nu_i(t)$
- Noise in the **tunneling rates** as $\tau_i^n(t) = \tau_i(t) + \delta_\tau \tilde{\nu}_i(t)$
- Uncorrelated errors
$$\langle \nu_i(t)\nu_j(t)\rangle = \delta_{i,j}$$
$$\langle \nu_i(t)\tilde{\nu}_j(t)\rangle = 0$$

- White noise: $f < f_{\min}$
- Pink noise: $f_{\min} \leq f \leq f_{\max}$
- Brown noise: $f_{\max} < f$

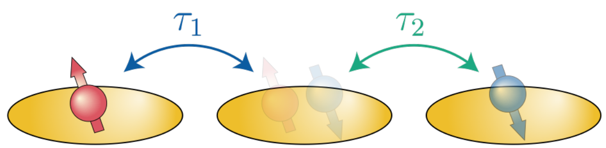
E. Paladino, et al., Rev. Mod. Phys. **86**, 361 (2014)

M. J. Gullans, and J. R. Petta, PRB **100**, 085419 (2019)



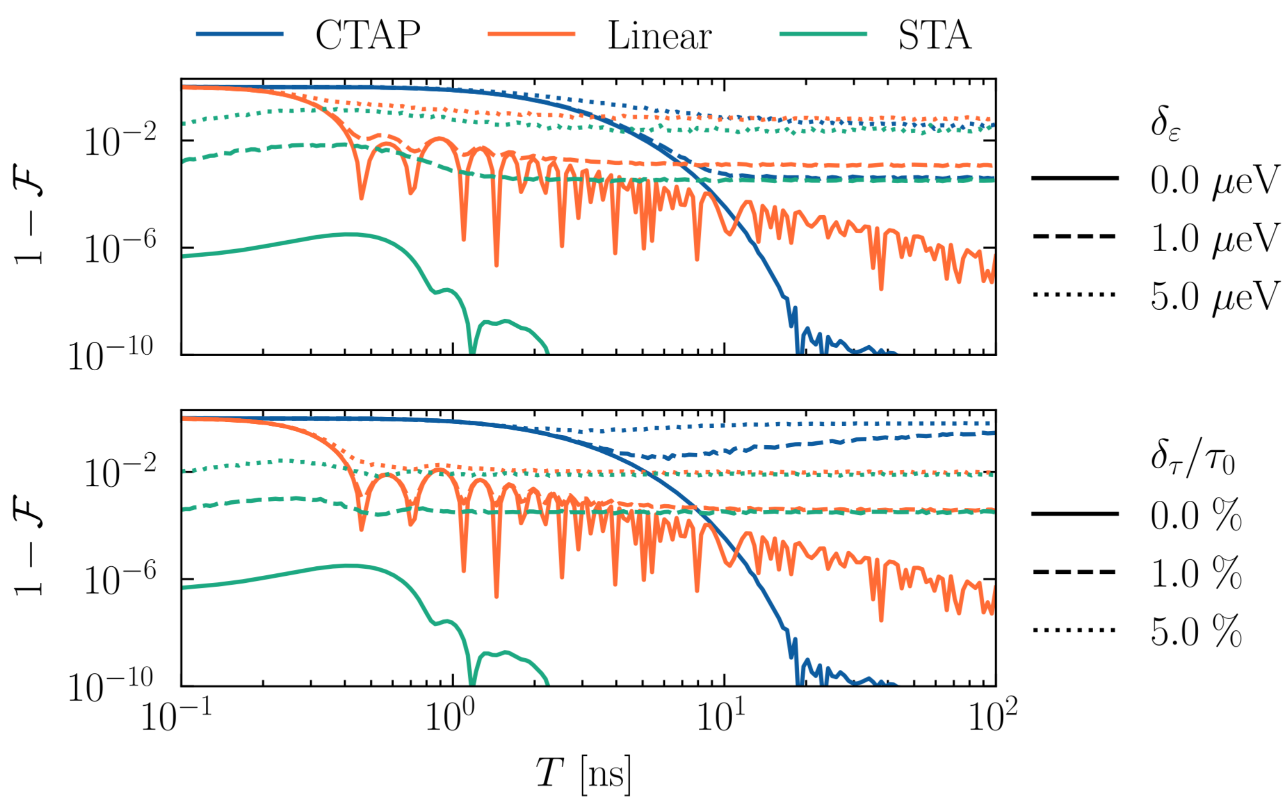


Noisy transfer



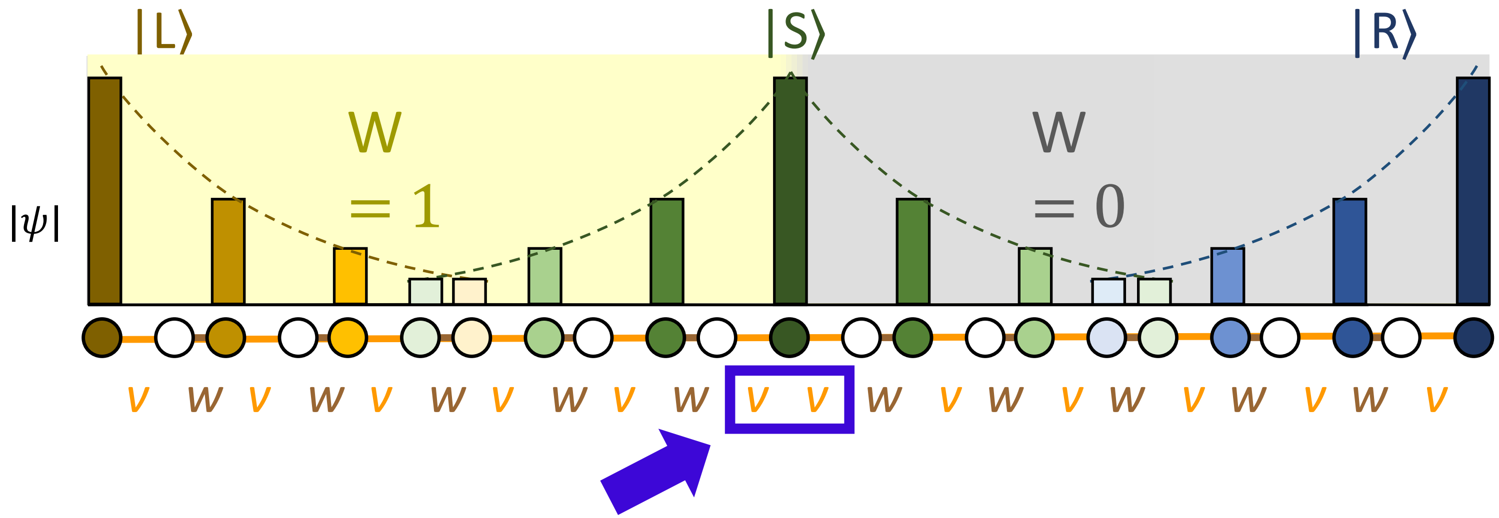
Parameters
$x_{\text{SOC}} = 1$
$\sigma = T/6$
$f_{\min} = 0.16$ mHz
$f_{\max} = 0.1$ MHz
$\tau_0 = 10\ \mu$eV

- Transfer fidelity defined as: $\mathcal{F} \equiv |\langle 0, 0, \downarrow | \Psi(T) \rangle|^2$

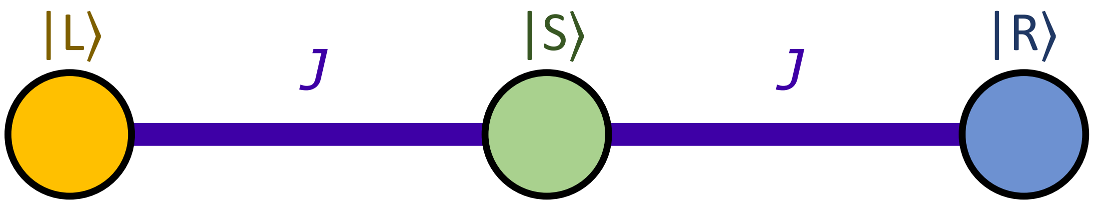


- **CTAP** highly sensitive to error in the tunneling rates
- **Linear** pulse obtain good results if the transfer time is large enough
- **STA** is the best among all the protocols for low transfer times

III. Topological domain walls

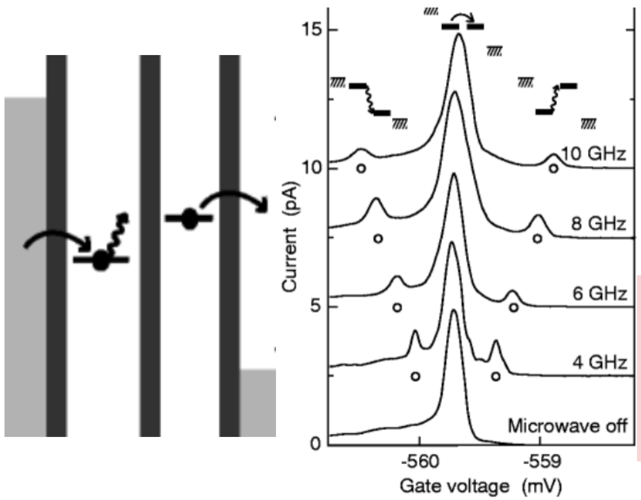


Effective model (boundary state manifold)



Driving with periodic AC fields

- Photoassisted Tunneling (PAT) in quantum dots

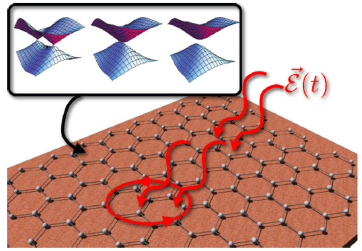


T. H. Oosterkamp et al., Nature 395, 873-876, 1998

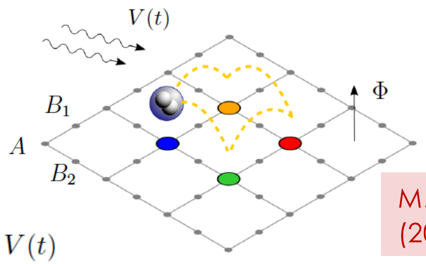
Bonds renormalization

Coherent destruction of tunnel,
P. Hänggi, PRL, 1991

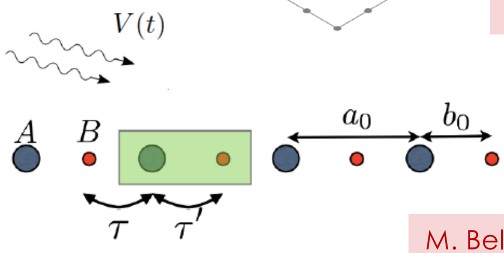
- Tuning electronic and topological properties in driven systems



P. Delplace et al., PRB 88, 245 (2013)



M. Bello et al., PRB 95, 094303 (2017)



A. Gómez León and GP,
B. PRL,110, 200403 (2013)

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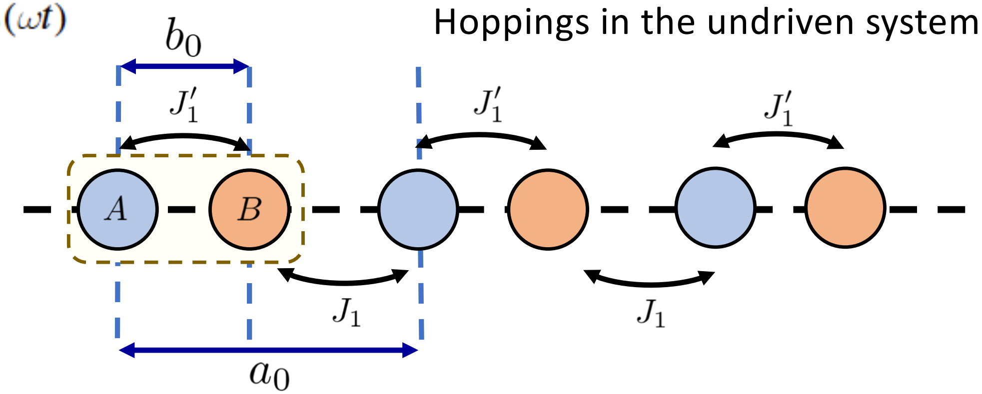
Driving with periodic AC fields

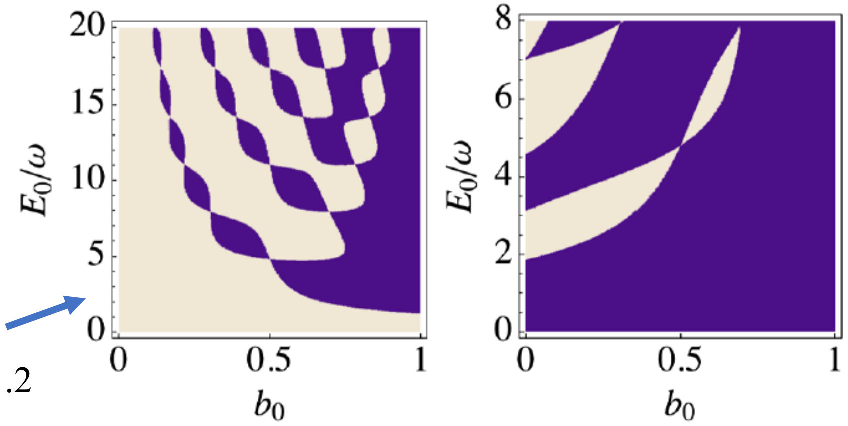
AC Driven Dimer Chain

A. Gómez León and G.P., PRL, 2013

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

Hoppings in the undriven system





$\frac{J_1'}{J_1} = 1.2$

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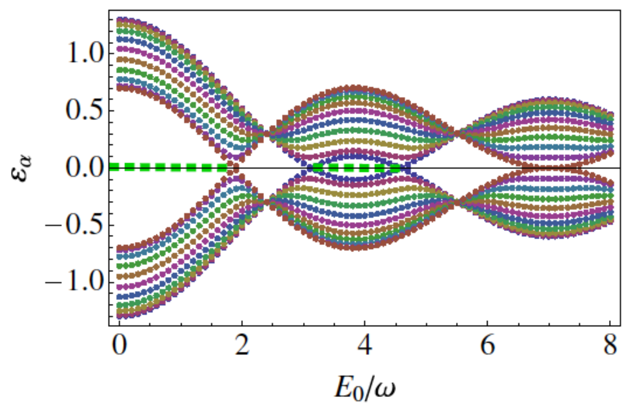


Undriven case :

W=0 , $J'_1/J_1>1$ **Light brown**

W=1, $J'_1/J_1<1$ **Blue**

Driving with periodic AC fields

AC driven transport to characterize topology

Dimer chain coupled to electron source and drain

High Frequency

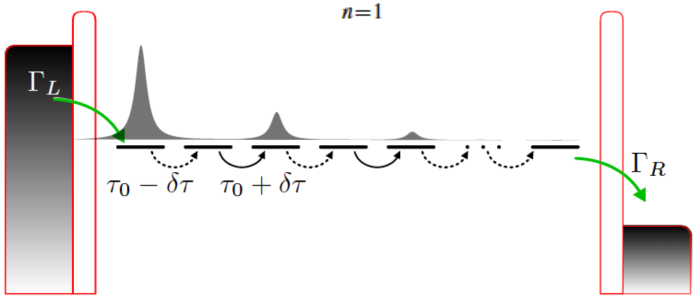
$$\tau'_{\text{eff}} = J_0(Ab/\omega)(\tau_0 - \delta\tau),$$

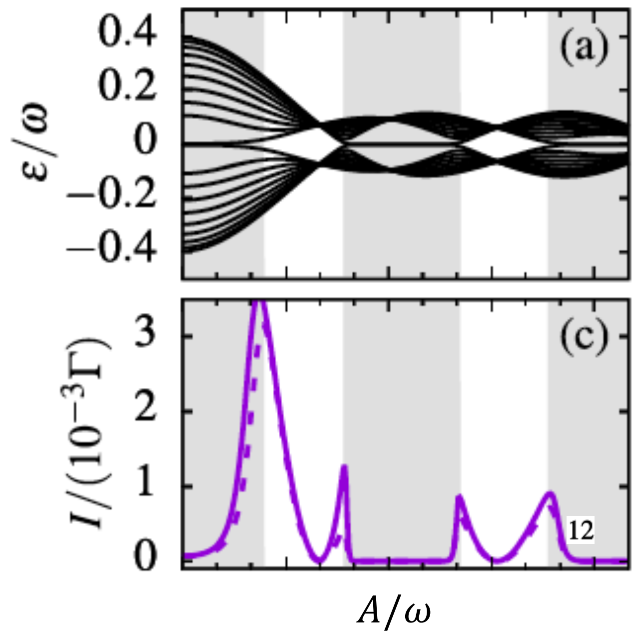
$$\tau_{\text{eff}} = J_0(A(a-b)/\omega)(\tau_0 + \delta\tau).$$

$\tau'_{\text{eff}} > \tau_{\text{eff}}$: Trivial

$\tau'_{\text{eff}} < \tau_{\text{eff}}$ Non-trivial

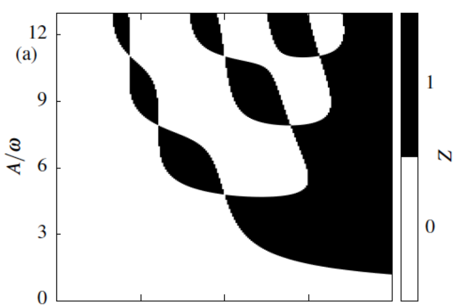
$$H(t) = H_{\text{SSH}} + A\sum_{n=1}^{N} x_n c_n^\dagger c_n \cos(\omega t)$$





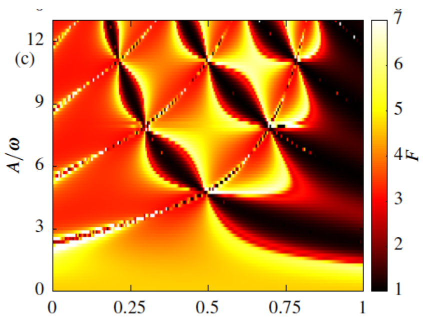
M. Niklas et al., Nanotechnology, 2017

A. Gómez León and G.P., PRL, 2013



b_0/a_0

Winding Number



b_0/a_0

Fano factor

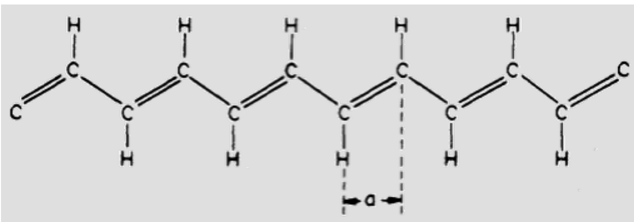
VOLUME 42, NUMBER 25 PHYSICAL REVIEW LETTERS 18 JUNE 1979

Solitons in Polyacetylene

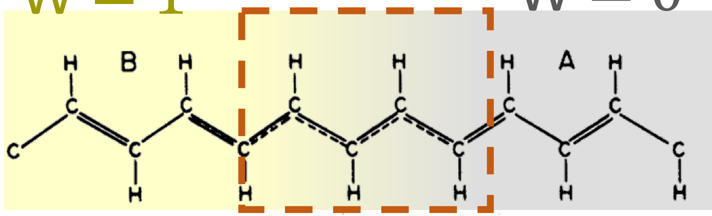
W. P. Su, J. R. Schrieffer, and A. J. Heeger
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 15 March 1979)

We present a theoretical study of soliton formation in long-chain polyenes, including the energy of formation, length, mass, and activation energy for motion. The results provide an explanation of the mobile neutral defect observed in undoped $(CH)_x$. Since the soliton formation energy is less than that needed to create band excitation, solitons play a fundamental role in the charge-transfer doping mechanism.

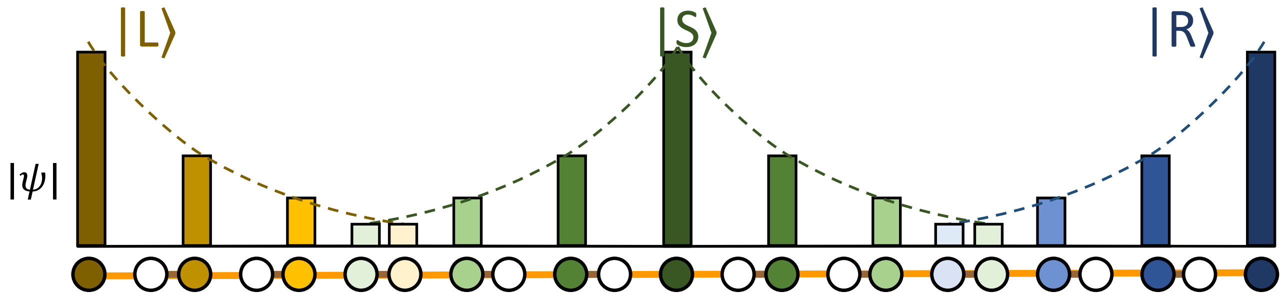
W = 0

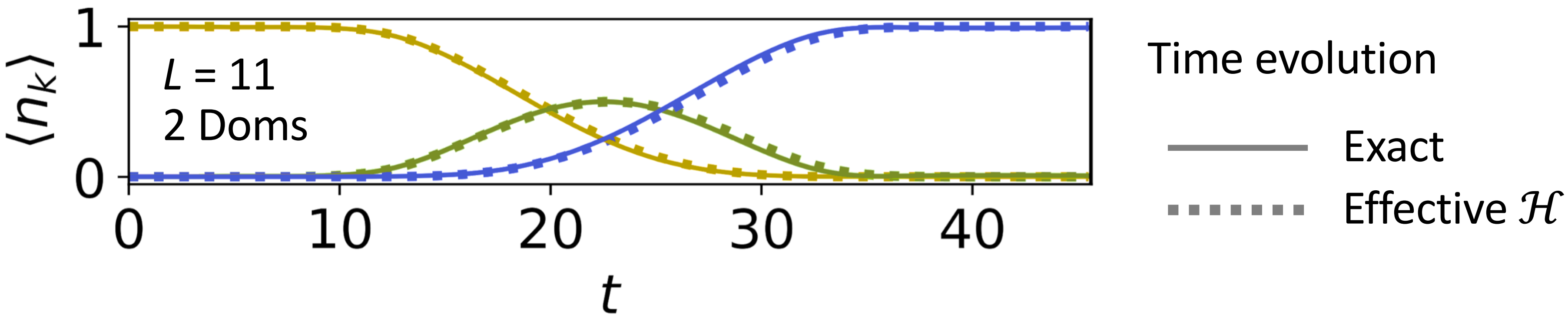


W = 1 W = 0

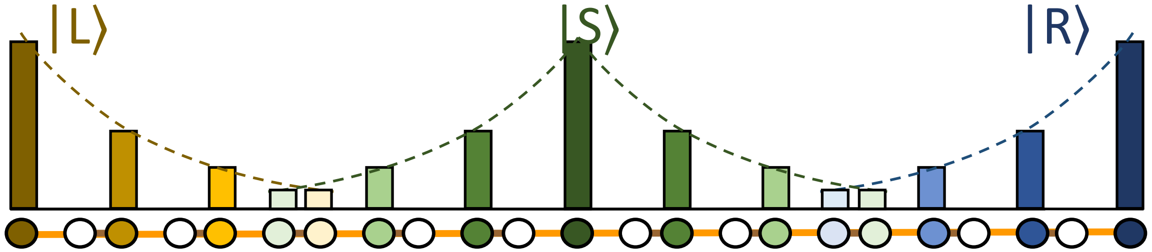


Topological domain wall


|L⟩
|S⟩
|R⟩
|ψ|

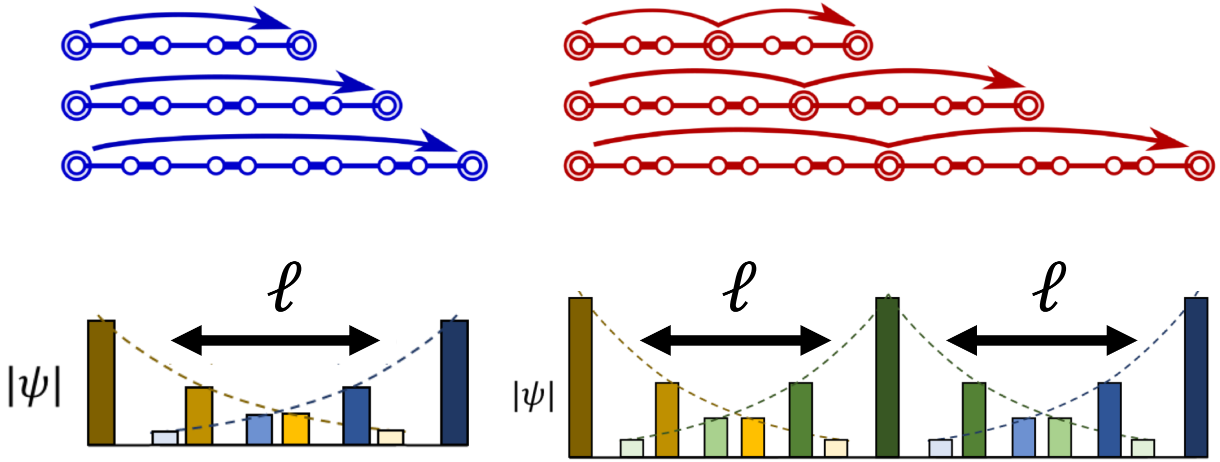

⟨n_k⟩
1
0
L = 11
2 Doms
0
10
20
30
40
t
Time evolution
Exact
Effective ℋ

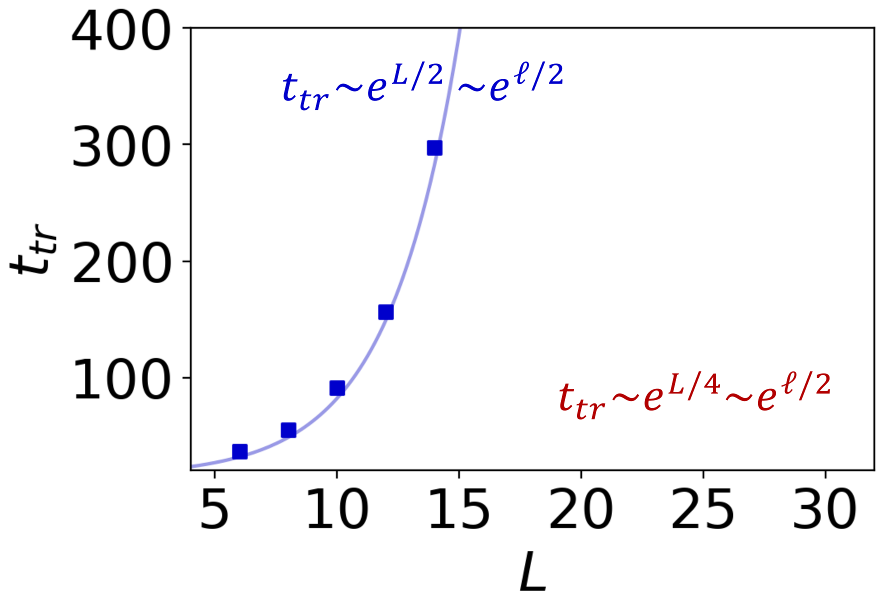
III. Topological domain walls



One domain

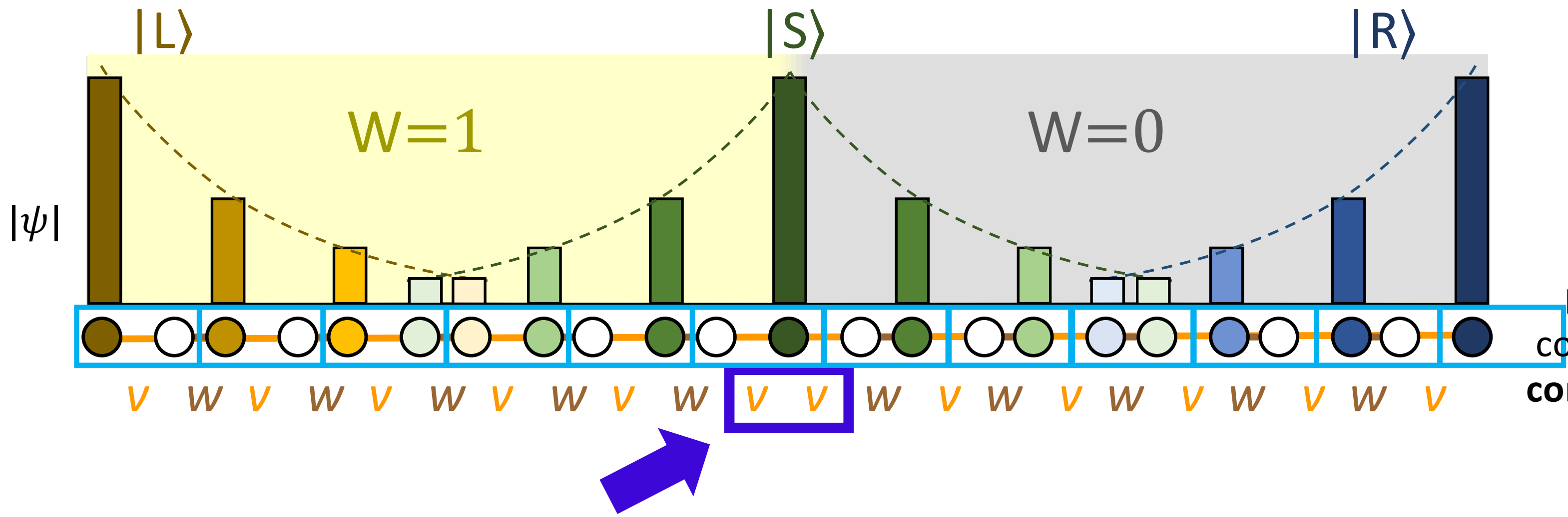
Two domains





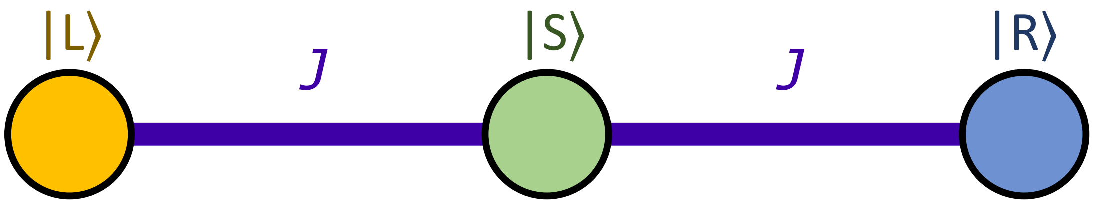
Transfer time depends exponentially
on domain length ℓ only

III. Topological domain walls



Bulk-boundary corresp. works for **complete unit cells**

Effective model (boundary state manifold)



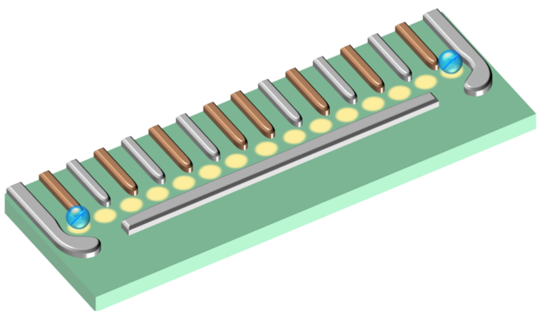
Summary

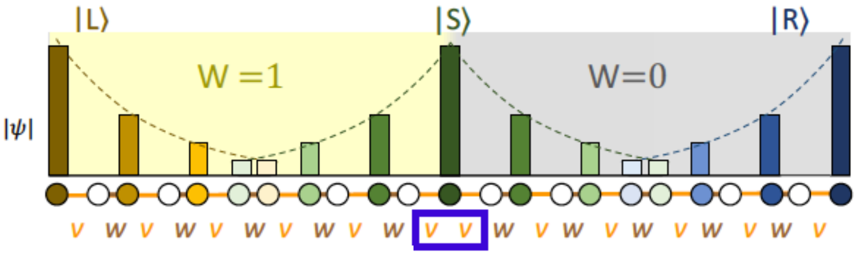
Quantum dot networks: solid state platform for quantum state transfer and quantum simulation

ac driven protocol to simulate the extended SSH in a QD array with new topological phases and edge states

Outlook

Topological domain walls as quantum amplifiers (J. Zurita et al., arXiv:2208.00797)





Transfer time (L = 26):
1 dom: 1131.2 ns
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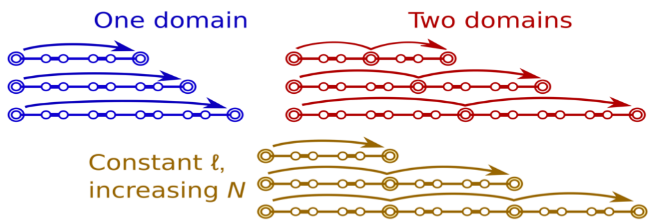
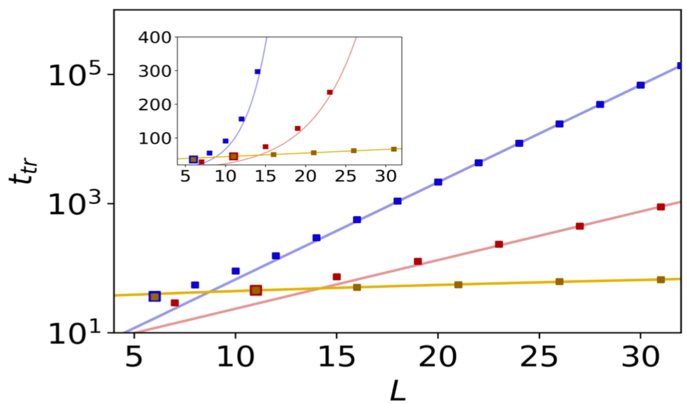


$t_{tr} \sim e^{\ell/2}$



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Outlook

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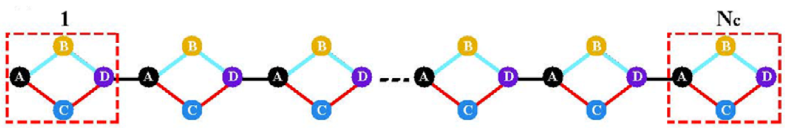
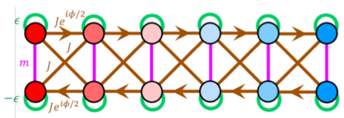
ac driven protocol to simulate the extended SSH in a QD array with new topological phases and edge states

Outlook

Investigate other quasi-1D hamiltonians for transfering Information mediated by edge states





J. Zurita, et al., Advances Quantum Tech., 3, 1900105 (2020).

J. Zurita et al., Quantum 5, 591 (2021)

Electron Dipole Spin Resonance (EDSR)

Spin Orbit Interaction (SOI)

SOI+ $E(t)=E_0\cos(\omega t)$ → $B_0\cos(\omega t)$ Effective magnetic field

- **Rashba SOI**: Structural inversion asymmetry

$$H_{so} = \alpha(p_x\sigma_y - py\sigma_x) + \beta(-px\sigma_x + py\sigma_y)$$

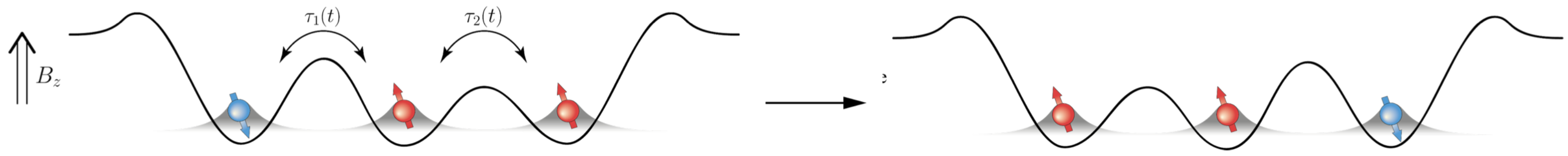
- Dresselhaus SOI: Lack of bulk inversion symmetry → (GaAs, InAs, In Sb..)

$$B_{eff}(x,y)=\mathbf{n}\otimes B_{ext}$$

$x(t)$ → $B_{eff}\,(t)$

$$n_x= (-\alpha y-\beta x)\frac{2m*}{\hbar}; ny = (\alpha x + \beta y)\frac{2m*}{\hbar}; nz = 0$$

Triple QD: HH half filling



$J^{ab} \equiv \tau_a \tau_b / U \qquad a, b = \{N, F\}$

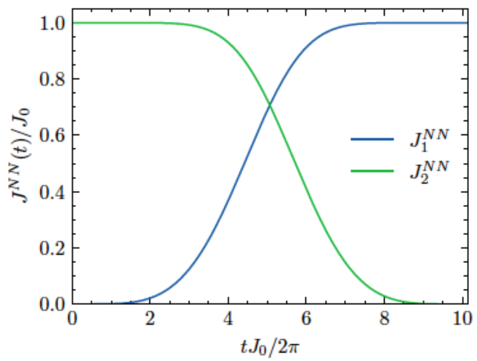
$J_0 \equiv \max(J_1(t), J_2(t))$

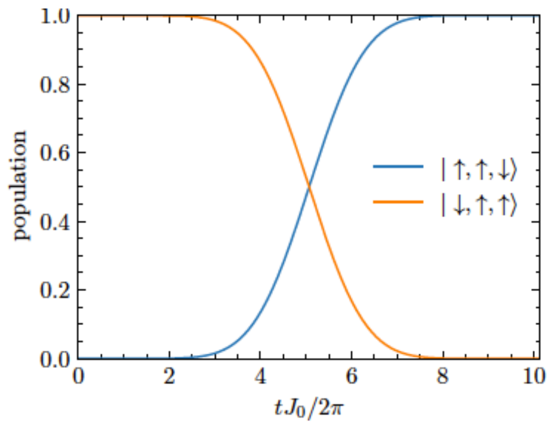
For $J_i^{NN} = J_i^{FF} = J_i$

$$|\mathrm{DS}\rangle = \sin\theta \,|\downarrow,\uparrow,\uparrow\rangle - \cos\theta\,|\uparrow,\uparrow,\downarrow\rangle$$

$\tan\theta \equiv J_2/J_1$

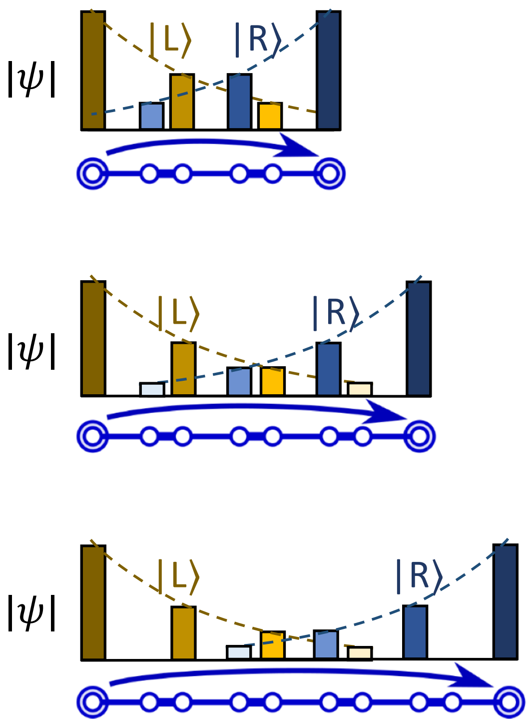
STA





D. Fernández et al., in progress

Slow dynamics



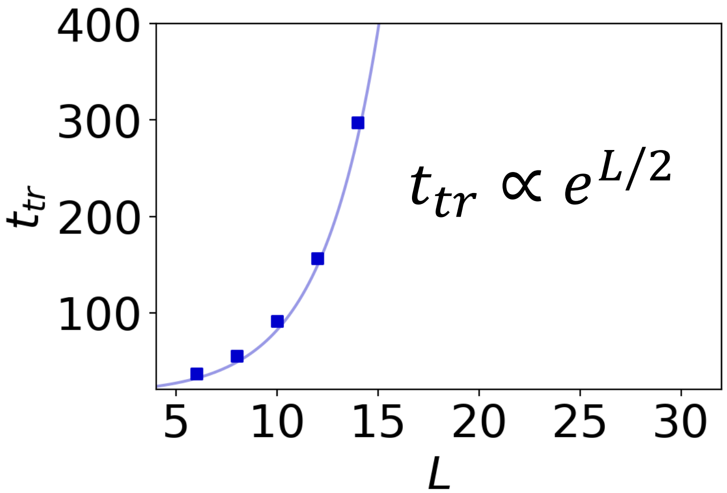
L = 6

L = 8

L = 10

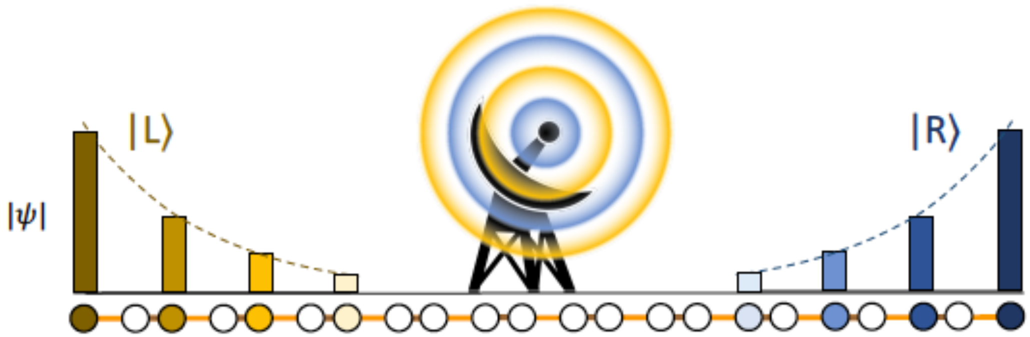
Transfer times

$$t_{tr} \propto (\langle \mathrm{L}|\mathcal{H}|\mathrm{R}\rangle)^{-1}$$



Topological domain walls as quantum amplifiers (J. Zurita et al., arXiv:2208.00797)

Can we add amplifiers?



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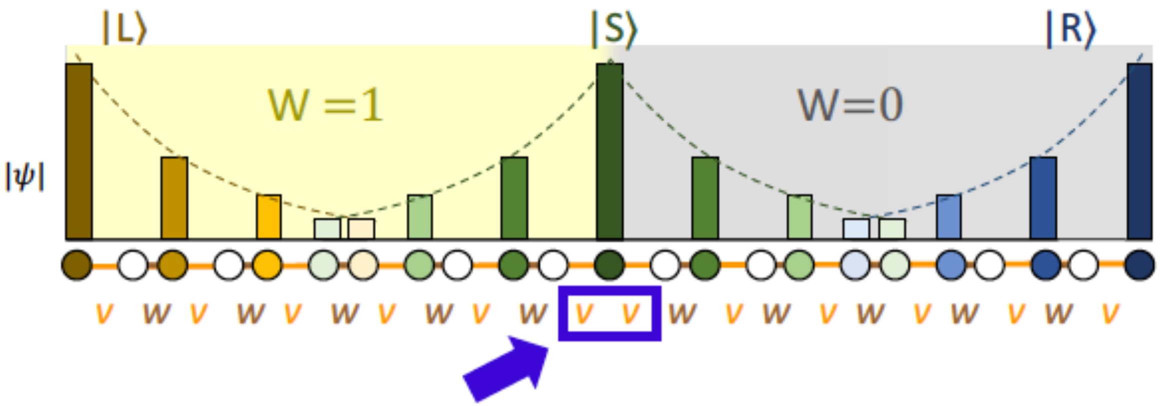

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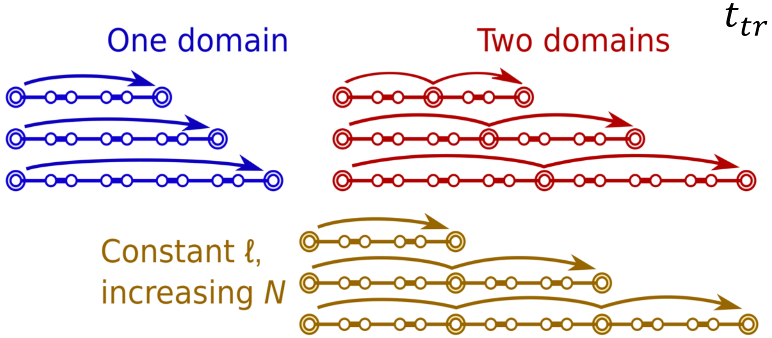
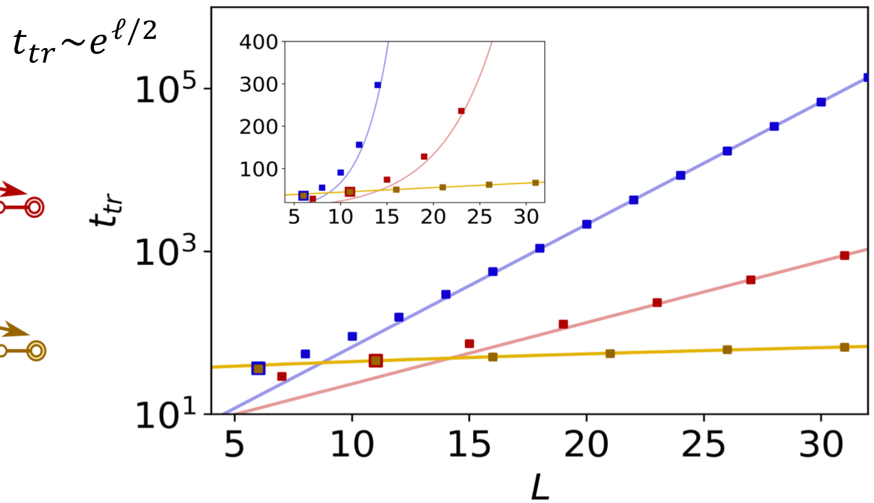


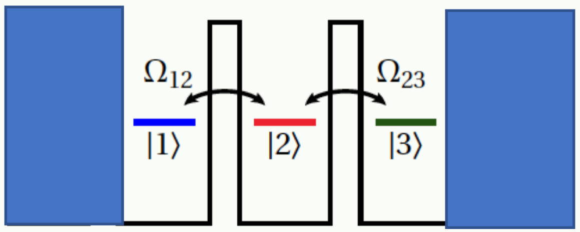


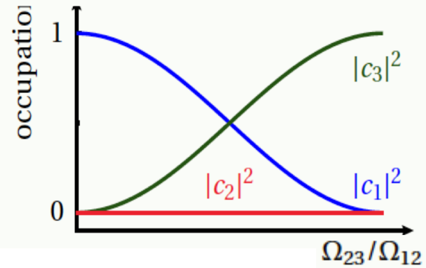
Quantum State Transfer in QDs

CTAP A. Greentree et al., PRB, 70, 235317 (2004)

$$\Omega_{12}(t) = \Omega^{\max} \exp\left[-\left(t - \frac{t_{\max}+\sigma}{2}\right)^2 / (2\sigma^2)\right]$$

$$\Omega_{23}(t) = \Omega^{\max} \exp\left[-\left(t - \frac{t_{\max}-\sigma}{2}\right)^2 / (2\sigma^2)\right]$$





J. Huneke et al., PRL 110,036802 (2013)

Dark State

$$\varepsilon = 0$$

$$|\varphi\rangle = |D_0\rangle = \cos\theta|1\rangle - \sin\theta|3\rangle$$

$$\theta = \arctan(\Omega_{12}/\Omega_{23})$$

$$|\mathcal{E}_0 - \mathcal{E}_\pm| \gg |\langle \dot{\mathcal{D}}_0 | \mathcal{D}_\pm \rangle|.$$

Shortcuts to Adiabaticity (STA): versatil ways to speed up adiabatic passages.

(D. Guéry-Odelin et al., Rev. Modern Phys., 91, 045001, 2019)

Inverse Engineering: impose the desired evolution of the occupation and infer from it the time evolution of the parameters.

$$\tilde{H}(t) = \tilde{\Omega}_{12}(t)c_1^+c_2 + \tilde{\Omega}_{23}(t)c_2^+c_3 + h.c$$

$$|\Psi(t)\rangle = \cos\chi\cos\eta|1\rangle - i\sin\eta|2\rangle - \sin\chi\cos\eta|3\rangle$$

Boundary conditions $\chi(0) = 0,\ \chi(t_f) = \pi/2,\ \eta(0) = 0\quad \eta(t_f) = 0$

+ Ansatz for $\chi,\ \eta$

$$i\hbar\partial_t\Psi(t) = \tilde{H}(t)\Psi(t) \longrightarrow \tilde{\Omega}_{12}(t), \tilde{\Omega}_{23}(t)$$

Y. Ban, et al., Nanotechnology, 29, 505201 (2018)

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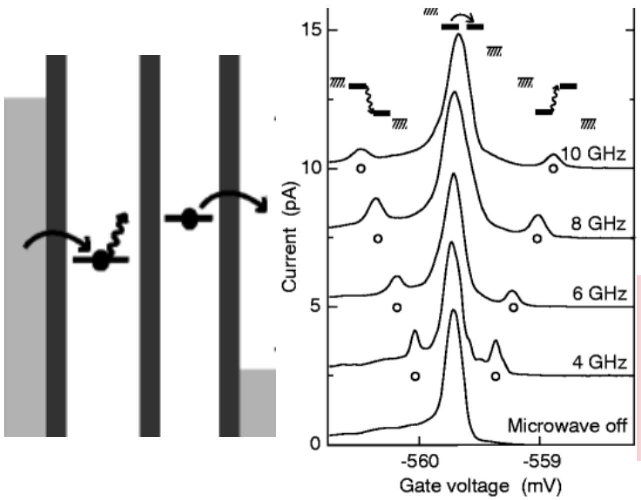

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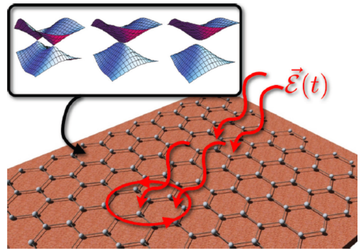
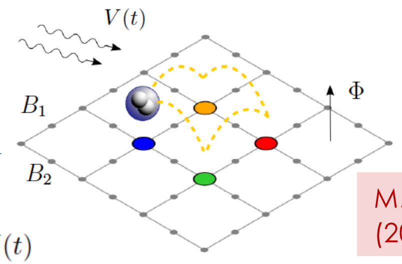
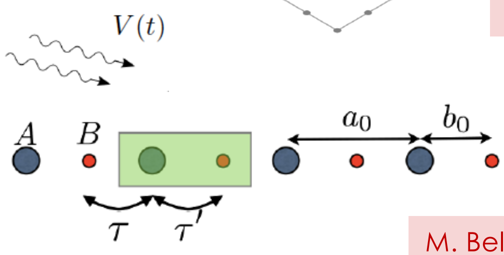


P. Delplace et al., PRB 88, 245 (2013)



M. Bello et al., PRB 95, 094303 (2017)



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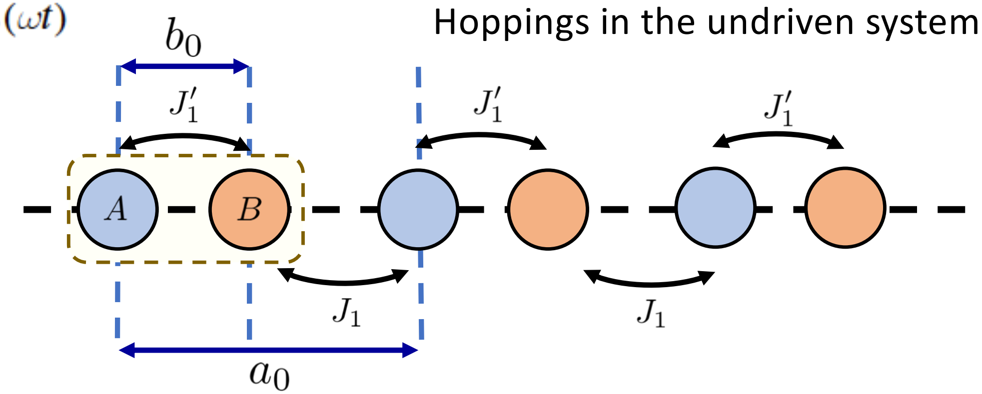

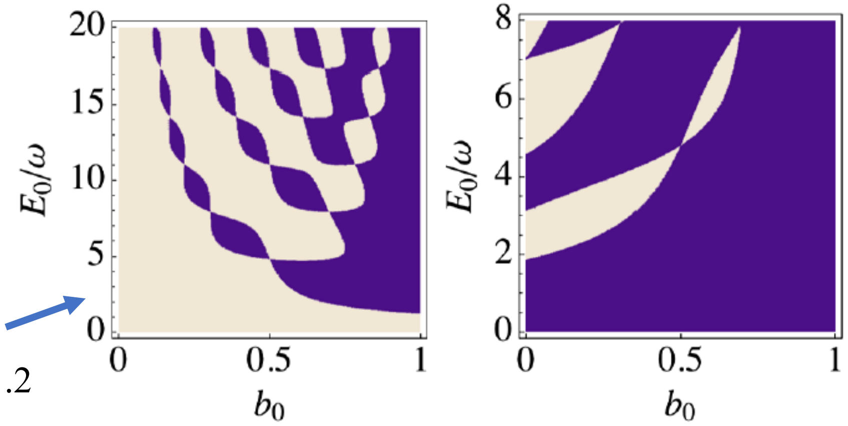

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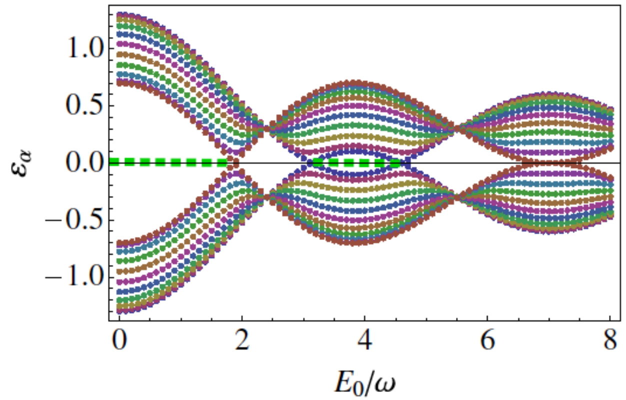


Undriven case :

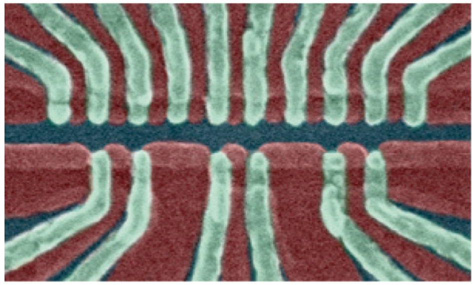
W=0 , $J'_1/J_1>1$ **Light brown**

W=1, $J'_1/J_1<1$ **Blue**

Driving protocol

what we have…

- monomer array of QDs with long-range hopping



- Exponentially decaying hoppings with distance

what we can achieve…

- spatially modulated hoppings that create bond ordering
- certain key symmetries that provide for topological protection
- control and tunability of long-range hoppings