Adilet Imambekov (1982 - 2012)

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Bethe Ansatz

Exactly solvable case of a one-dimensional Bose-Fermi mixture

Adilet Imambekov and Eugene Demler
Department of Physics, Harvard University, Cambridge MA 02138
(Dated: February 2, 2008)

We consider a one dimensional interacting bose-fermi mixture with equal masses of bosons and fermions, and with equal and repulsive interactions between bose-fermi and bose-bose particles. Such a system can be realized in experiments with ultracold boson and fermion isotopes in optical lattices. We use the Bethe-ansatz technique to find the ground state energy at zero temperature for any value of interaction strength and density ratio between bosons and fermions. We prove that the mixture is always stable against demixing. Combining exact solution with the local density approximation we calculate density profiles and collective oscillation modes in a harmonic trap. In the strongly interating regime we use exact wavefunctions to calculate correlation functions for bosons and fermions under periodic boundary conditions.

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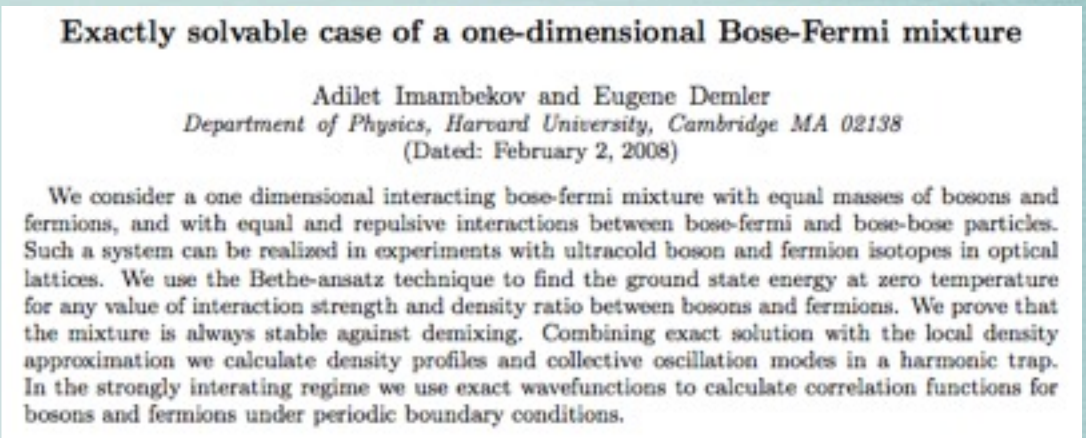

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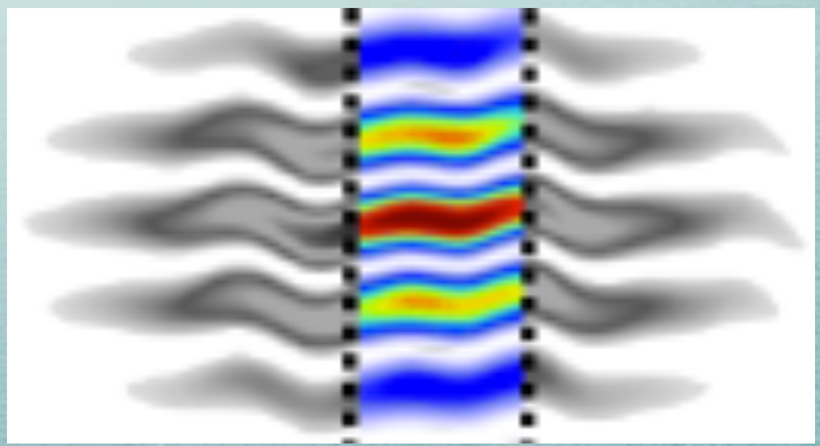
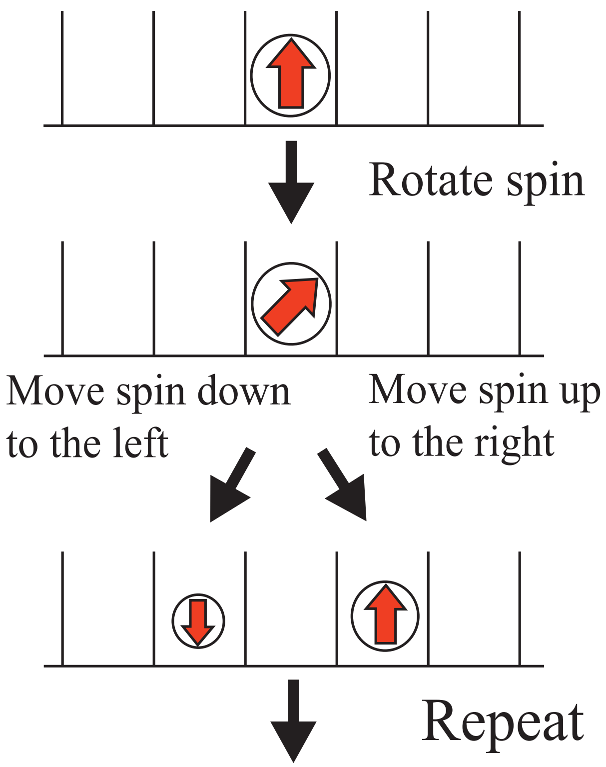
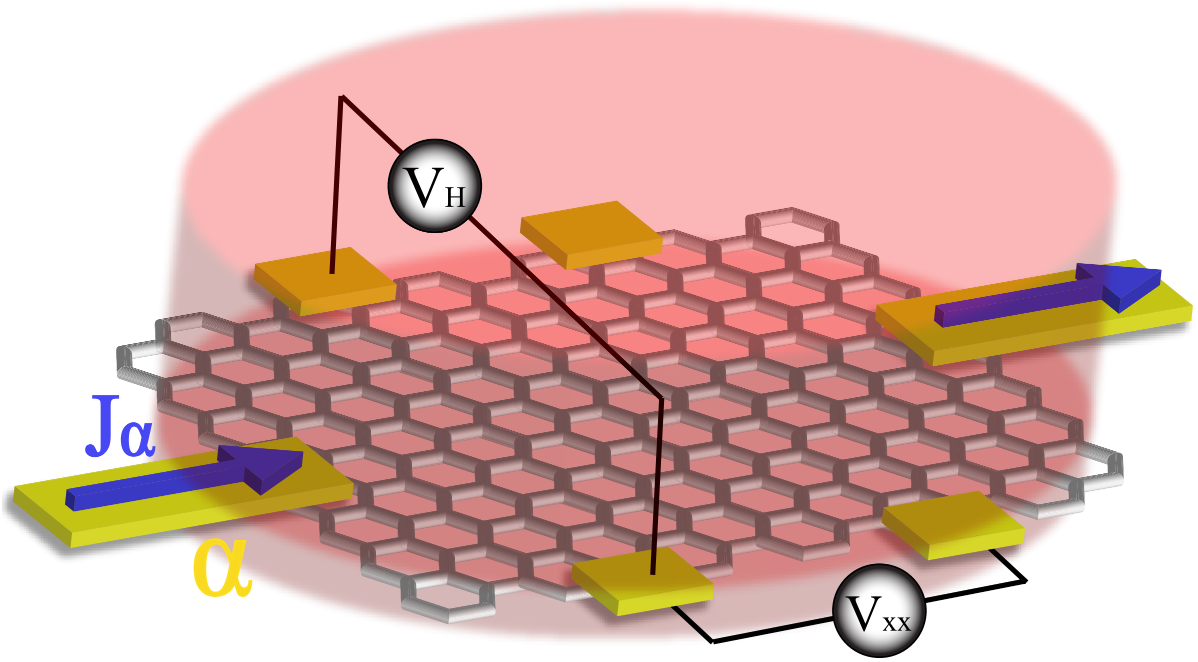
Distribution of Interference patterns



Novel topological phenomena in non-equilibrium systems





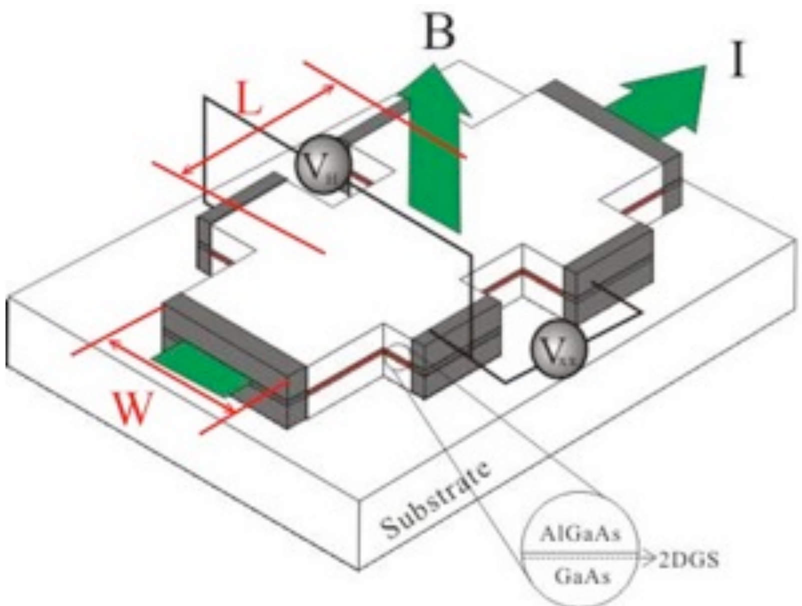
Takuya Kitagawa (Harvard University)

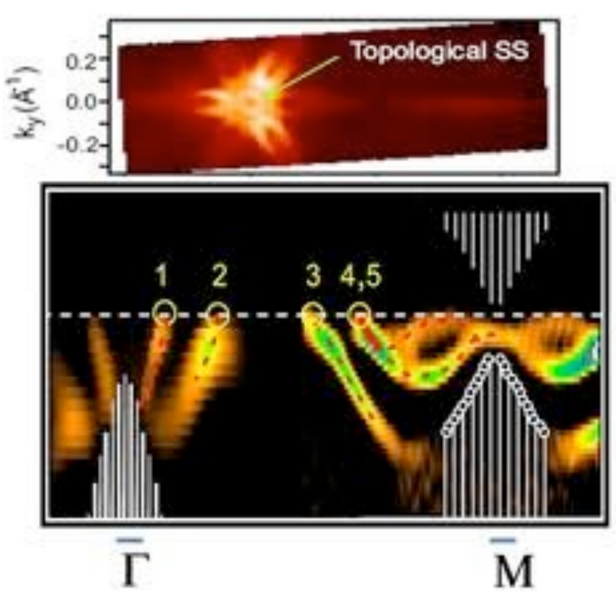
in collaboration with Mark Rudner, Erez Berg , Takashi Oka,
Liang Fu, Eugene Demler (Theory)
Andrew White's group, Immanuel Bloch's group (Experiment)

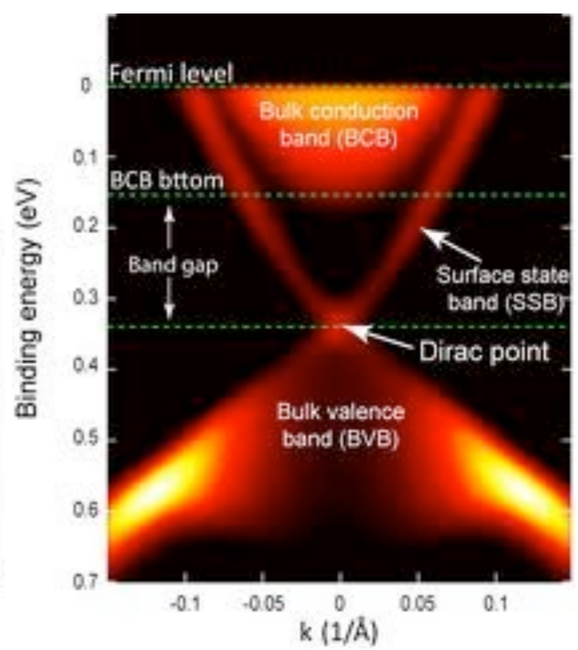
New Topological phenomena in driven systems

New Topological phenomena in driven systems

Topological phases in equilibrium







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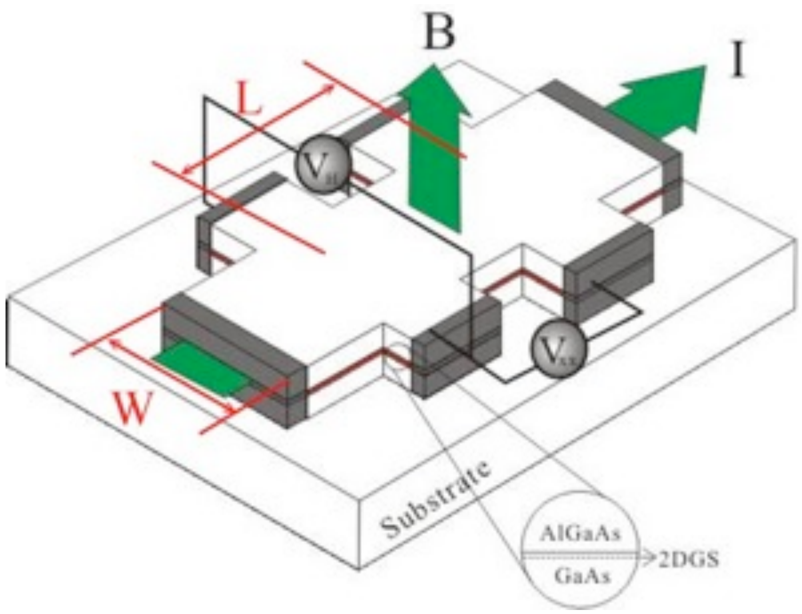
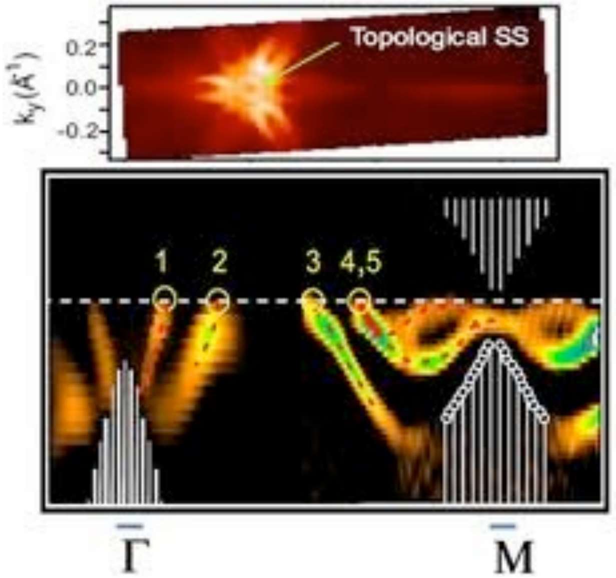
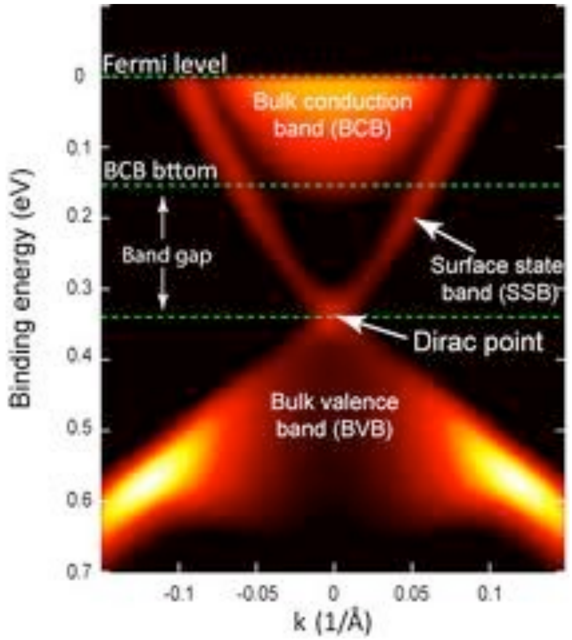
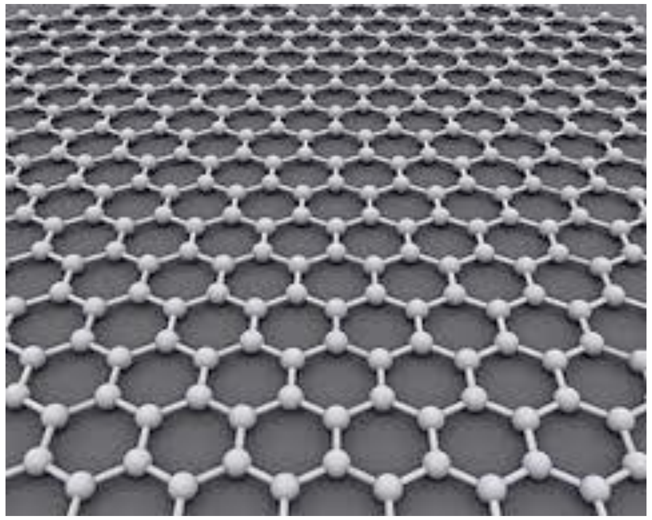






Switchable properties?



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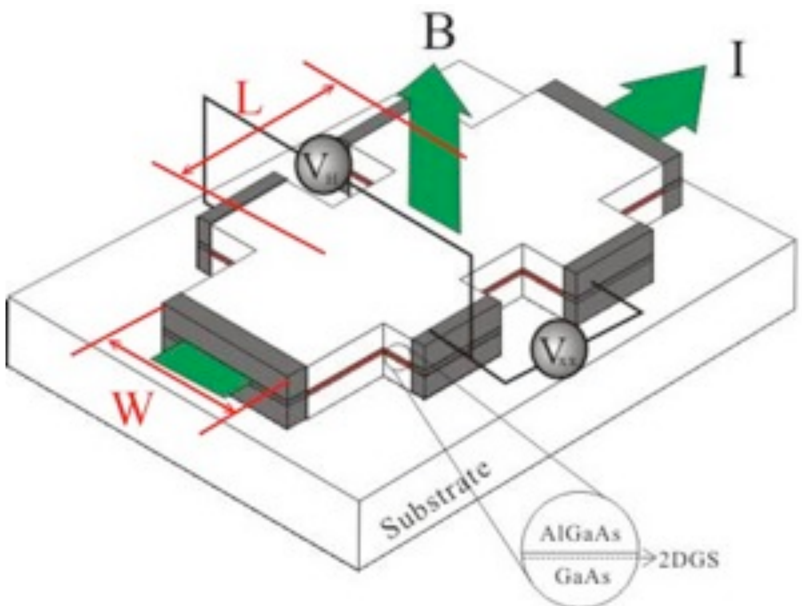

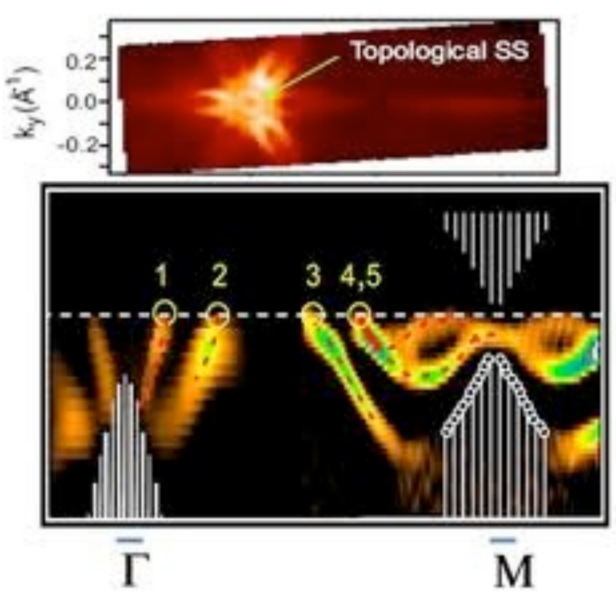

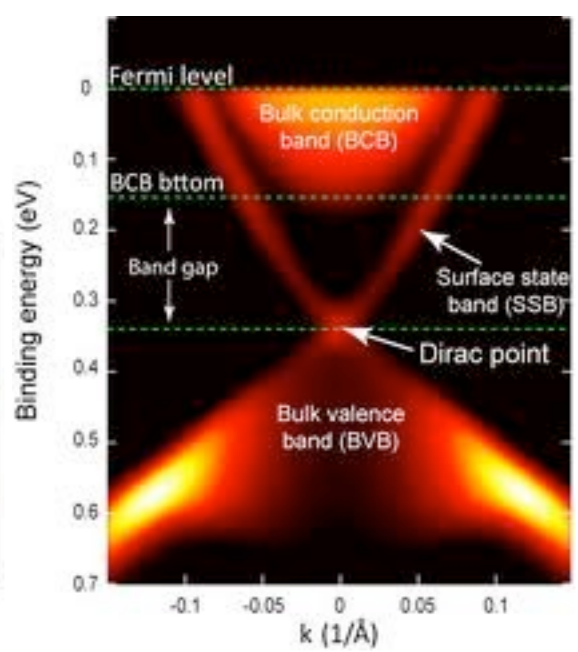

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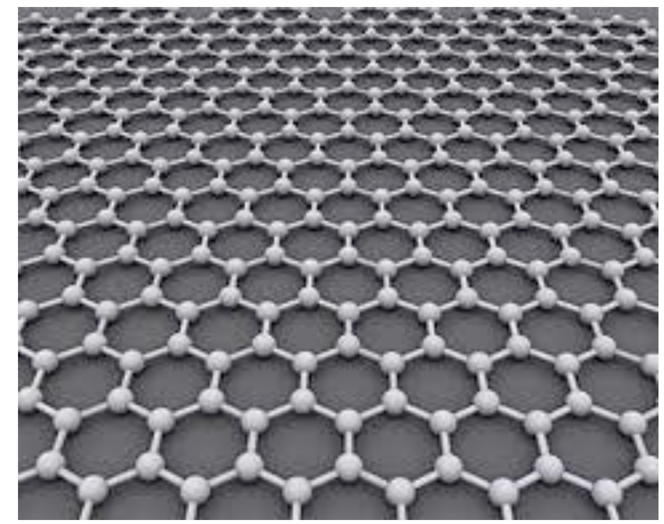

Light

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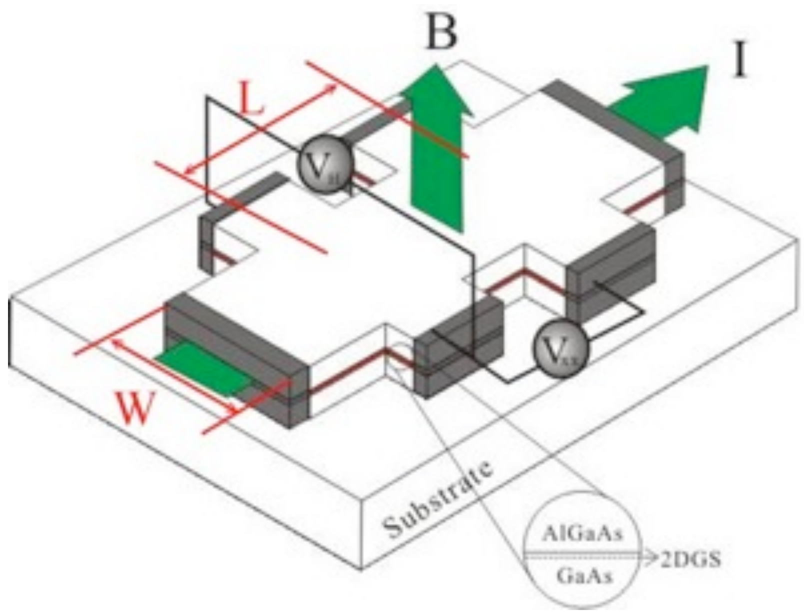

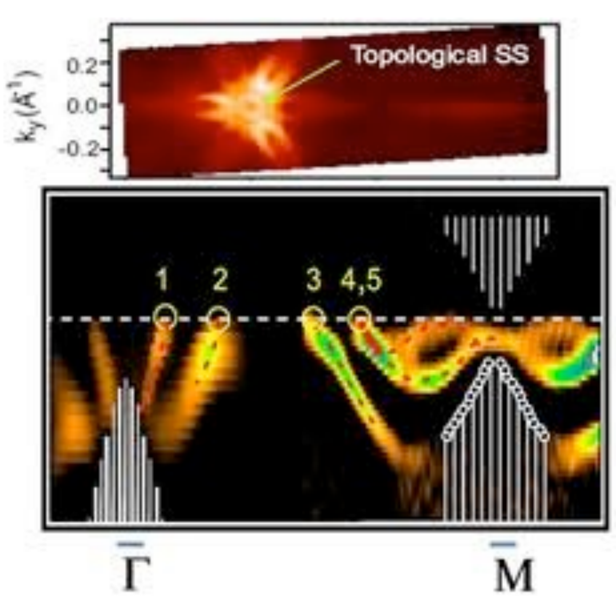

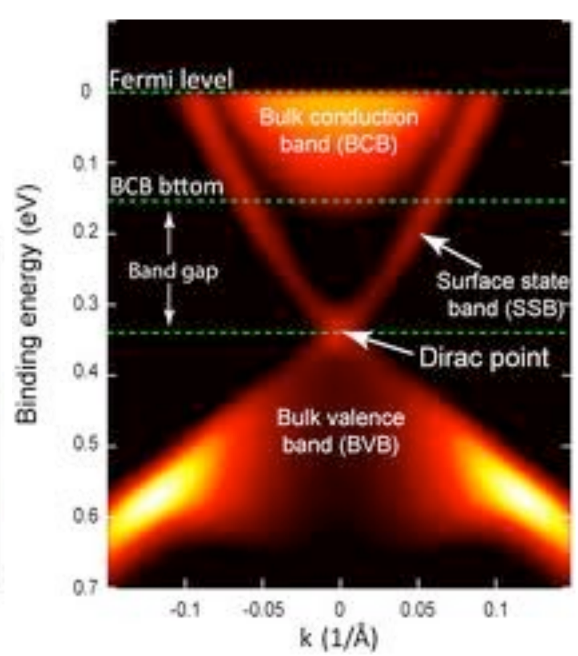

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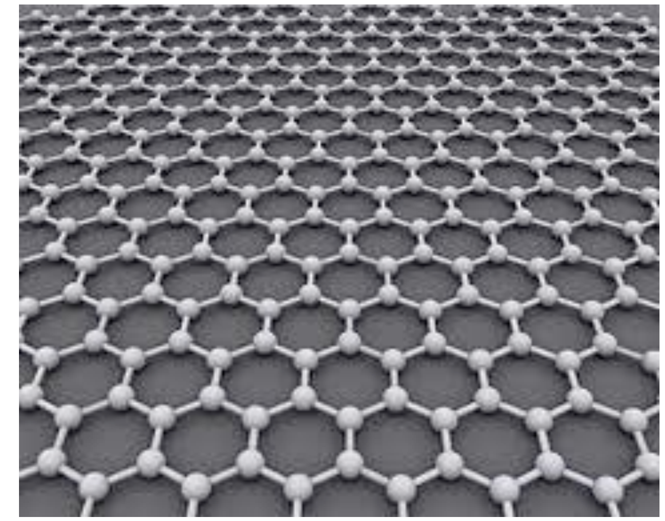

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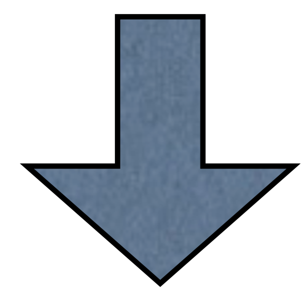

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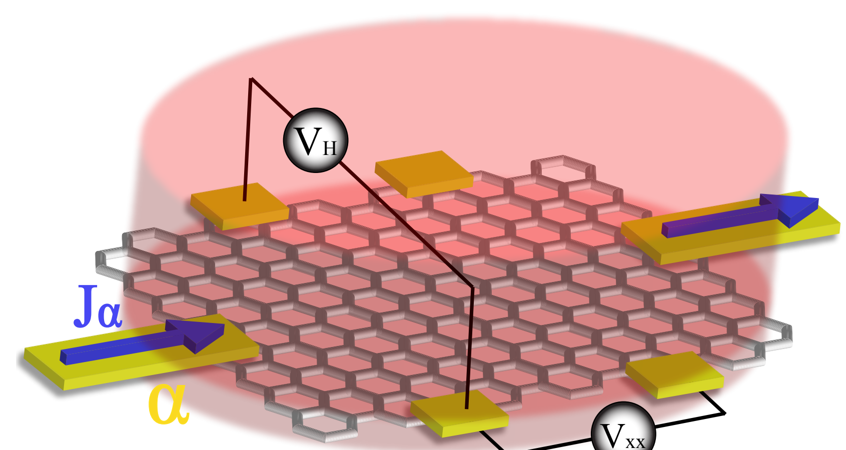

T. Kitagawa, T. Oka, et al,
[Phys. Rev. B 84, 235108 (2011)]

New Topological phenomena in driven systems

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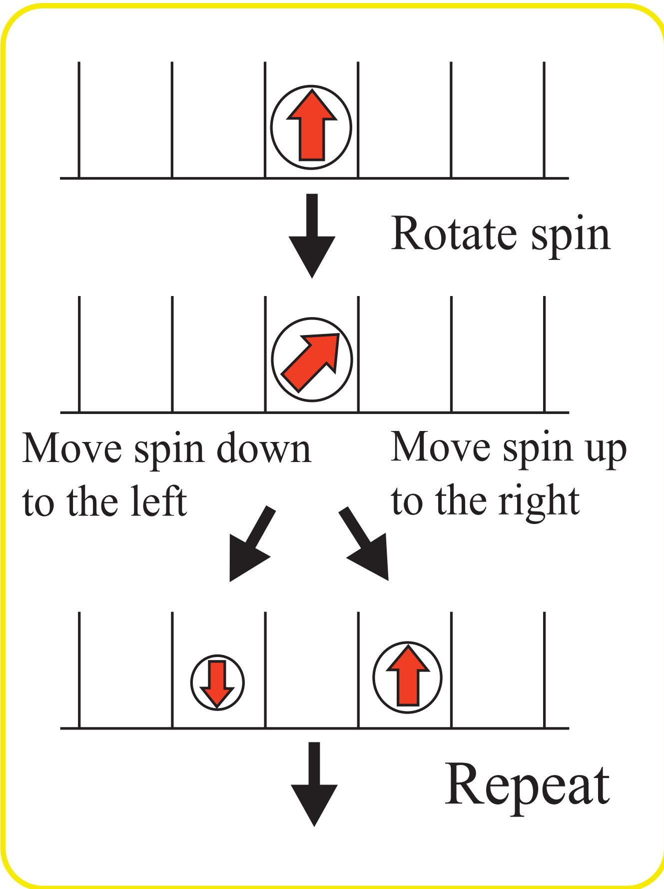

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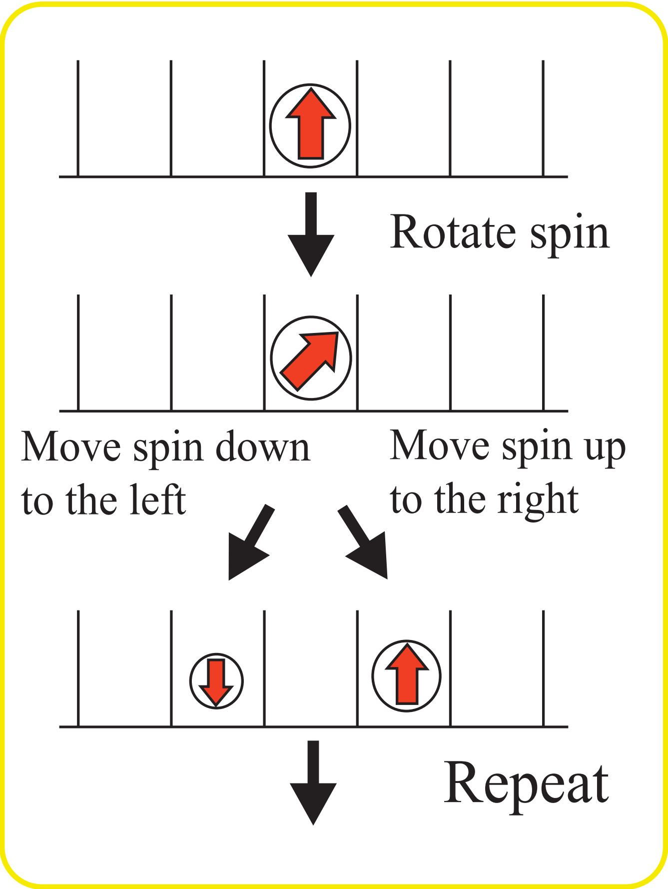

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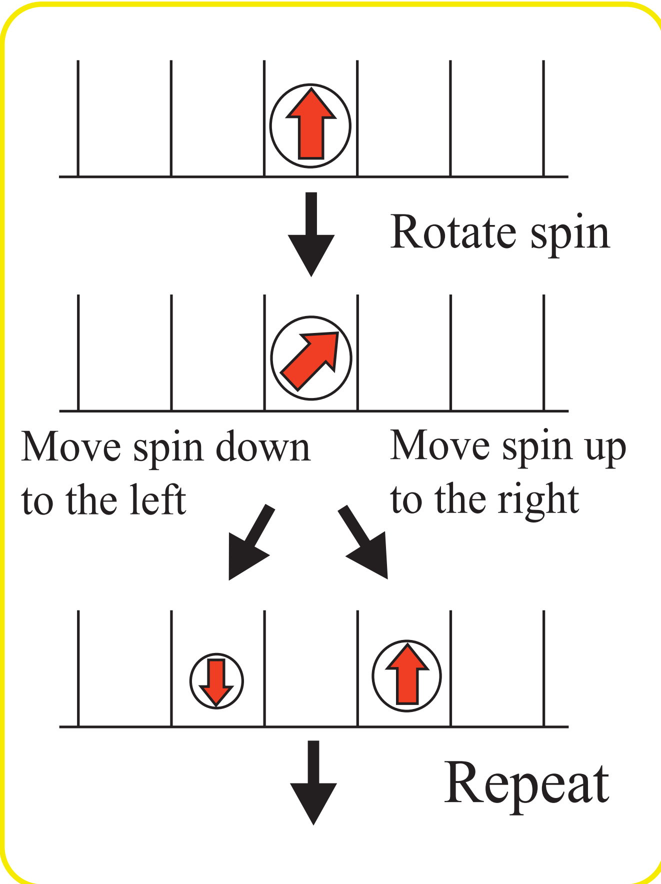

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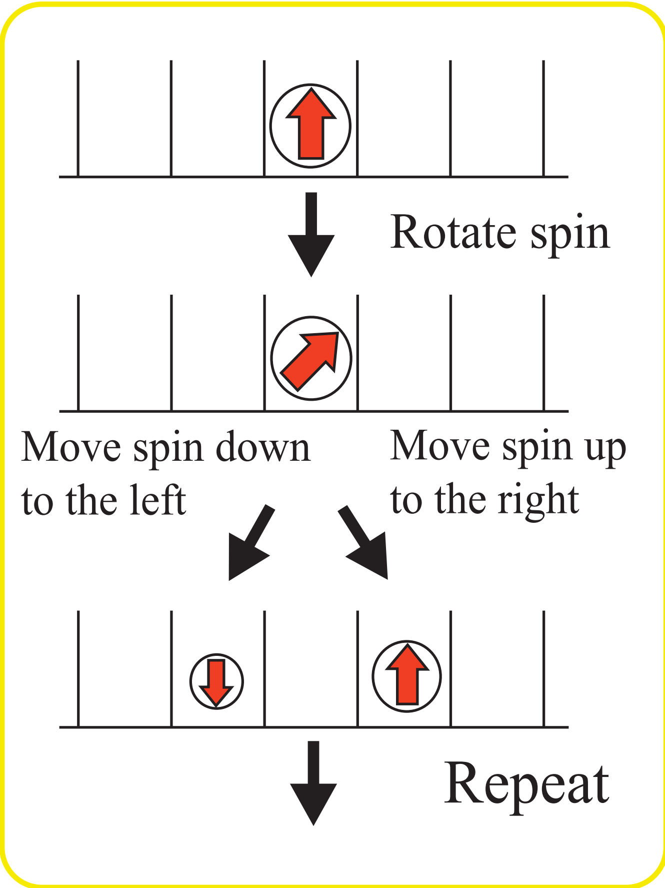

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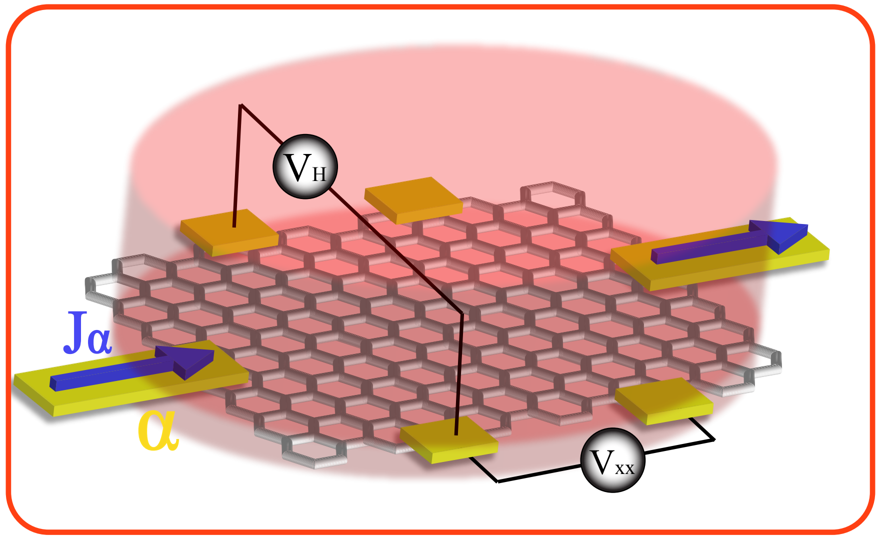
condensed matter



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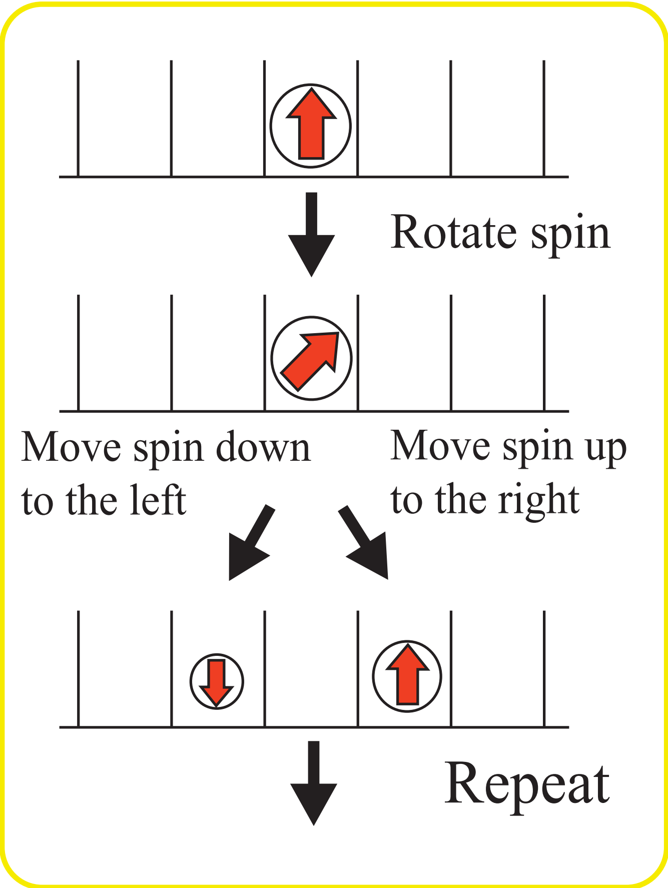

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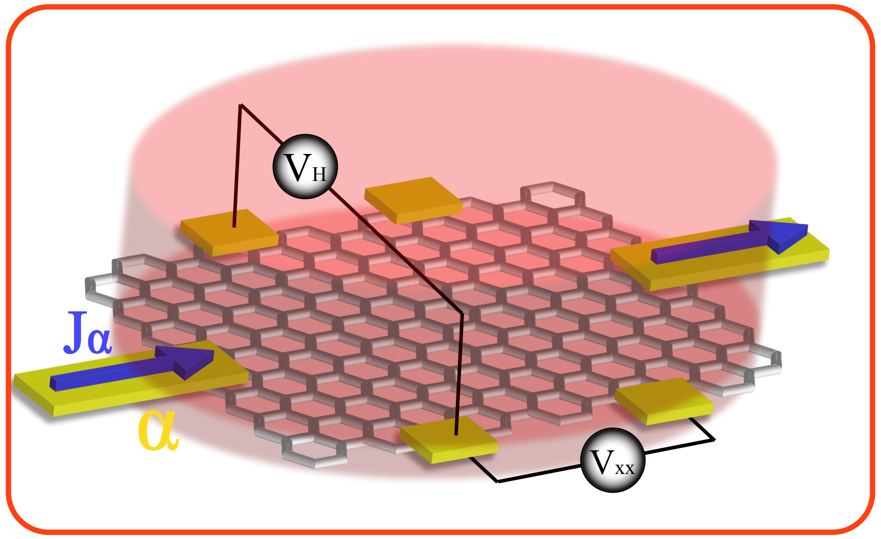

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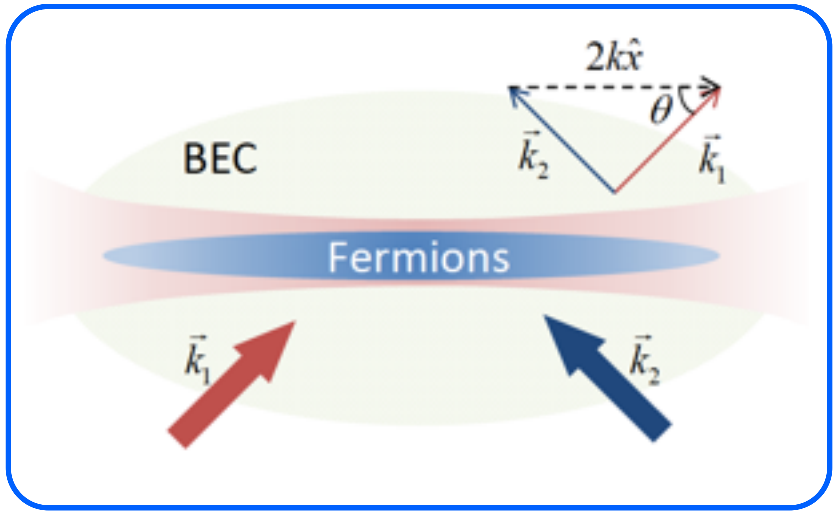
cold atom



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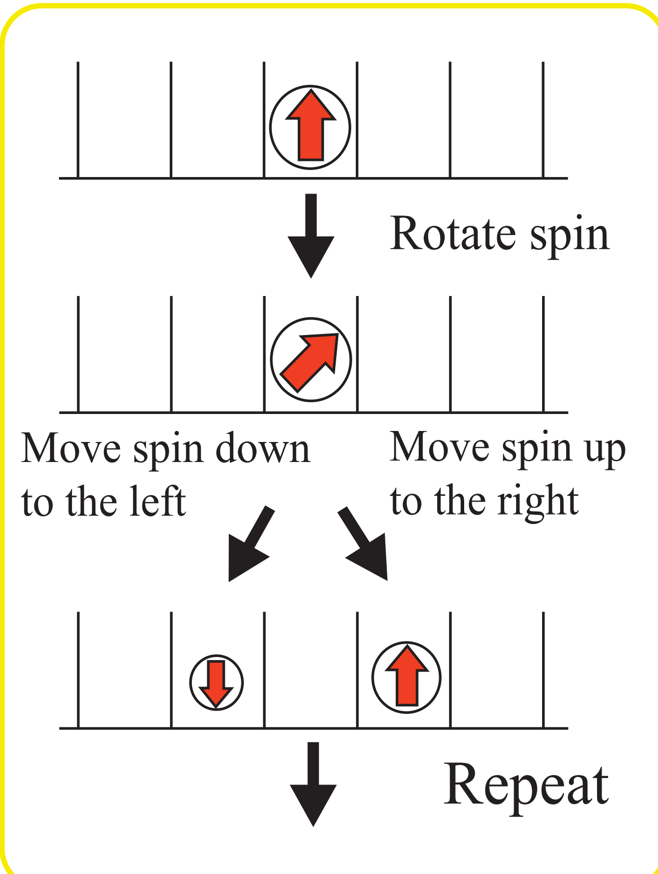

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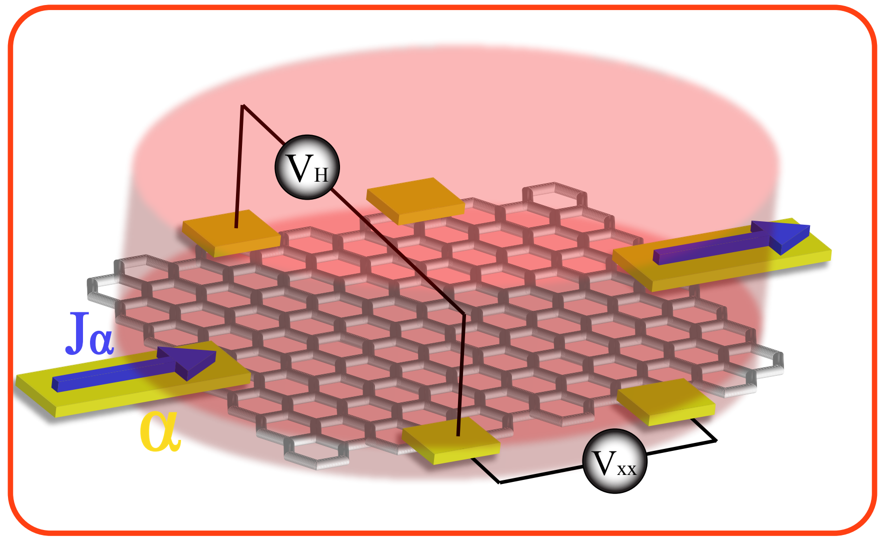

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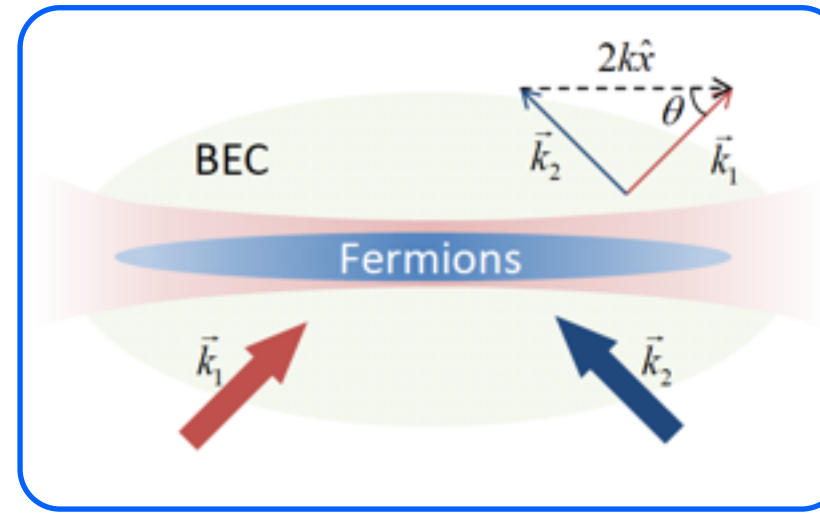

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Outline

1. Overview of topological phases

2. Topology of periodically driven systems

    a. Design of static topology through driving

3. Examples from driven hexagonal lattice system;
Graphene under circularly polarized light

4. Detection scheme of topological band

5. Conclusion

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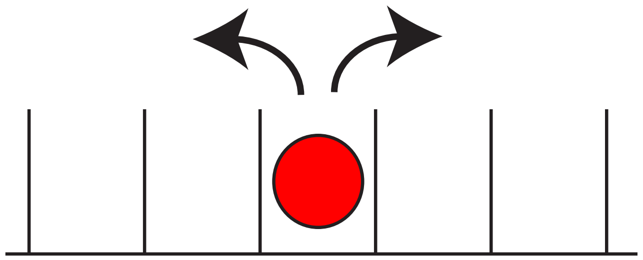
Floquet approach to periodically driven systems

Consider *non-interacting*, single particle Hamiltonian in a lattice which is periodically driven

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

where T is one period of dynamics



Floquet approach to periodically driven systems

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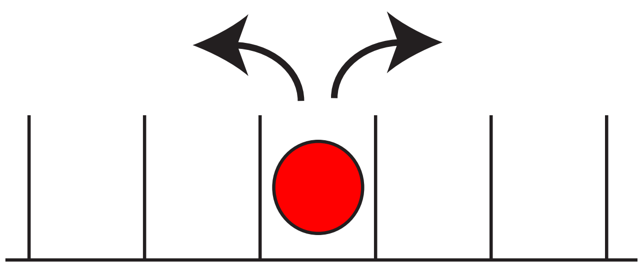
Ex. 1D



We characterize such dynamics through the evolution operator after one period called Floquet operator:

$$U(T) = \mathcal{T}\left(e^{-i\int_0^T H(t')dt'}\right)$$

$\mathcal{T}$ is time ordering

Topological behavior is captured in the topology of Floquet operator

Takuya Kitagawa, Harvard University

Effective Hamiltonian

Evolution operator of one period

$$U(T) = \mathcal{T}\left(e^{-i\int_0^T H(t')dt'}\right)$$ $\mathcal{T}$ is time ordering

We can define a local, static Hamiltonian H_{eff} through

$$U(T) = \mathcal{T}e^{-i\int_0^T H(t)dt} \equiv e^{-iH_{\text{eff}}T}$$

“Stroboscopic” simulation of H_{eff}

see, T.Kitagawa et al (2010) PRB

Takuya Kitagawa, Harvard University

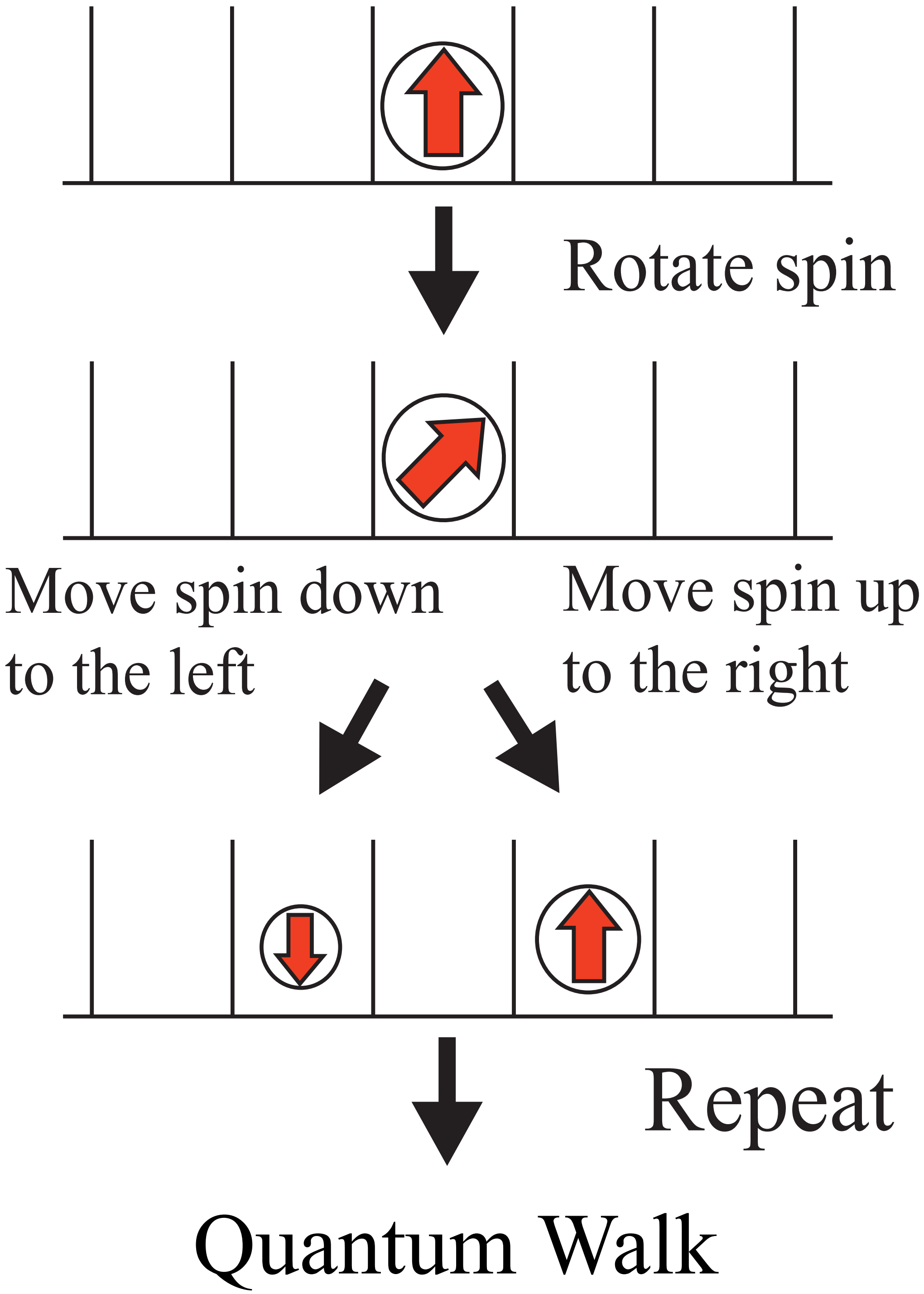
Topology of Effective Hamiltonian

		TRS	PHS	SLS	$d=1$	$d=2$	$d=3$
standard (Wigner-Dyson)	A (unitary)	0	0	0	-	$\mathbb{Z}$	-
	AI (orthogonal)	+1	0	0	-	-	-
	AII (symplectic)	−1	0	0	-	$\mathbb{Z}_2$	$\mathbb{Z}_2$
chiral (sublattice)	AIII (chiral unitary)	0	0	1	$\mathbb{Z}$	-	$\mathbb{Z}$
	BDI (chiral orthogonal)	+1	+1	1	$\mathbb{Z}$	-	-
	CII (chiral symplectic)	−1	−1	1	$\mathbb{Z}$	-	$\mathbb{Z}_2$
BdG	D	0	+1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	-
	C	0	−1	0	-	$\mathbb{Z}$	-
	DIII	−1	+1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
	CI	+1	−1	1	-	-	$\mathbb{Z}$

"Periodic table" of topological phases

(Qi et al PRB 2008, Schnyder, Ryu et al PRB 2008,
Kitaev AIP Conference proceeding 2009)

Example: quantum walk



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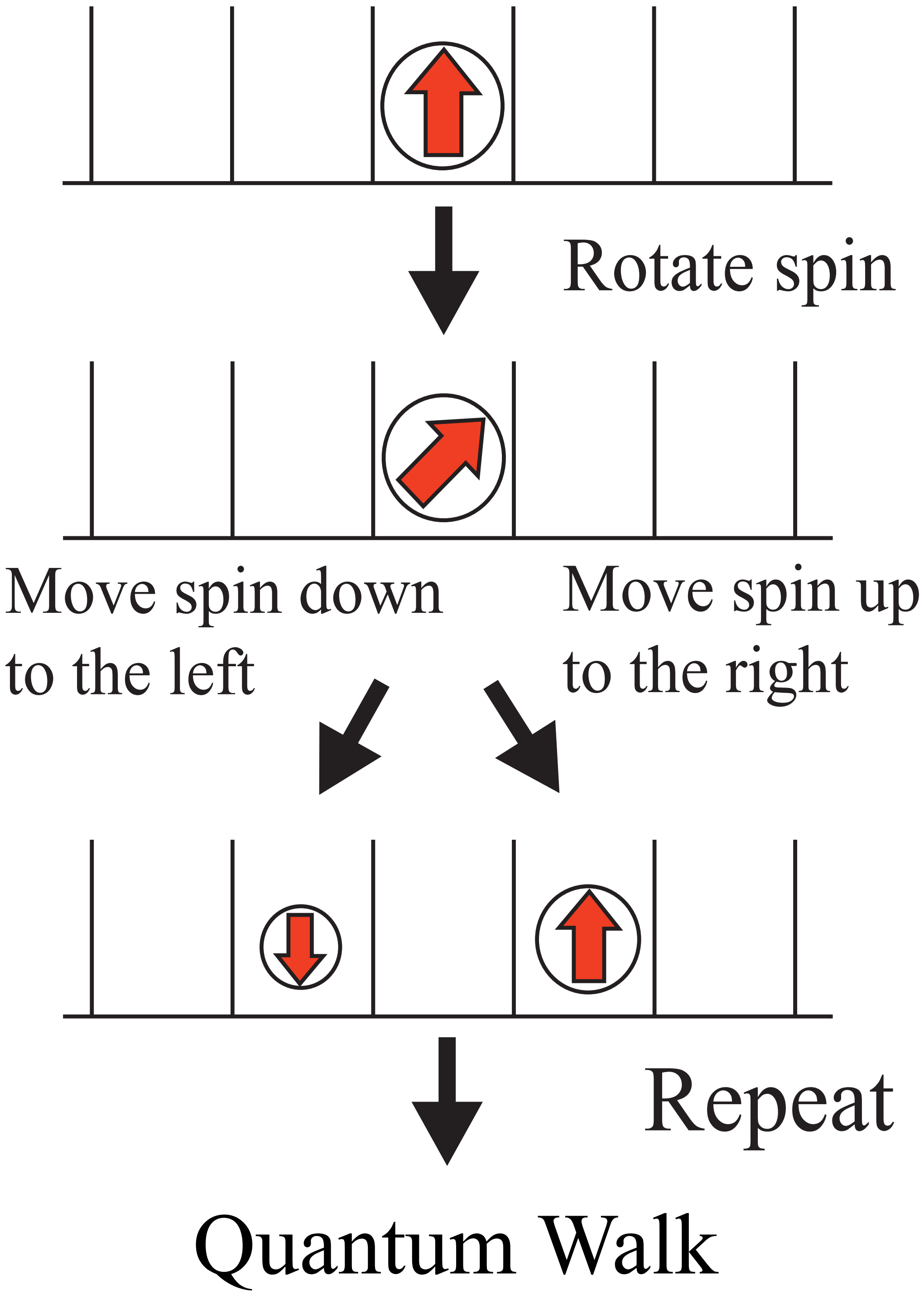

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$$R(\theta) = e^{-i\theta\sigma_y} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

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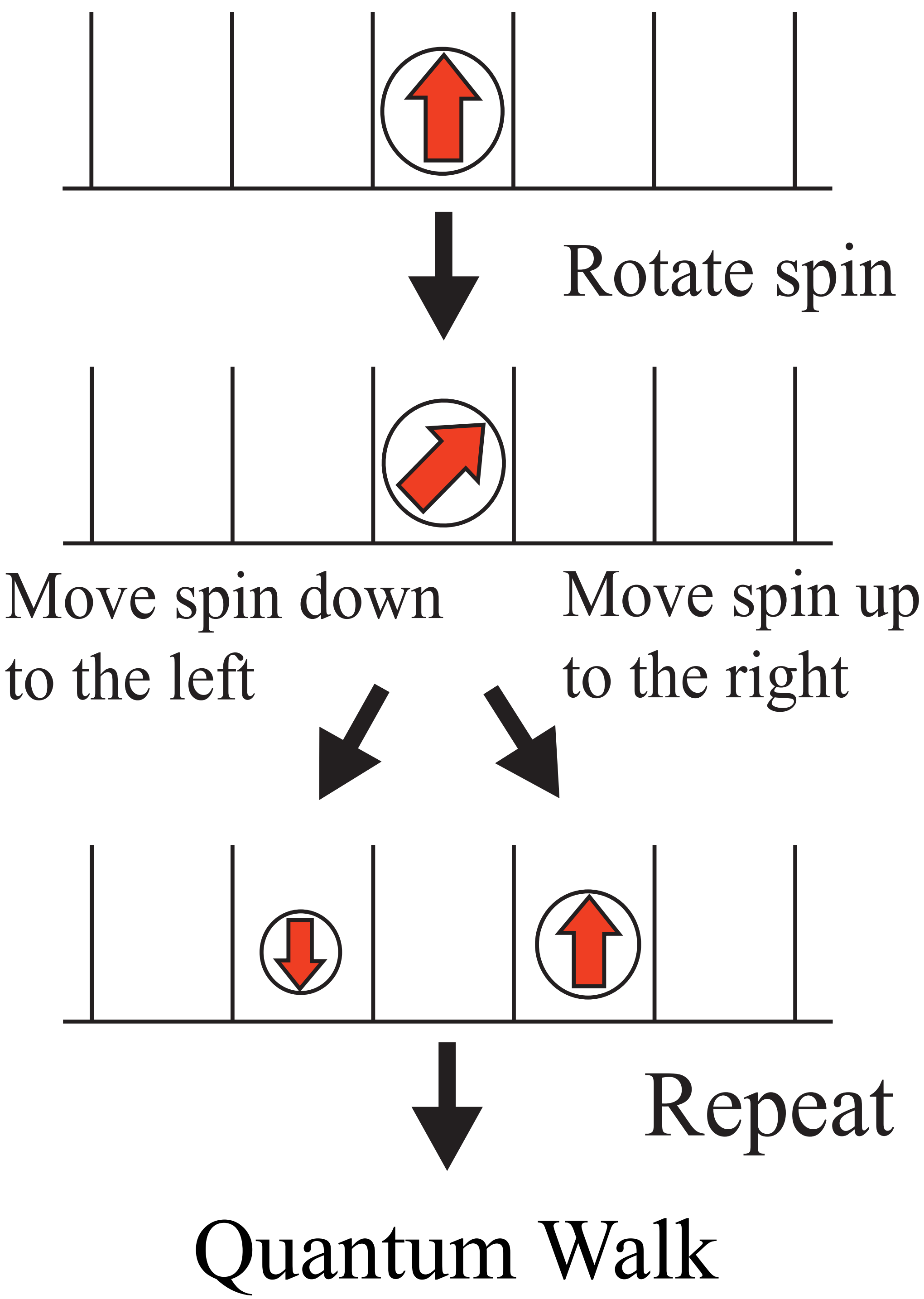

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$$T = \sum_x |x+1\rangle\langle x| \otimes |\uparrow\rangle\langle\uparrow| + |x-1\rangle\langle x| \otimes |\downarrow\rangle\langle\downarrow| = \sum_k e^{ik\sigma_z} \otimes |k\rangle\langle k|$$

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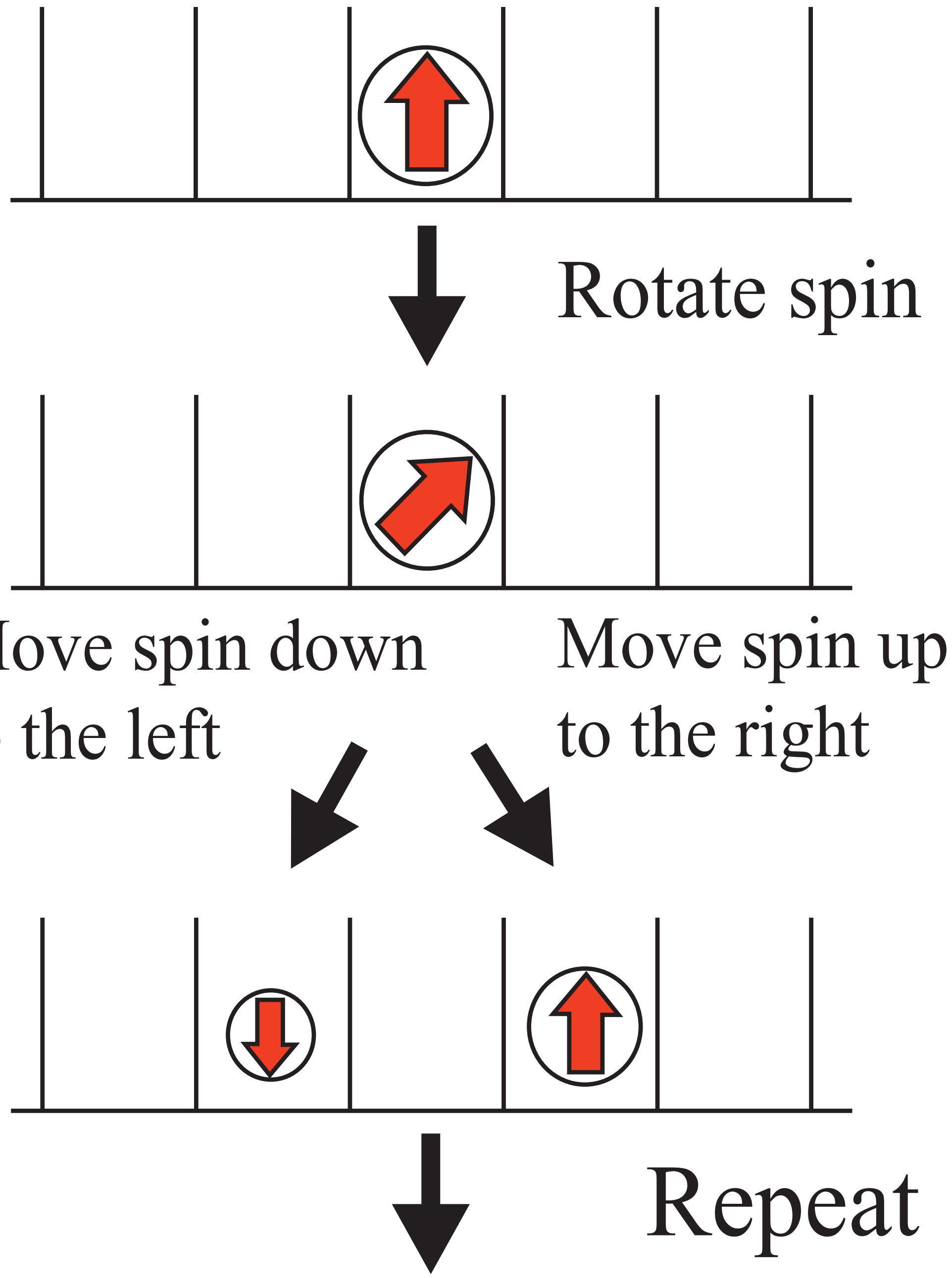

Quantum Walk

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\end{aligned}
$$

$$
\begin{aligned}
U_{onestep} &= TR(\theta) \\
&= \sum_k e^{ik\sigma_z} e^{-i\theta\sigma_y} \otimes |k\rangle\langle k|
\end{aligned}
$$

Hamiltonian formulation

$$U_{onestep} \equiv e^{-iH_{eff}(\theta)\delta t}$$

Effective Hamiltonian is 2 × 2 matrix

$$H(\theta) = \int_{-\pi}^{\pi} dk \left[E_\theta(k)\, \mathbf{n}_\theta(k) \cdot \boldsymbol{\sigma}\right] \otimes |k\rangle\langle k|,$$

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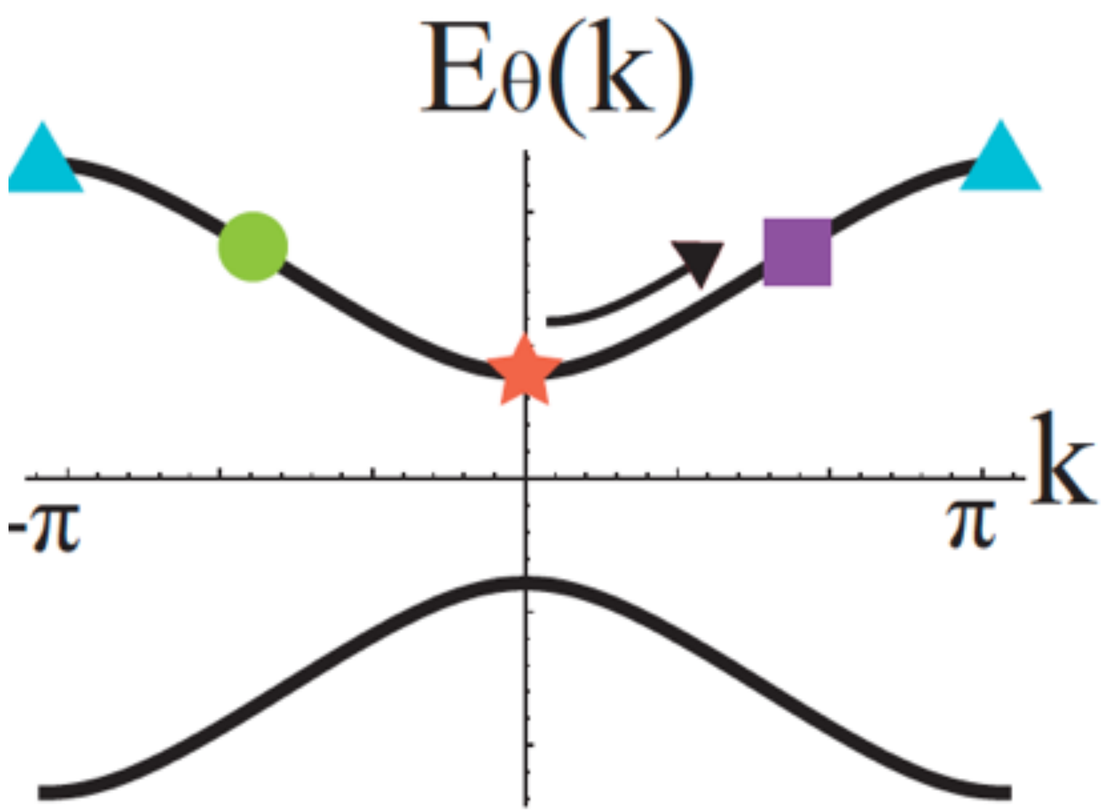

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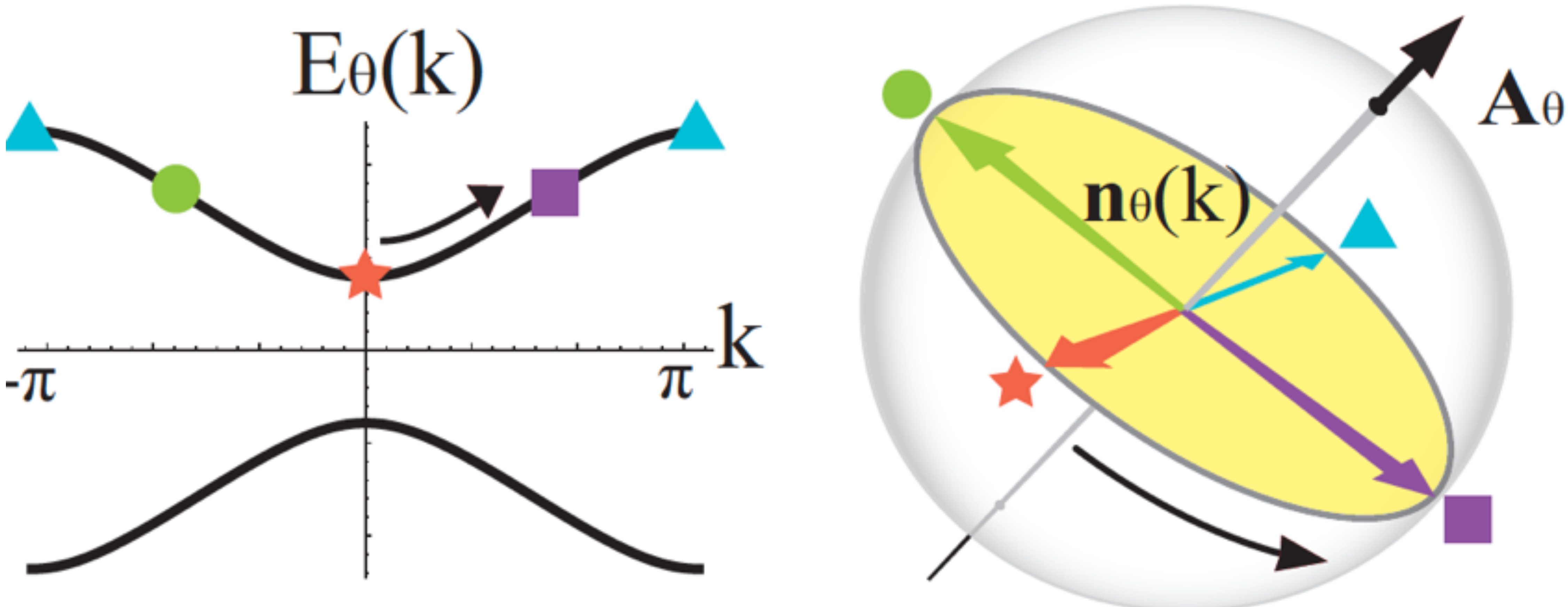

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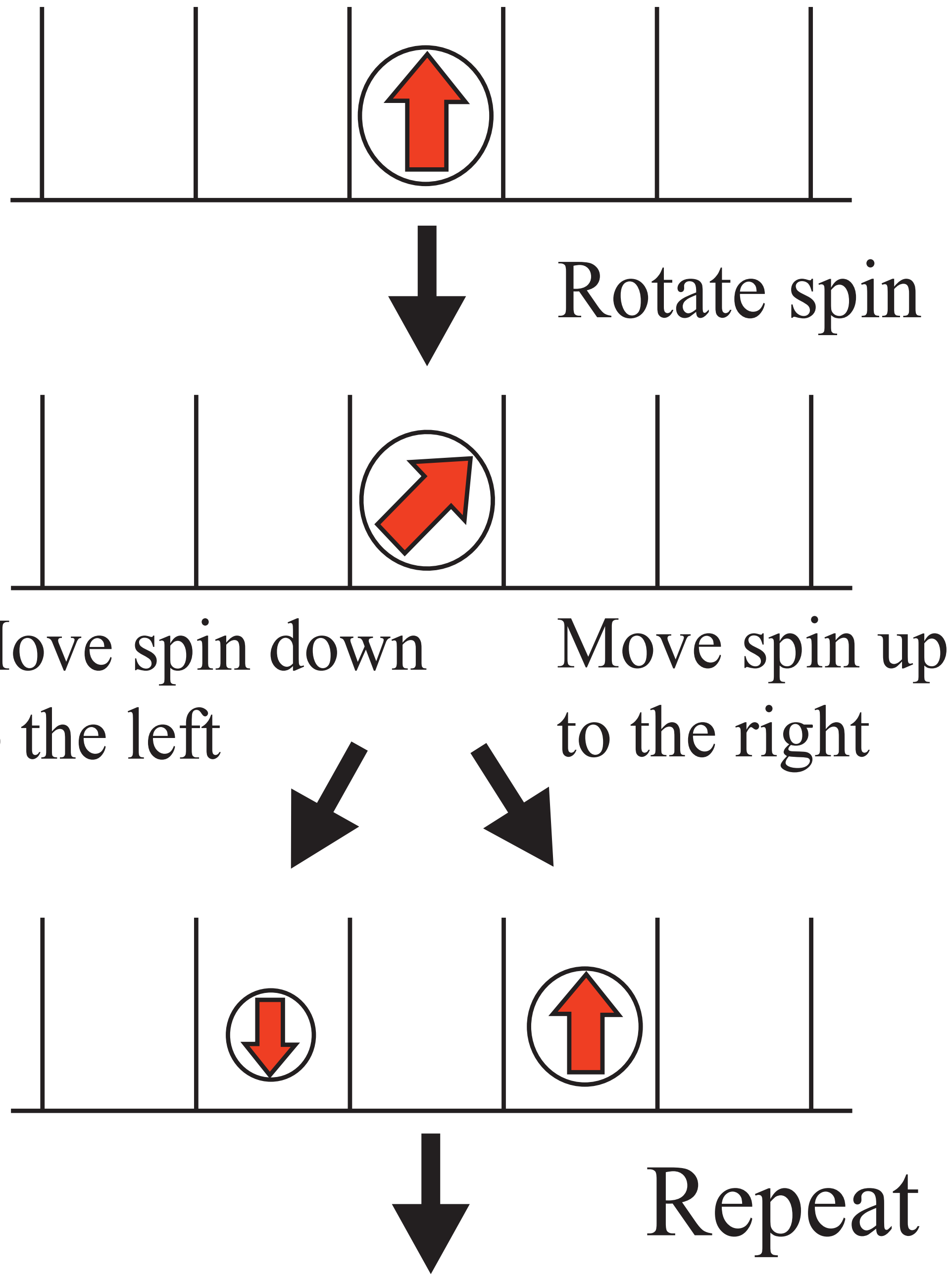
Example: quantum walk



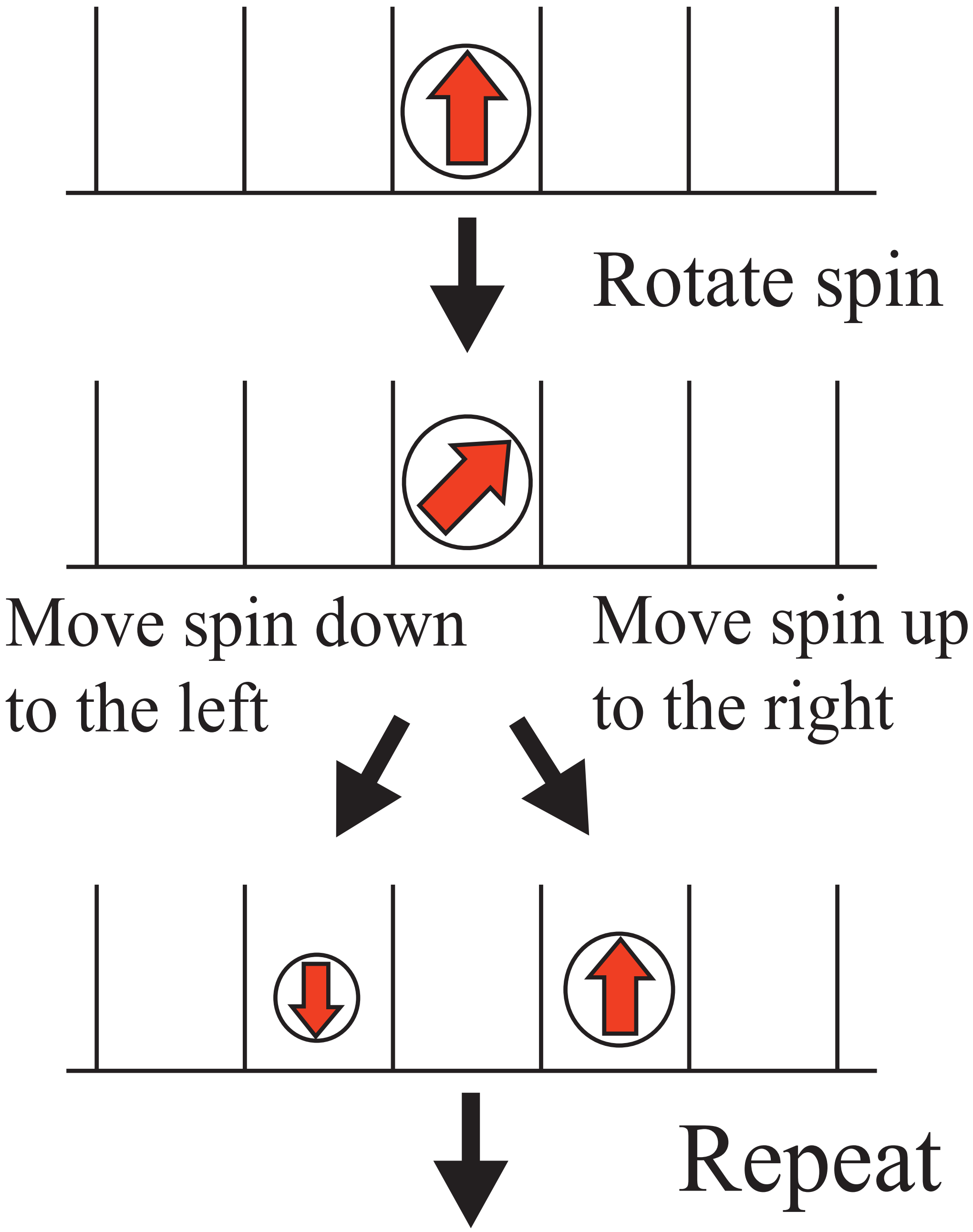
Quantum Walk

T. Kitagawa, et al Phys. Rev. A 82 033429 (2010)

Example: quantum walk

Realizes 1D topological phase!

Su-Schrieffer-Heeger model
Jackiw-Rebbi model



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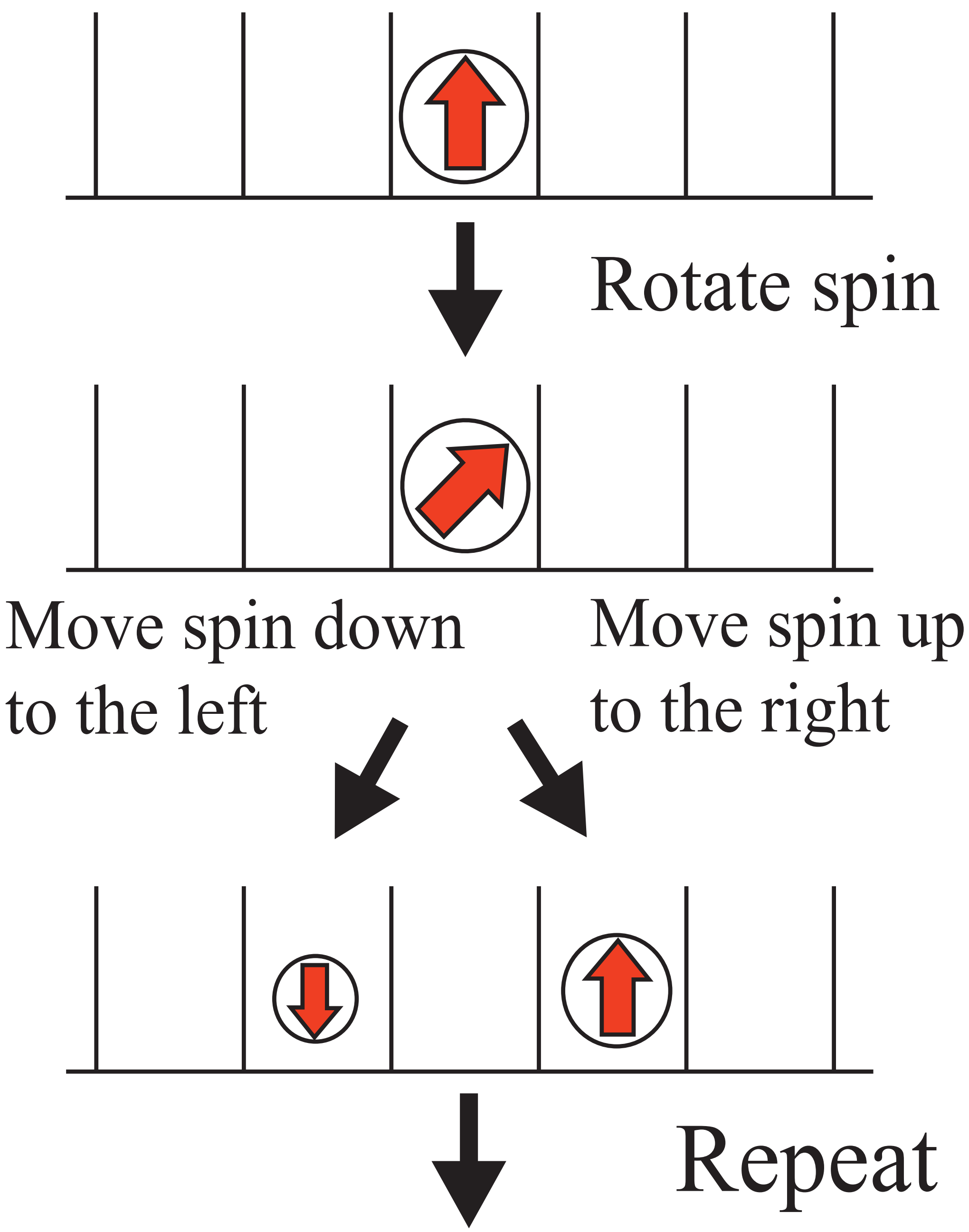

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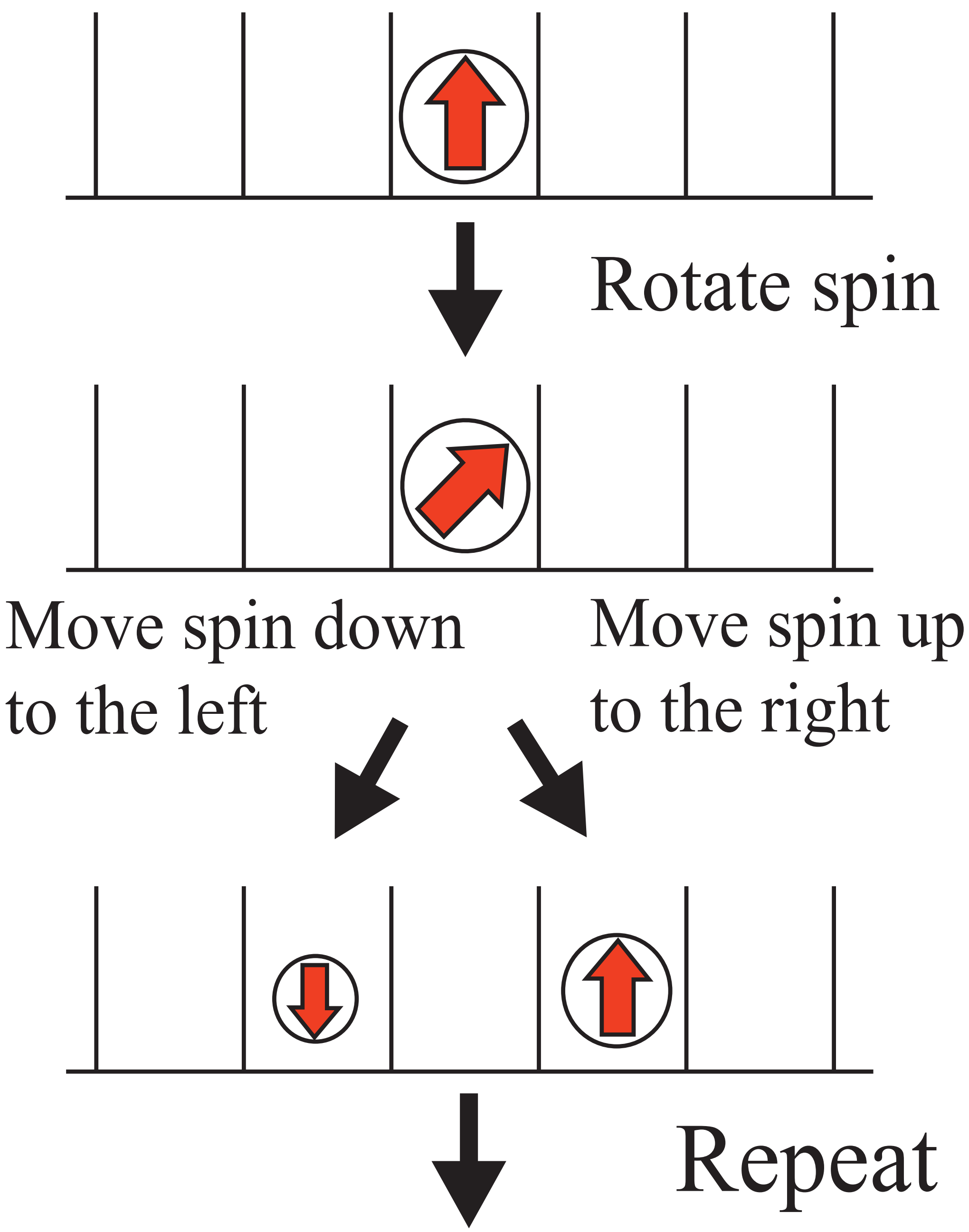

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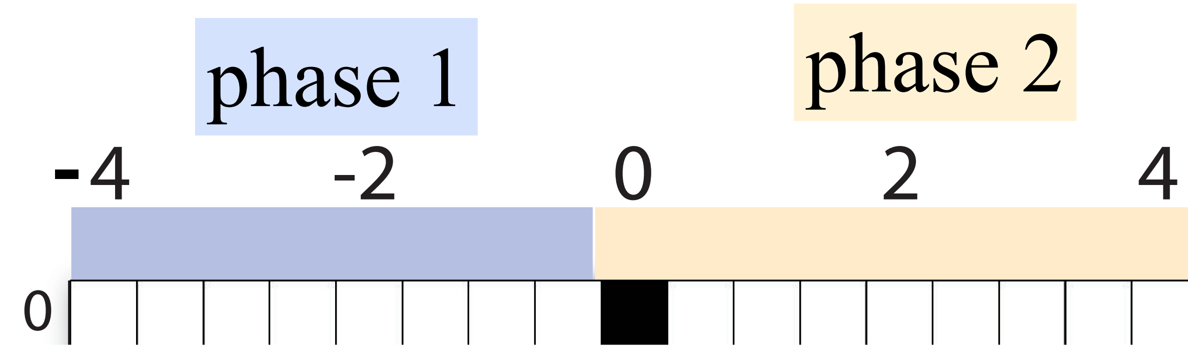

Exp. by A. White's group

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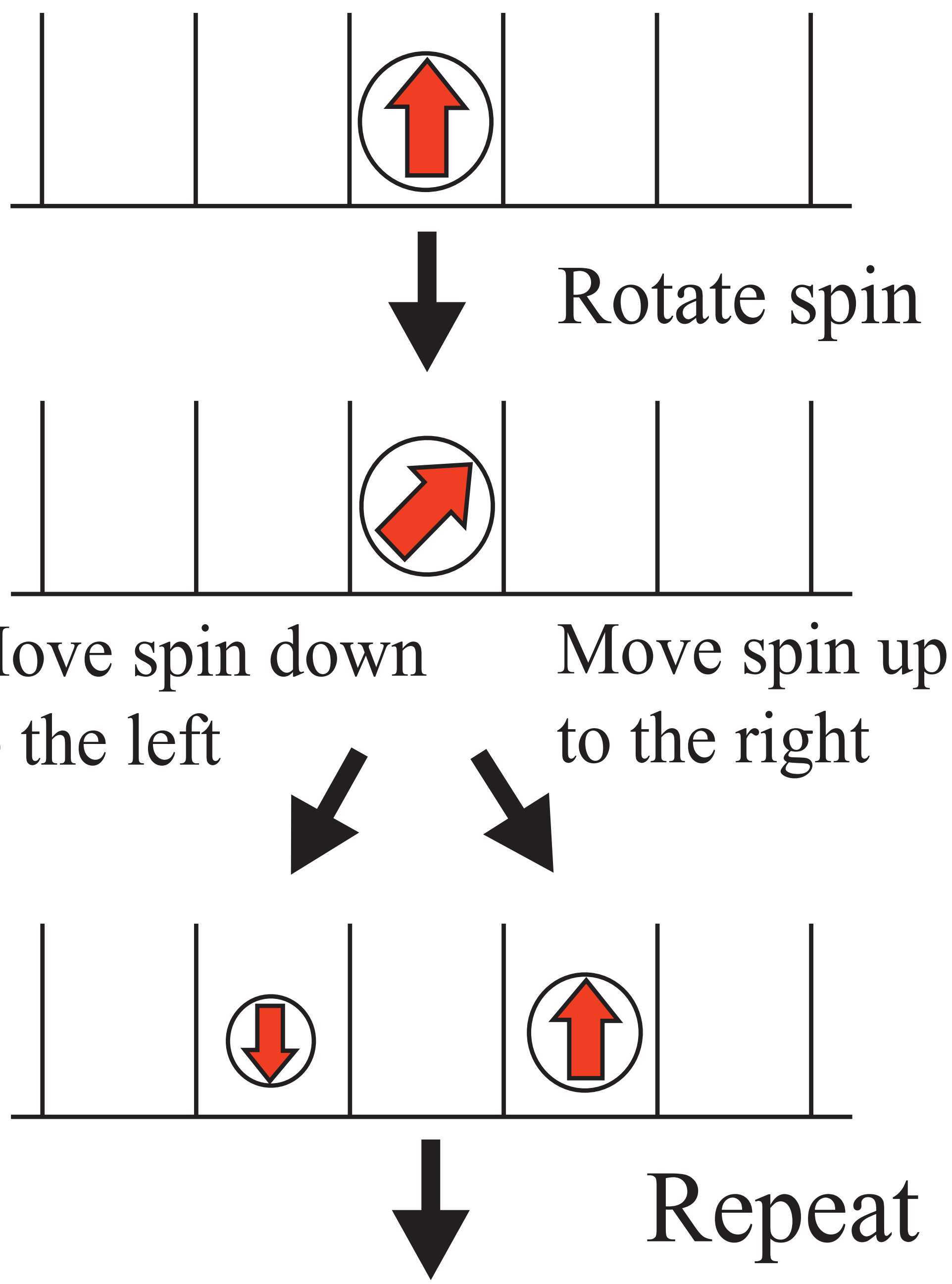
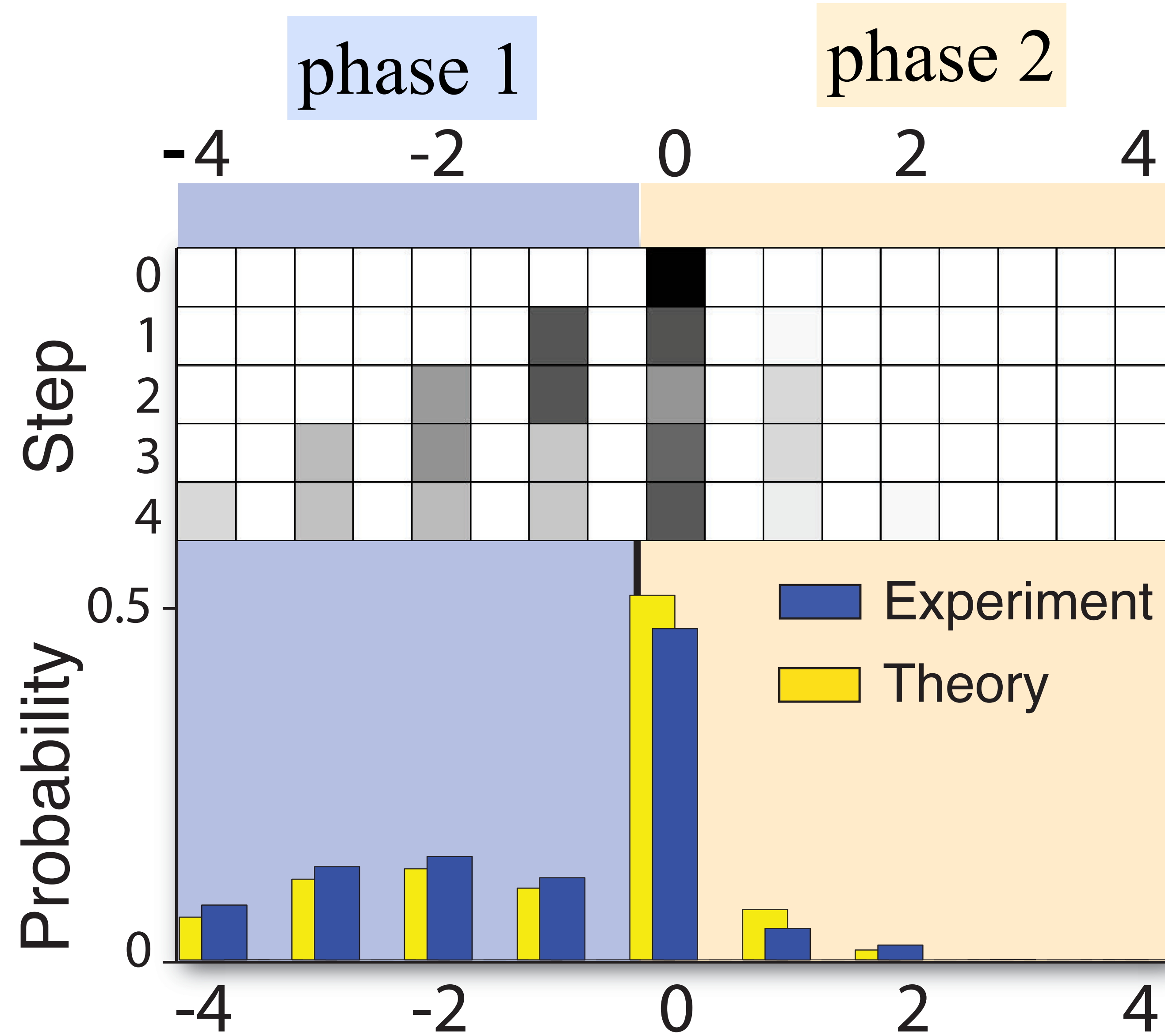
Jackiw-Rebbi model

Topologically protected zero energy bound state



Quantum Walk

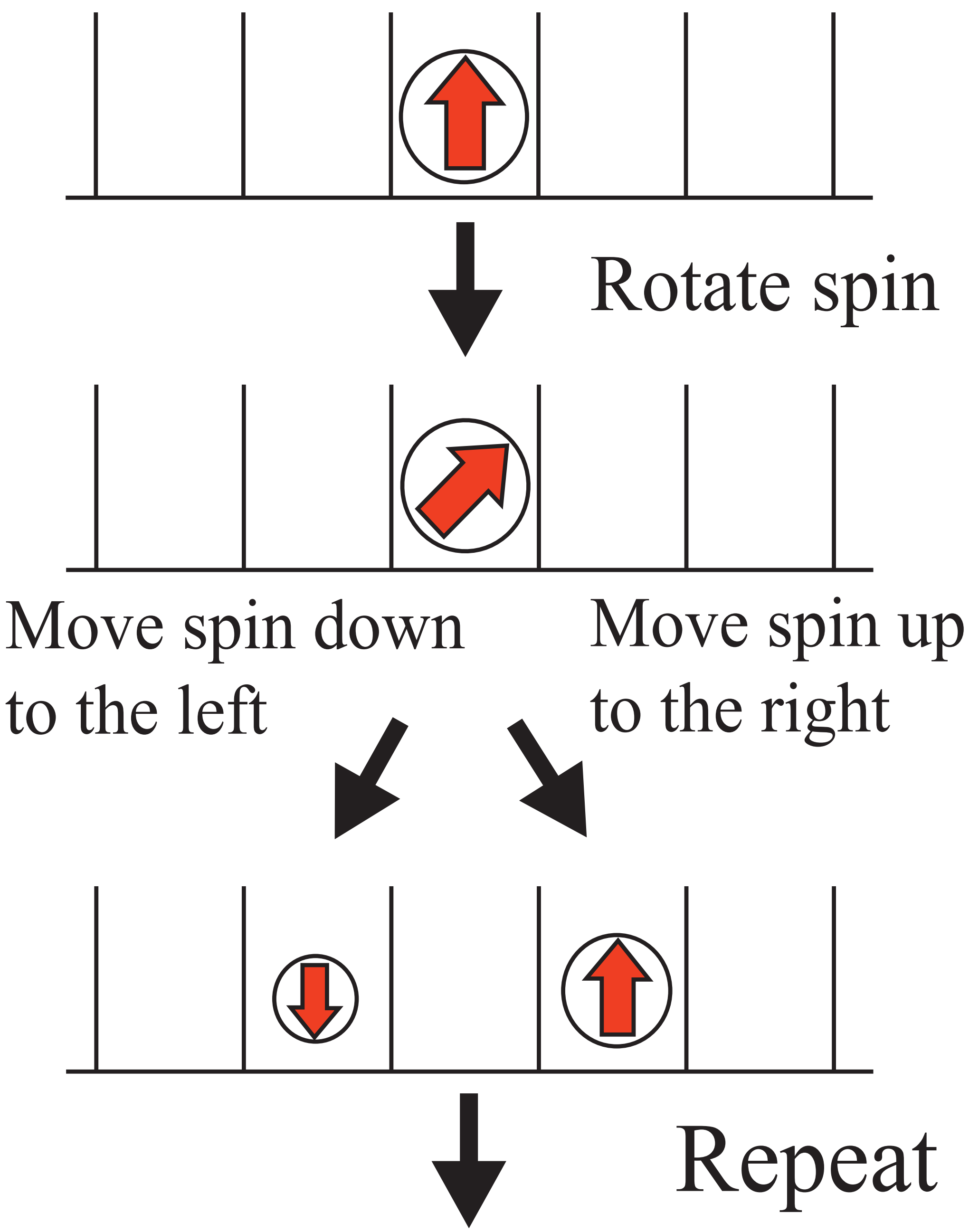
T. Kitagawa, et al Phys. Rev. A 82 033429 (2010)



Exp. by A. White's group

T. Kitagawa, M. A. Broome, et al, Nat. Comm. 3 882 (2012)

Example: quantum walk



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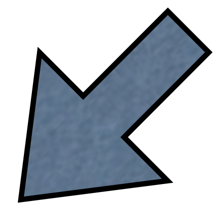

Realizes 1D topological phase!

Su-Schrieffer-Heeger model
Jackiw-Rebbi model

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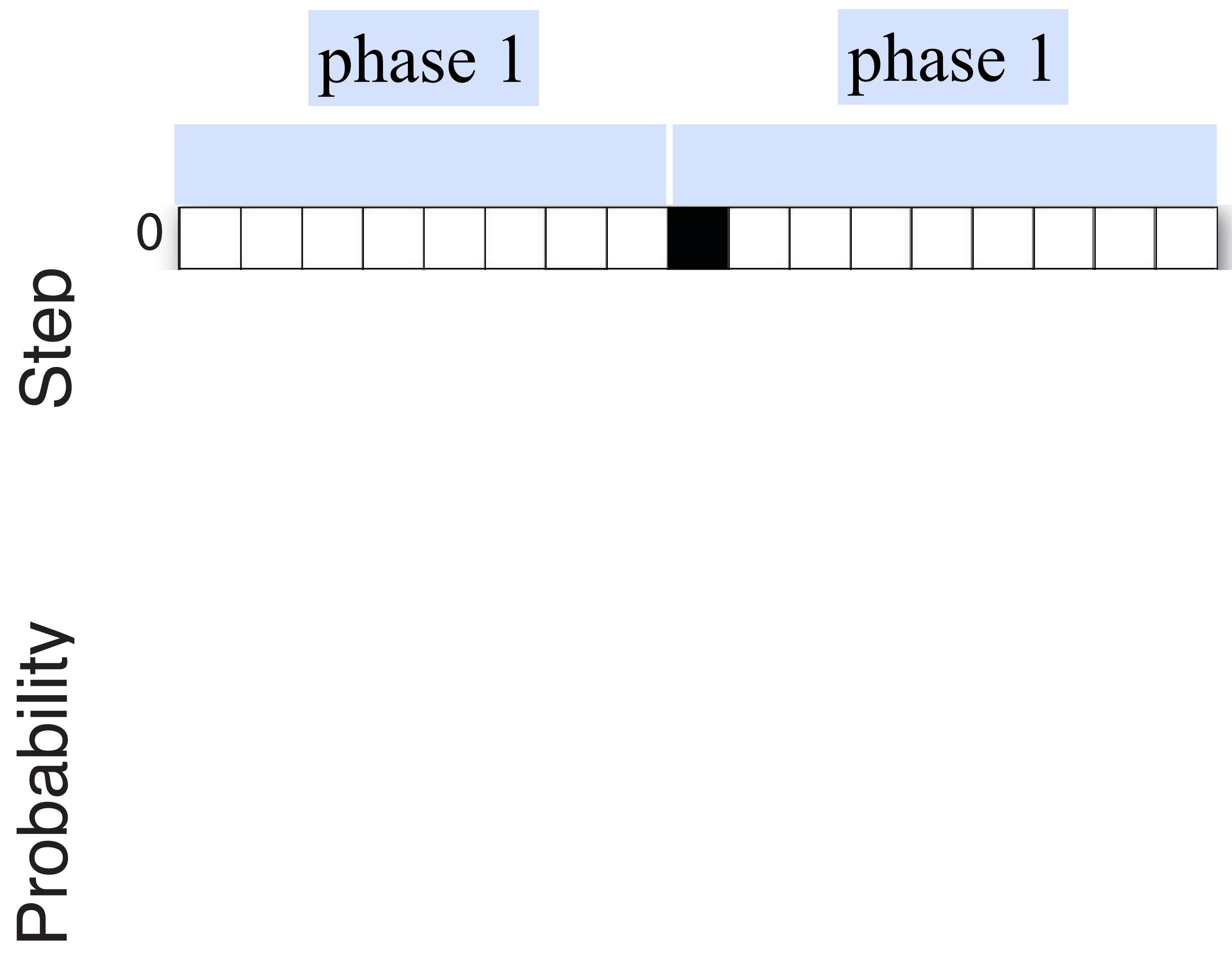

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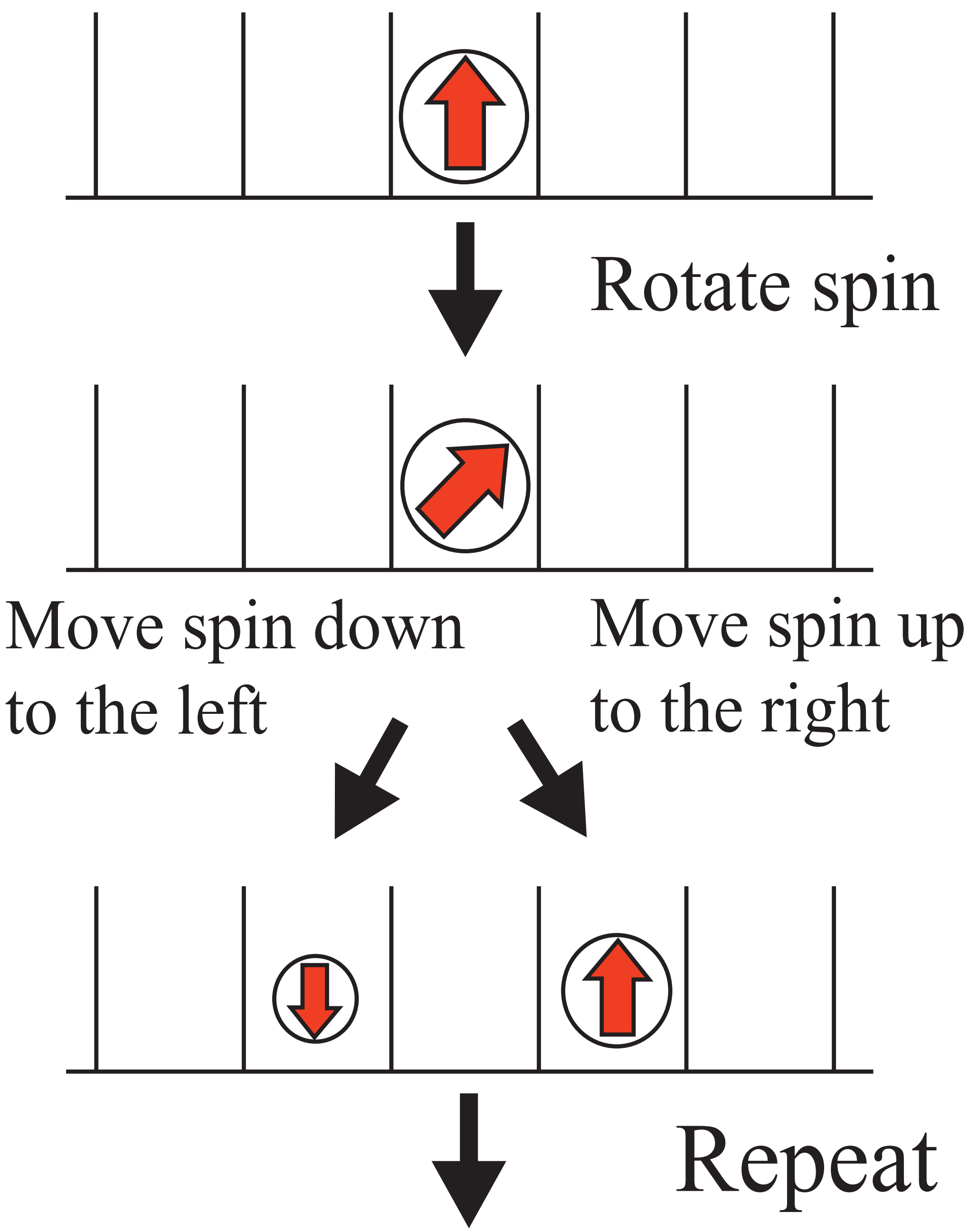

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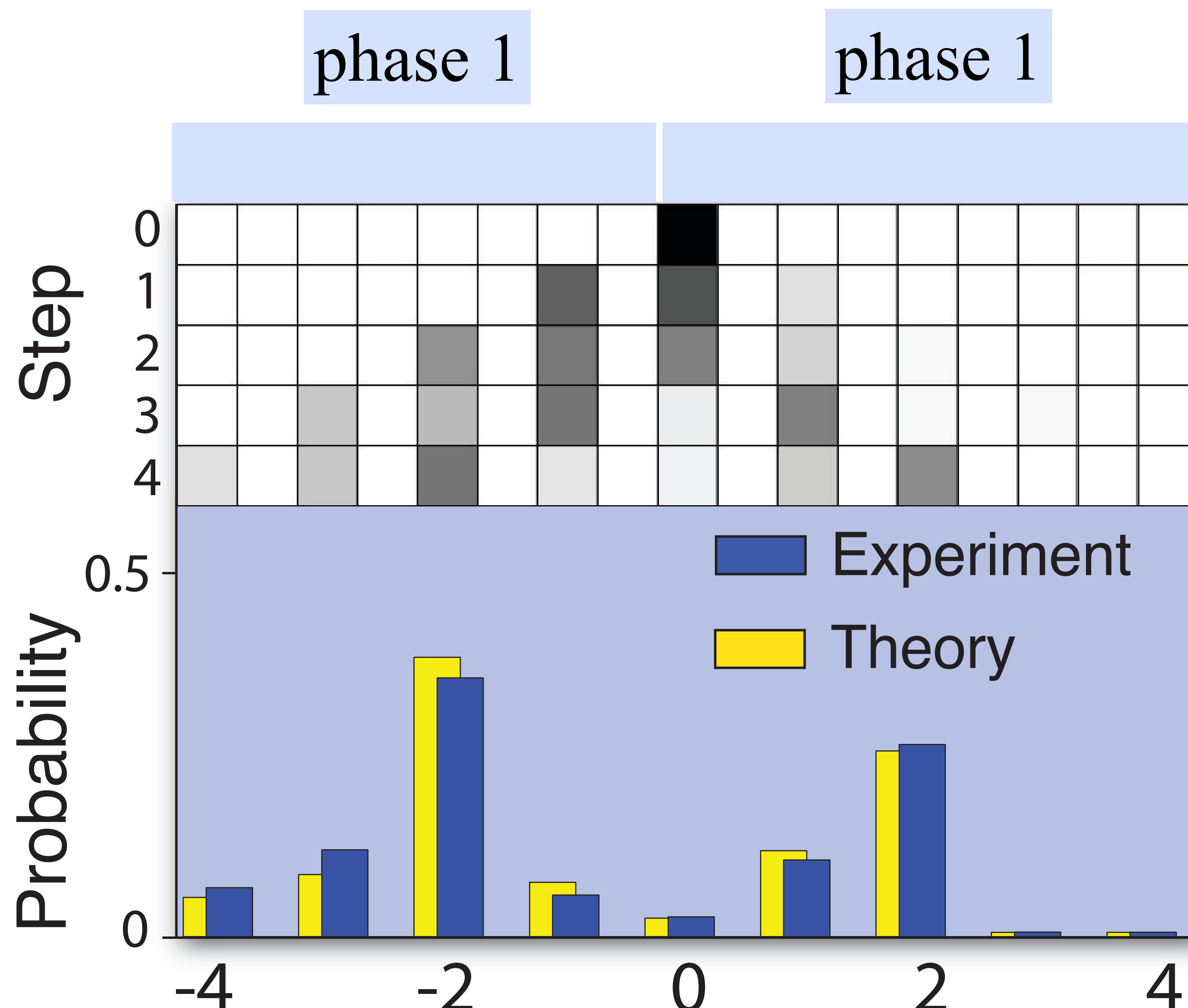

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T. Kitagawa, M. A. Broome, et al, Nat. Comm. 3 882 (2012)

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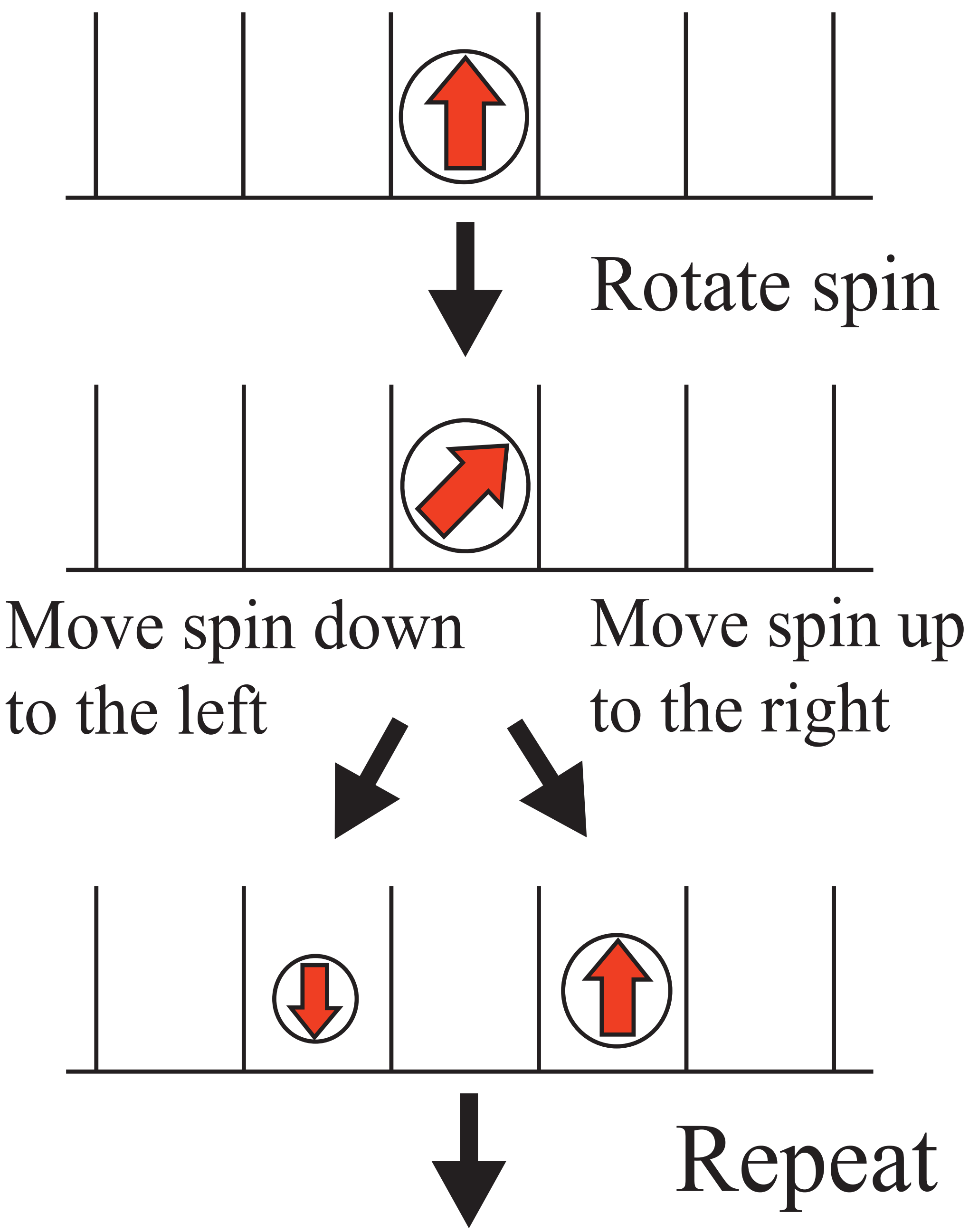
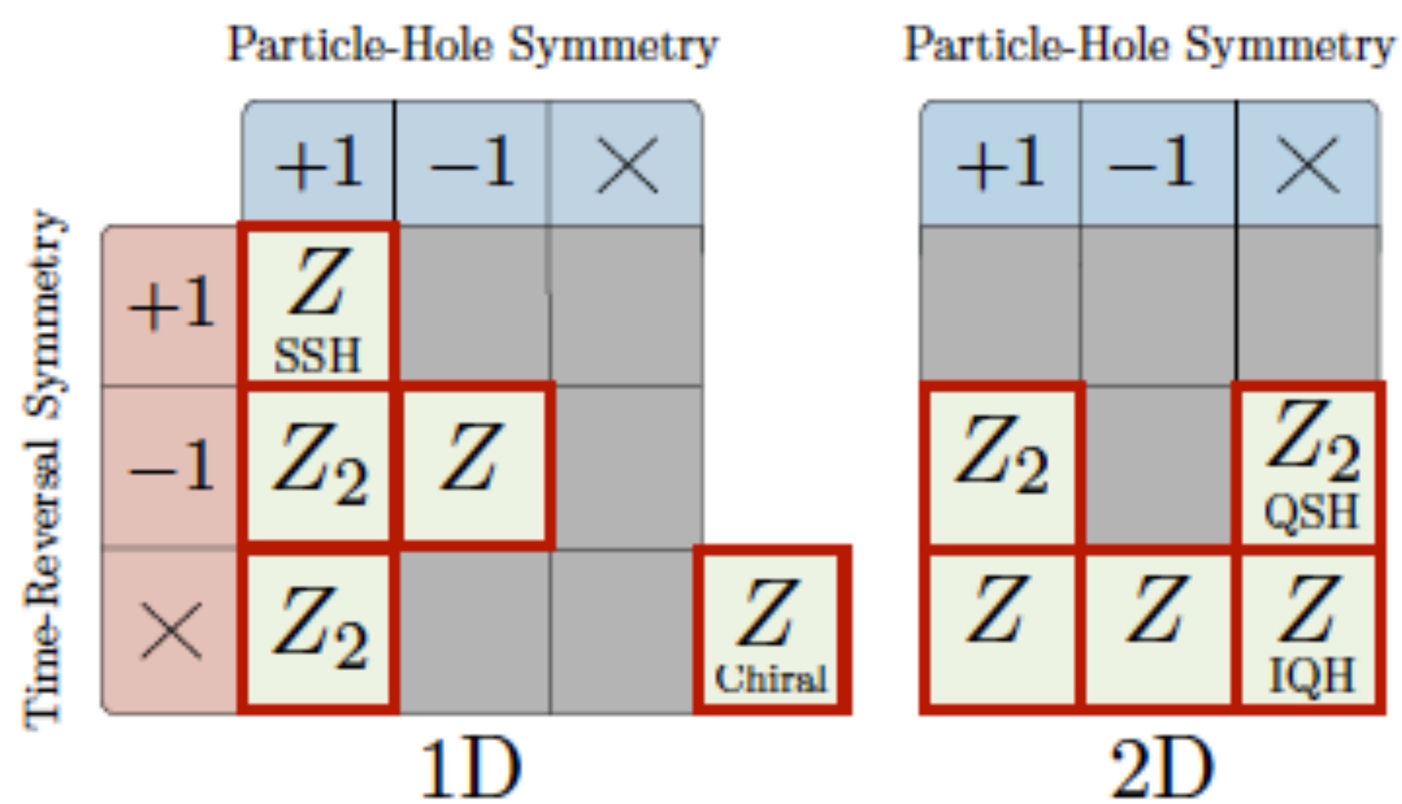


Quantum Walk

quantum walks allows versatile realizations of topological phases



T. Kitagawa, et al Phys. Rev. A 82 033429 (2010)

Outline

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2. Topology of periodically driven systems

   a. Design of static topology through driving

3. Examples from driven hexagonal lattice system;
Graphene under circularly polarized light

4. Detection scheme of topological band

5. Conclusion

Photo-induced integer quantum Hall effect without Landau levels

Non-equilibrium realization of Haldane model

Condensed matter realization

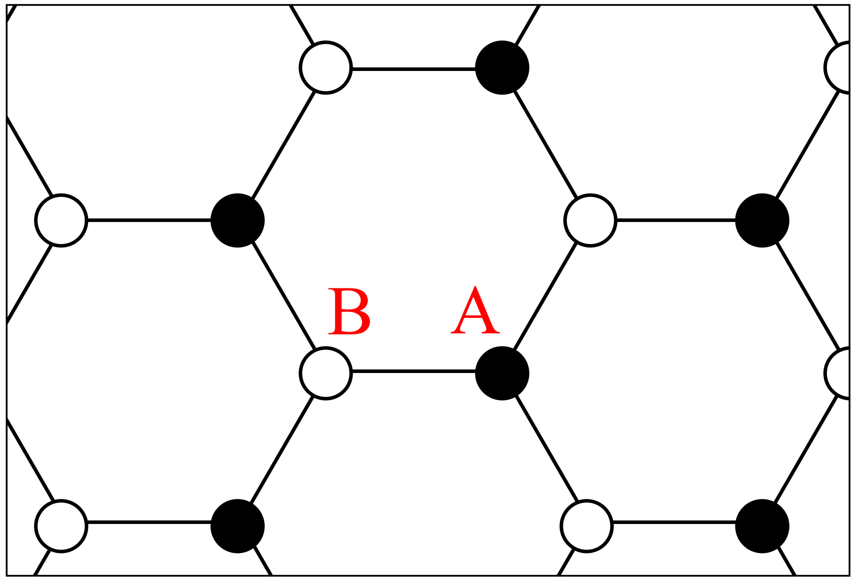
T. Kitagawa, et al, Phys. Rev. B 84, 235108 (2011)

Driven graphene

$$H(t) = -J \sum_{<ij>} e^{iA_{ij}(t)} c_i^\dagger c_j,$$

$$A_{ij}(t) = A\vec{r}_{ij} \cdot (\cos(t\Omega), \sin(t\Omega))$$

Circularly polarized light



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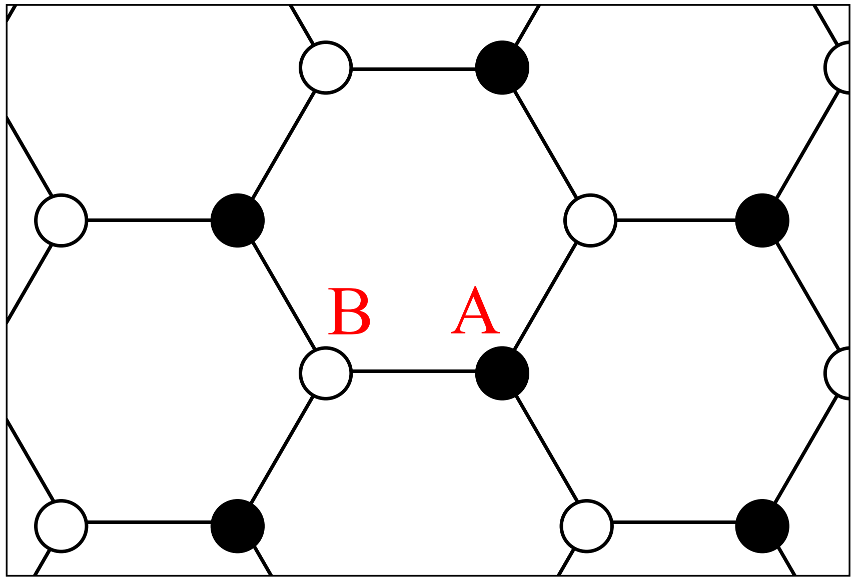
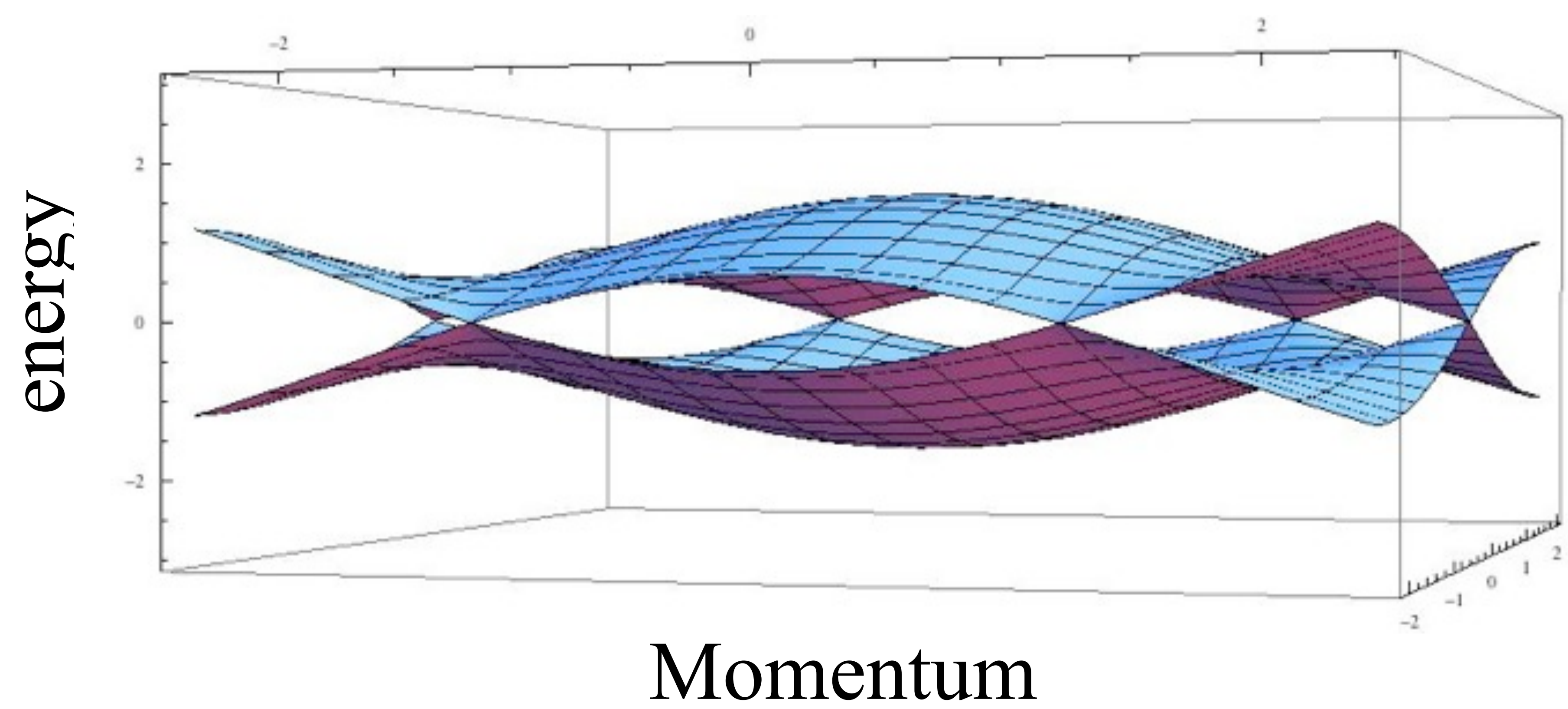


In the absence of light



Takuya Kitagawa, Harvard University

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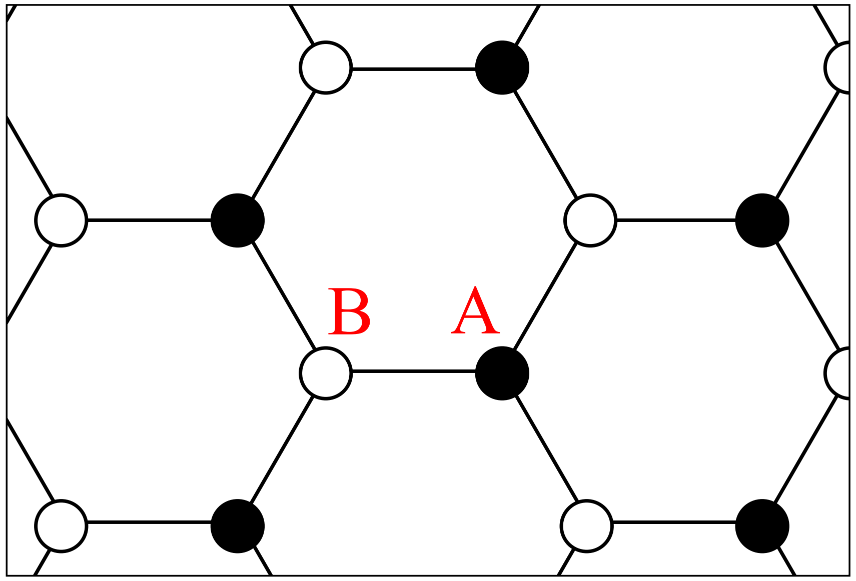
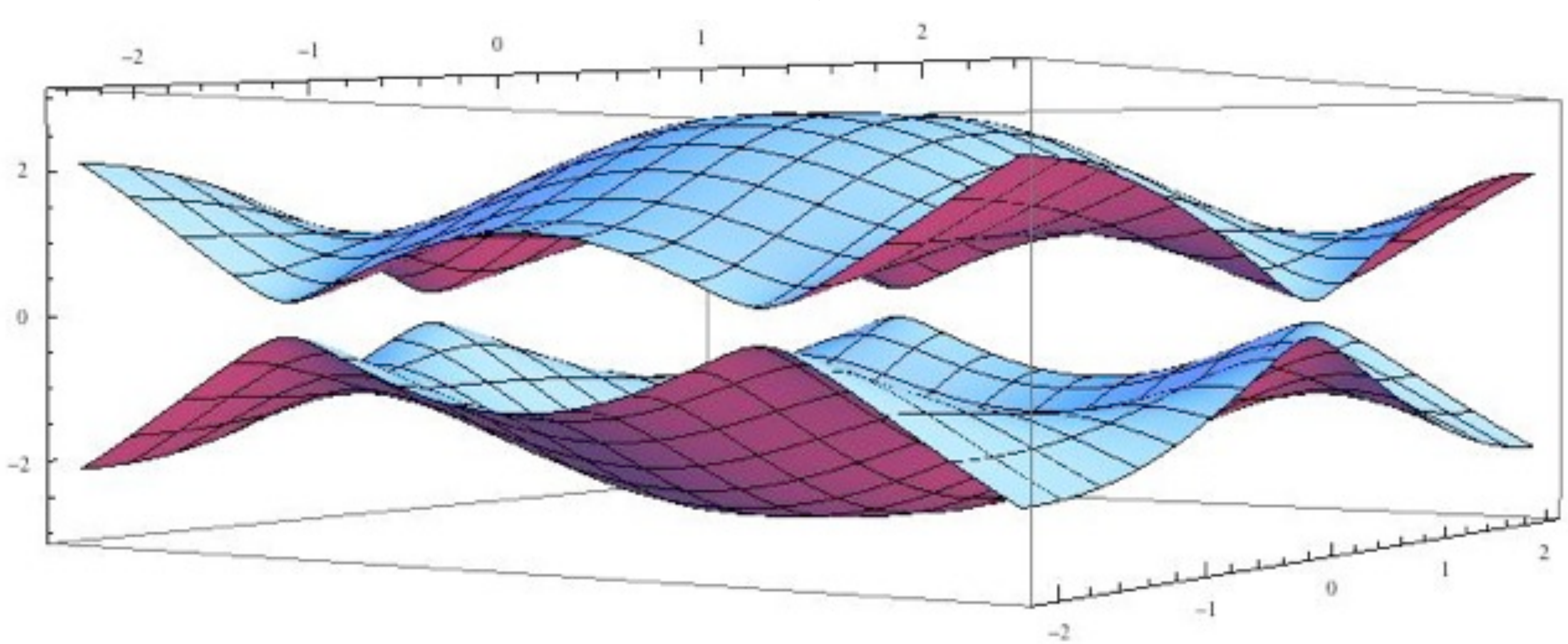


Circularly polarized light

Assume the driving frequency $\Omega \gg J$

$$A \neq 0$$



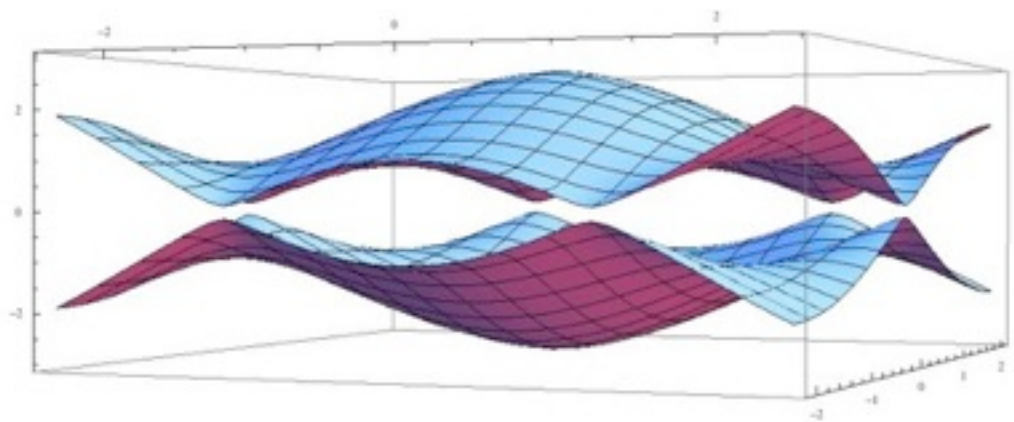
Qausi-energy

Momentum

c.f. Oka and Aoki, Phys. Rev. B 79, 081406 (R) (2009), see also Erratum

Effective Hamiltonian and Chern numbers

$$U(T) = \mathcal{T}e^{-i\int_0^T H(t)dt} \equiv e^{-iH_{\mathrm{eff}}T}$$



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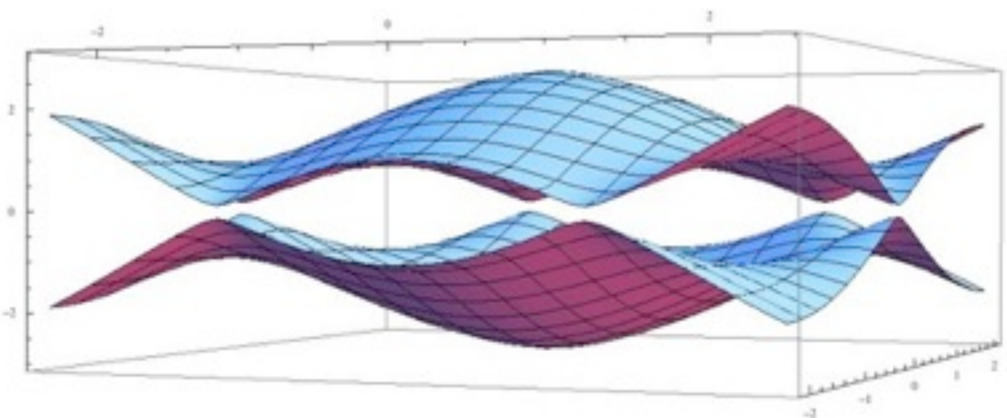

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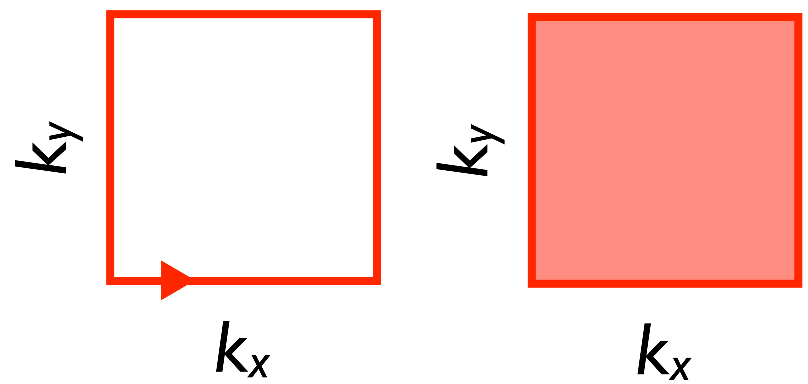

Phase accumulation of adiabatic move

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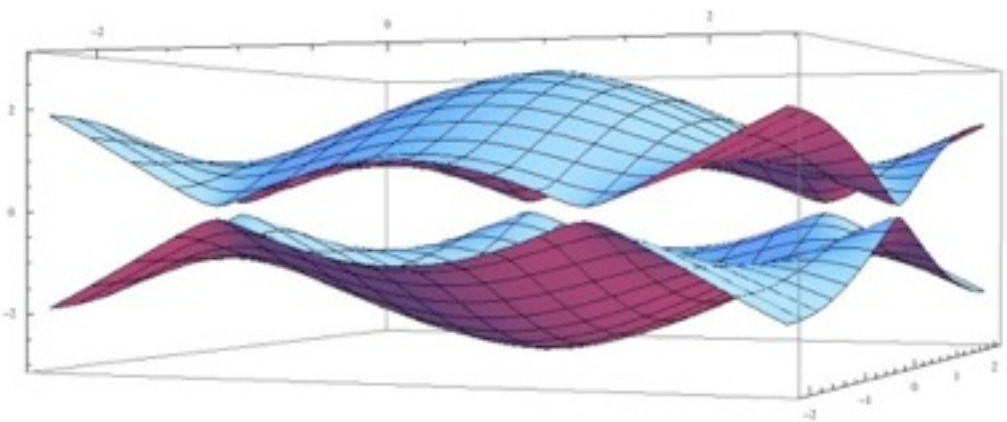

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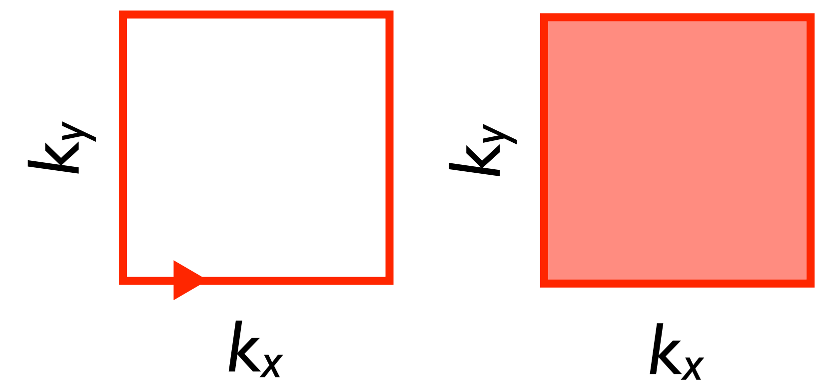
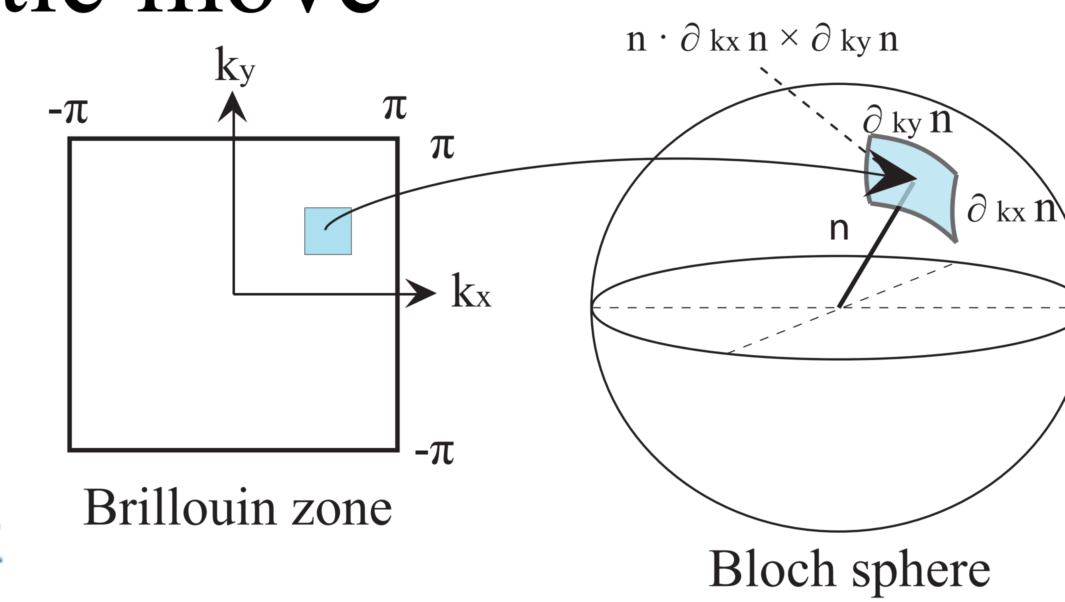


Phase accumulation of adiabatic move

$$H_{\rm eff}(\mathbf{k}) = \varepsilon(\mathbf{k})\,\mathbf{n}(\mathbf{k})\cdot\boldsymbol{\sigma}$$

$$C_{\pm} = \frac{\pm 1}{4\pi}\int_{\rm FBZ} \mathbf{n}\cdot(\partial_{k_x}\mathbf{n}\times\partial_{k_y}\mathbf{n})d^2\mathbf{k}$$



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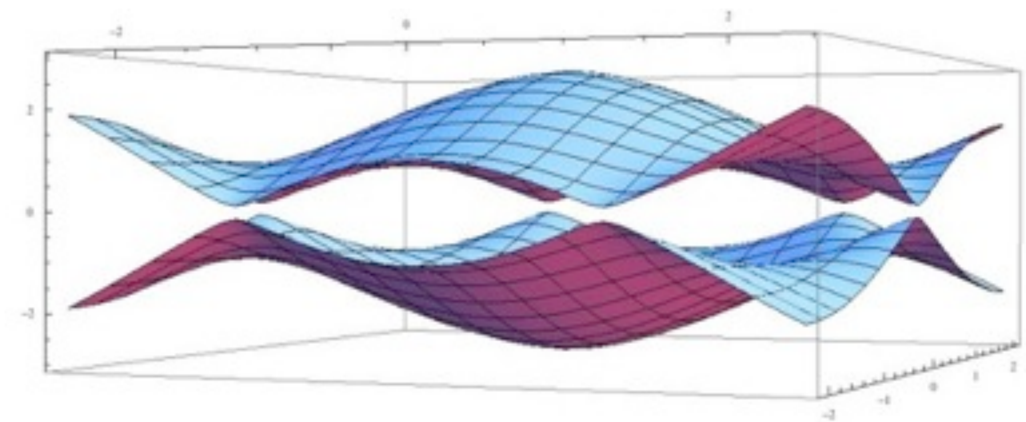

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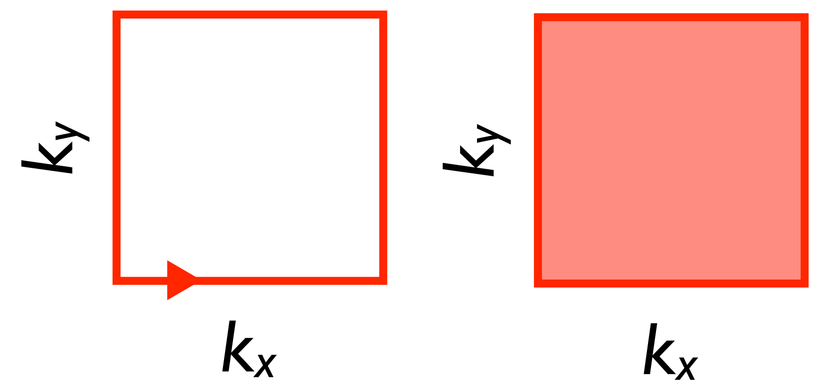

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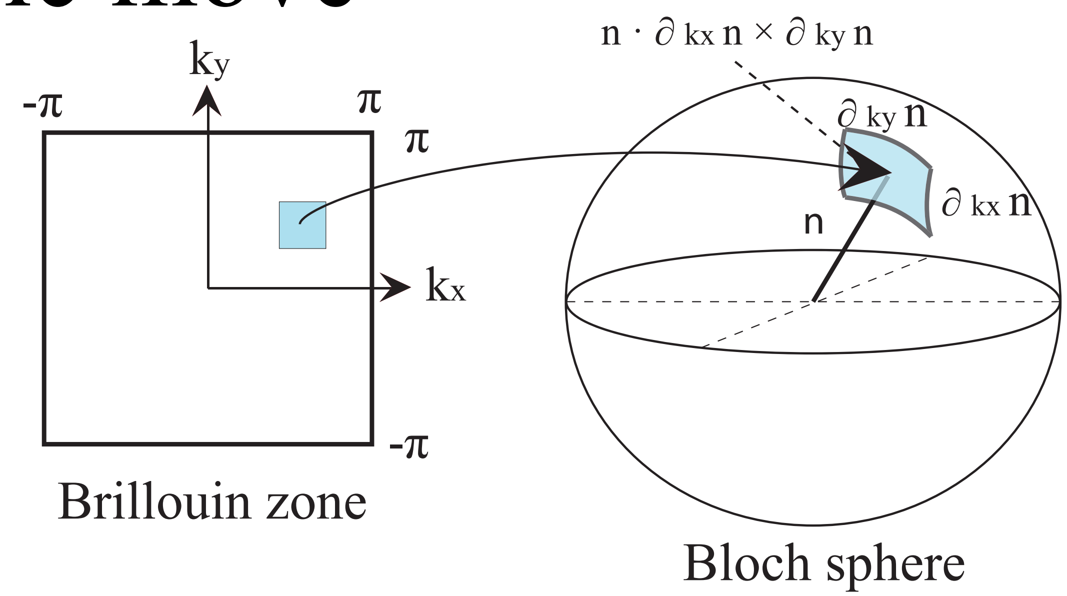

± 1 !

Takuya Kitagawa, Harvard University

Effective Hamiltonian from perturbation theory

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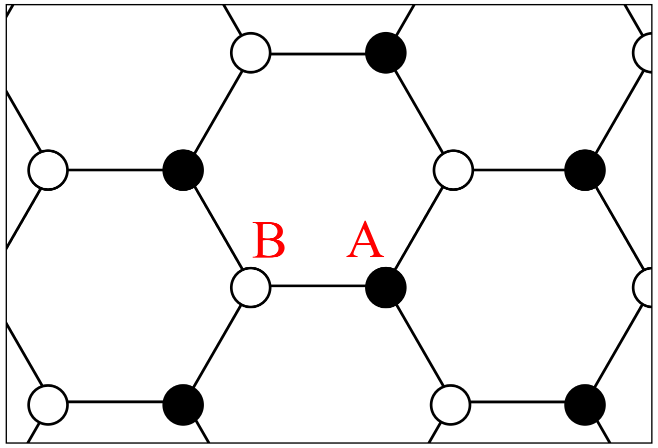

Assume high frequency $\Omega \gg J$ and weak intensity $\mathcal{A} = eAa/\hbar \ll 1$

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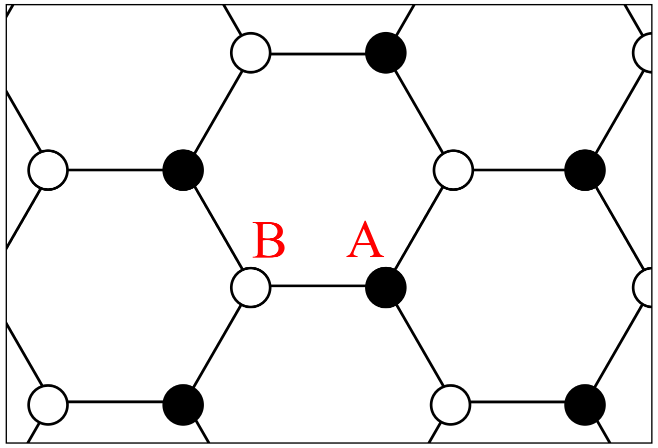

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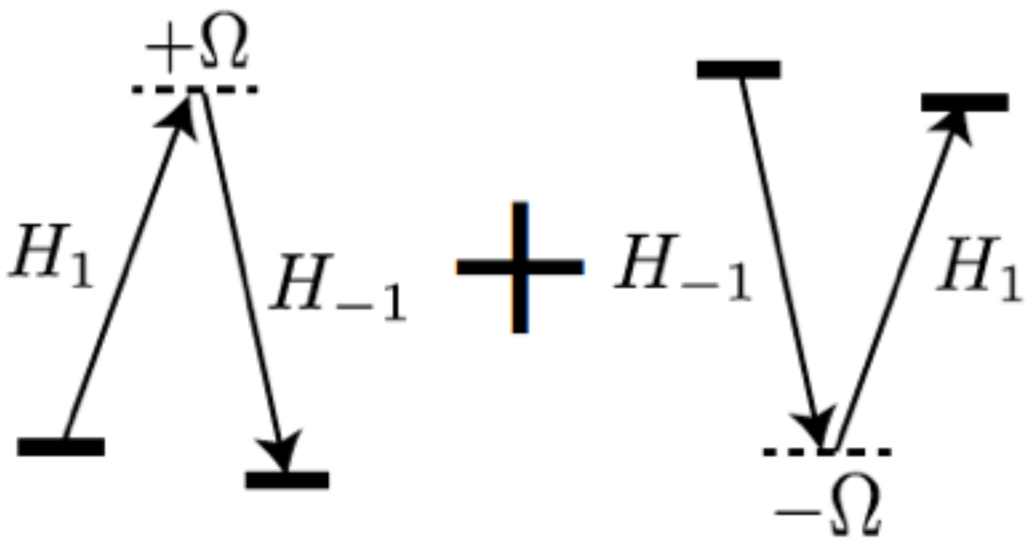

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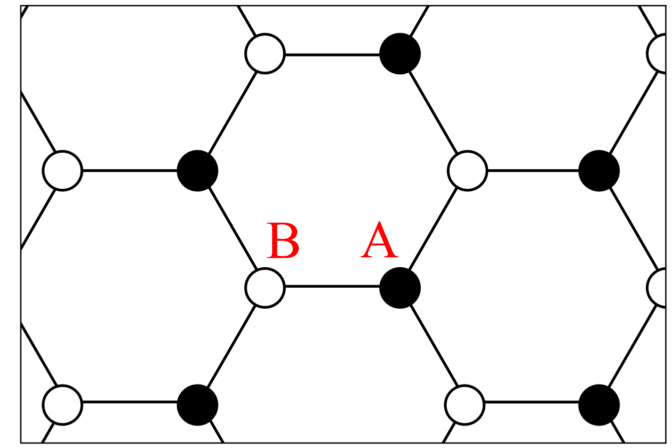

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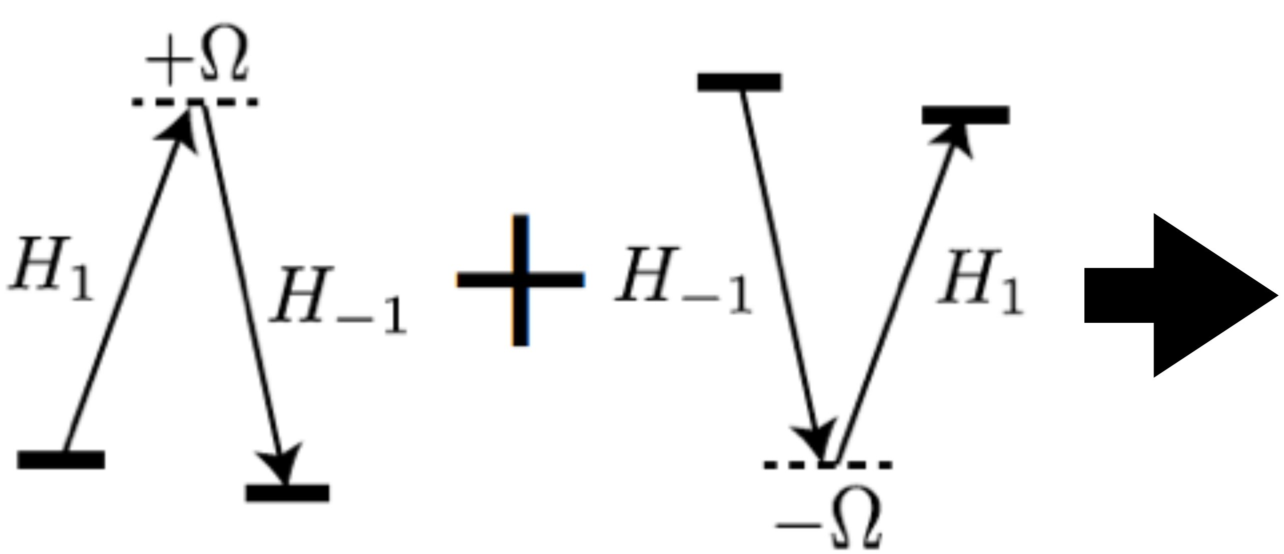

$$H_{\text{eff}} \approx H_0 + \frac{[H_{-1}, H_1]}{\Omega} + O(\mathcal{A}^4)$$

Takuya Kitagawa, Harvard University

Real space picture of effective Hamiltonian

$$H(t) = -J \sum_{<ij>} e^{iA_{ij}(t)} c_i^\dagger c_j, \qquad H_{\text{eff}} \approx H_0 + \frac{[H_{-1}, H_1]}{\Omega}$$

Takuya Kitagawa, Harvard University

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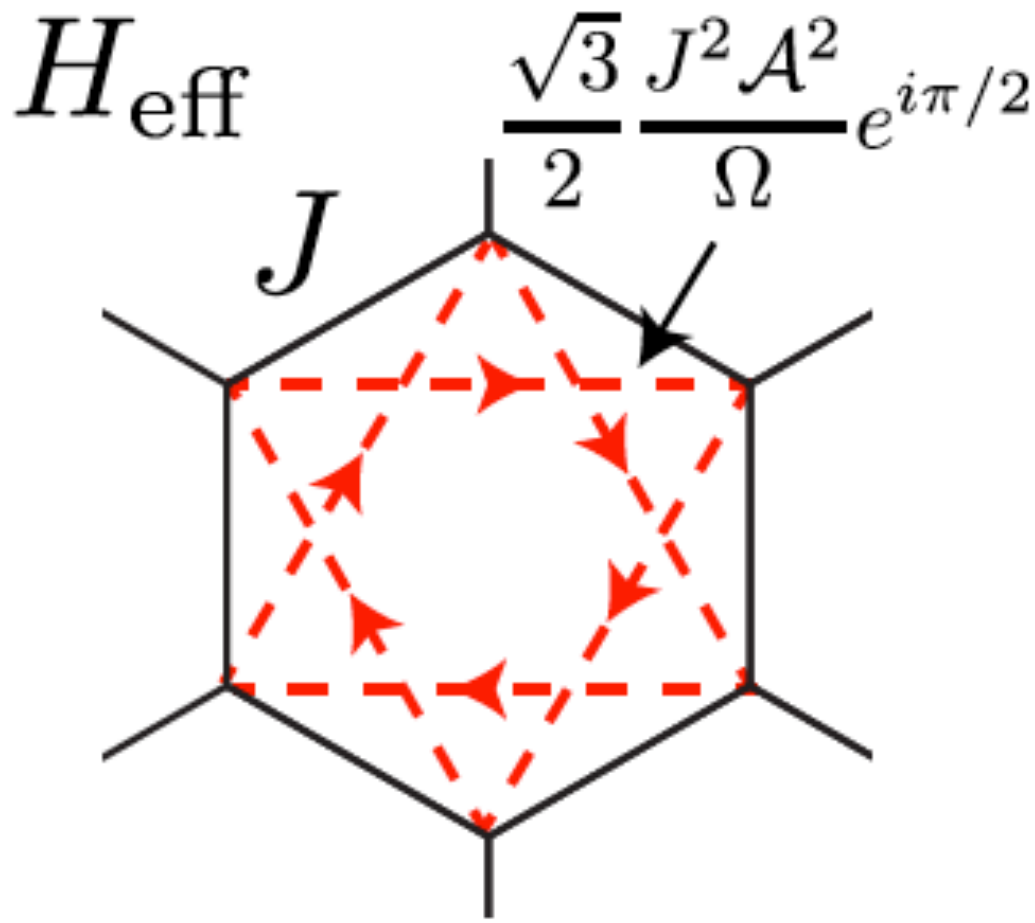

Non-equilibrium realization of Haldane model!

F.D.M. Haldane, Phys. Rev. Lett. 61, 2015(1998)

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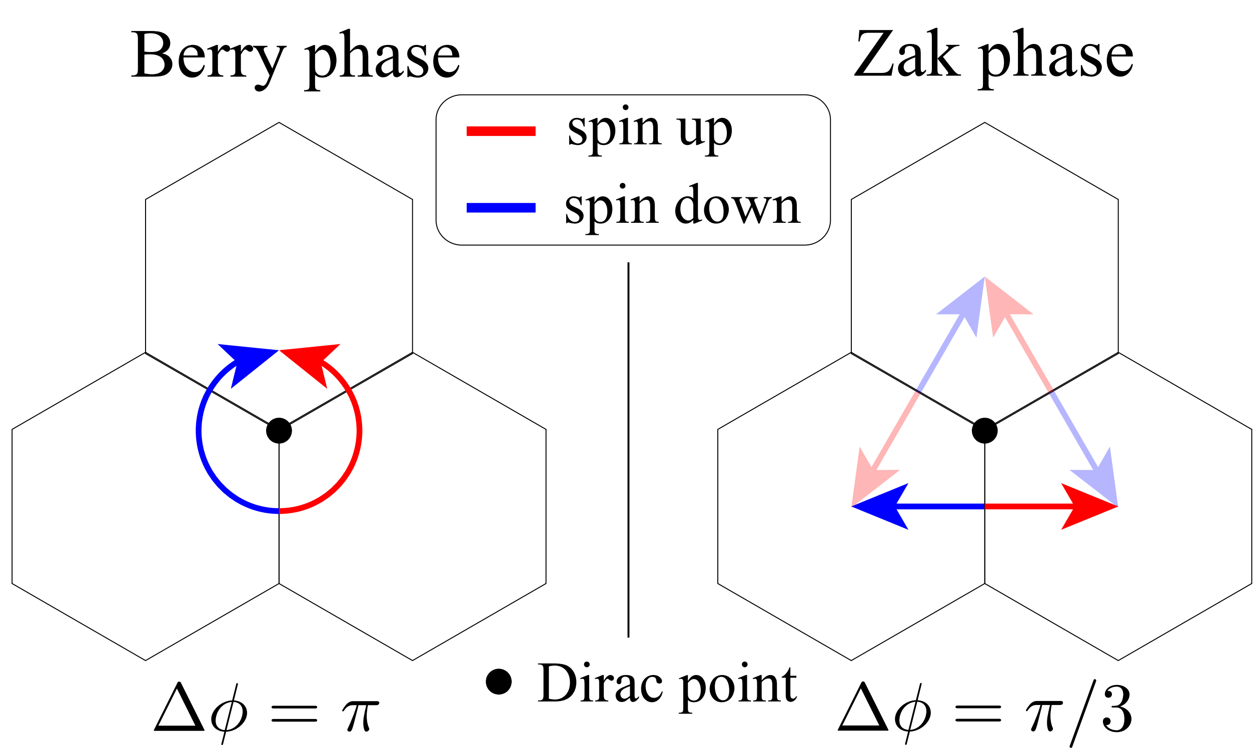
Measurement of topology of bands

Theory : D. Abanin, T. Kitagawa, and E. Demler

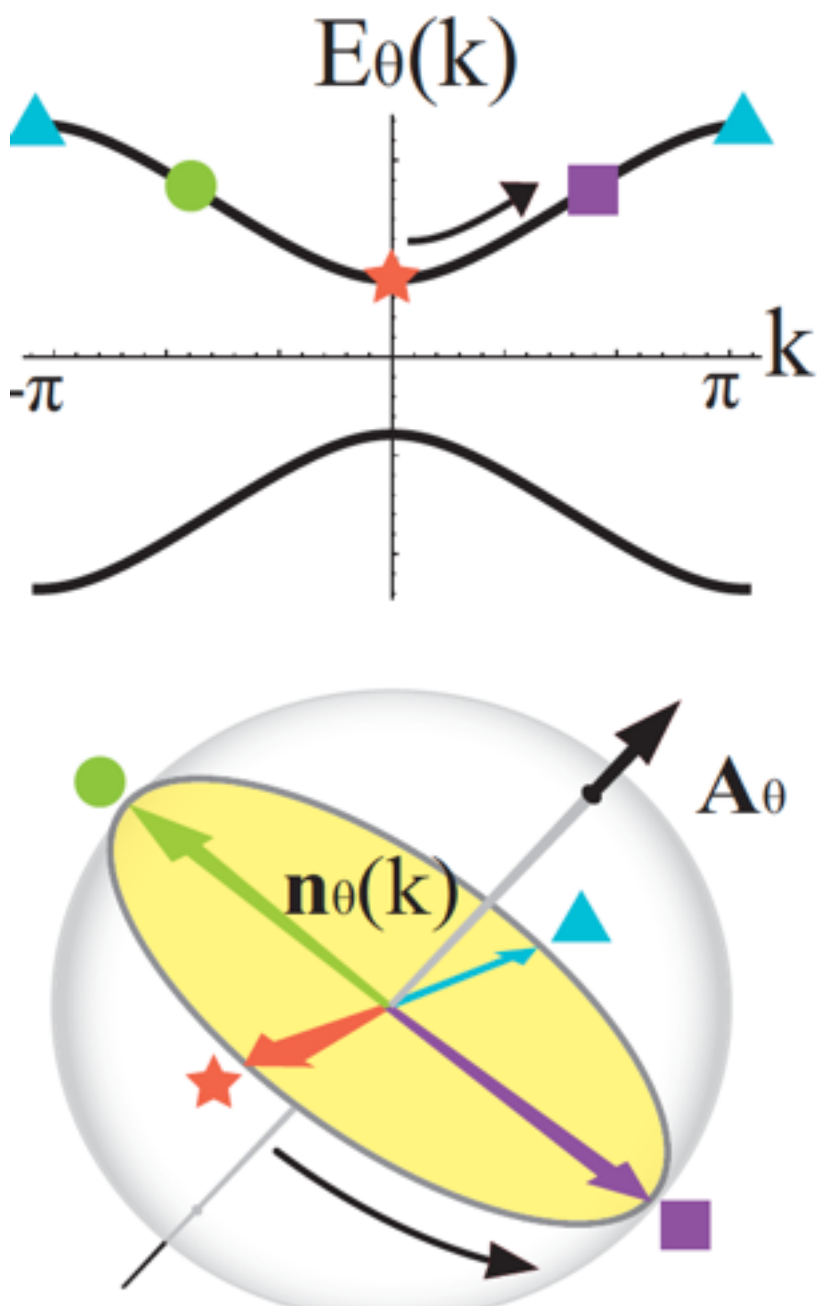
Experiment: M. Aidelsburger, M. Atala, J. Barreiro, I. Bloch



Topology of bands

Topology of bands

1D:SSH phase



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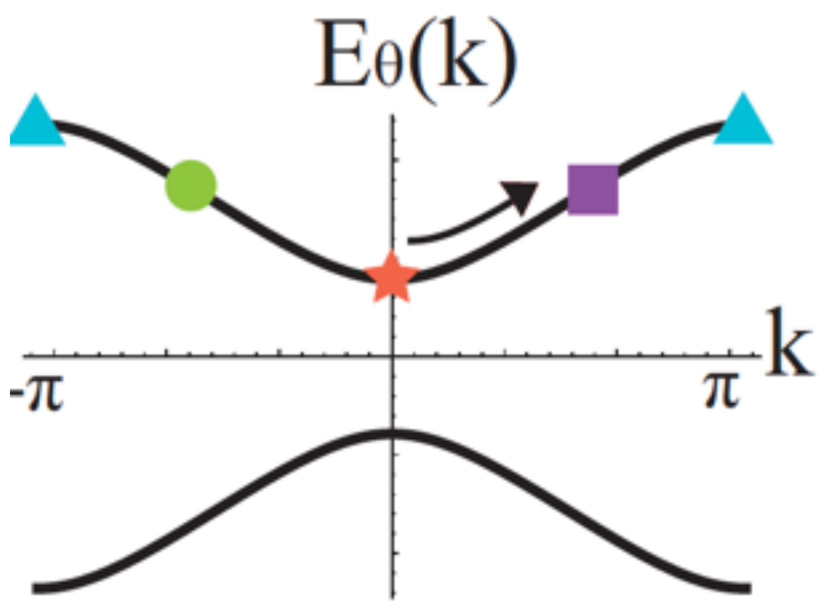
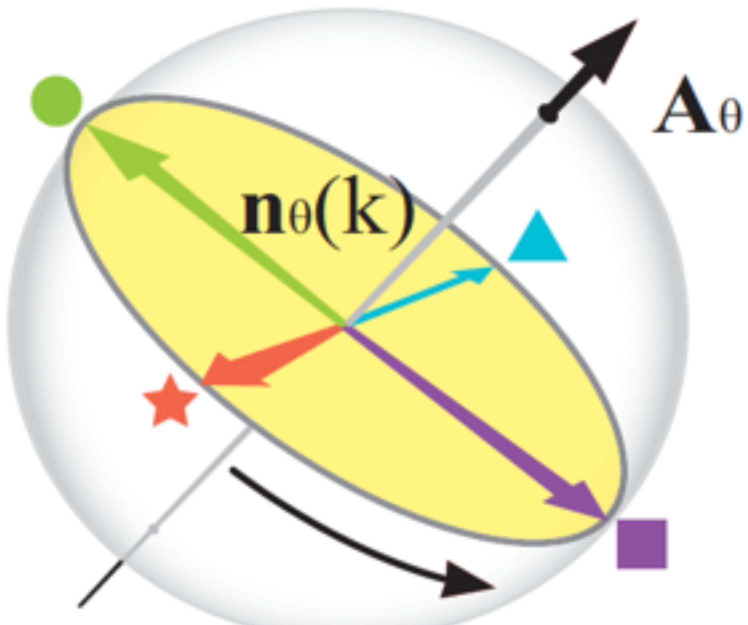
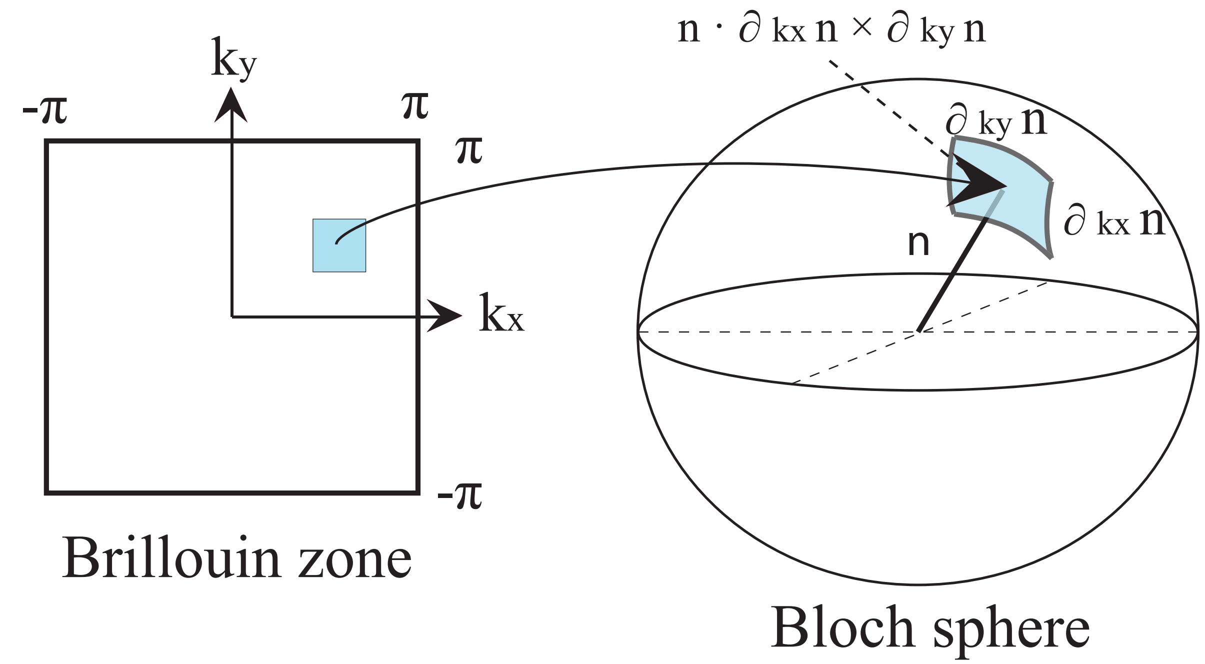




2D: IQH



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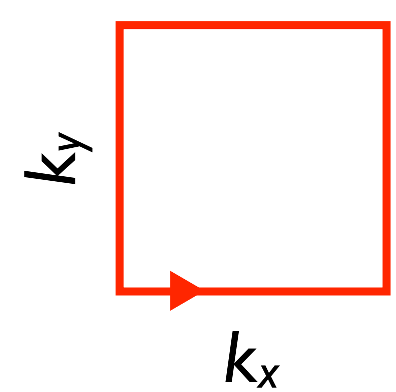
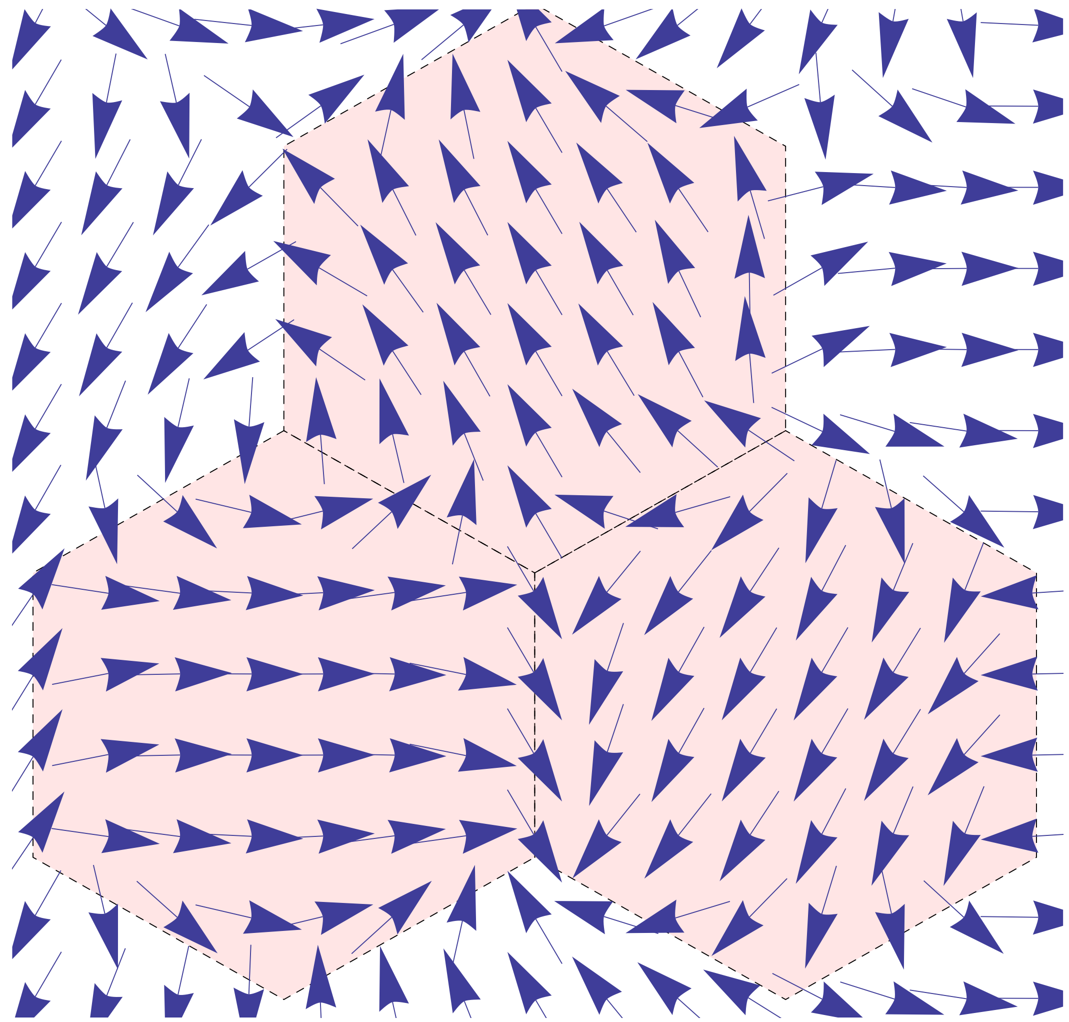


Naive measurement



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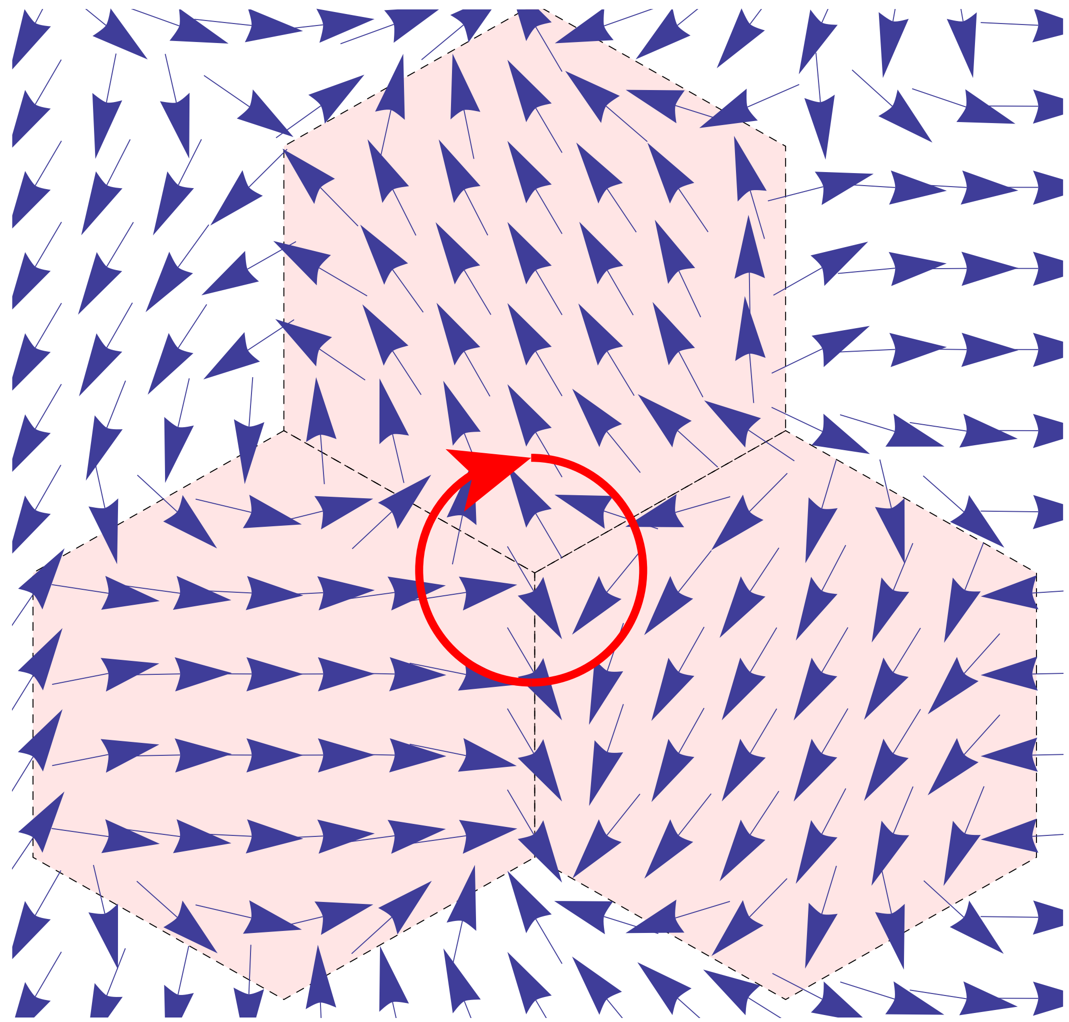

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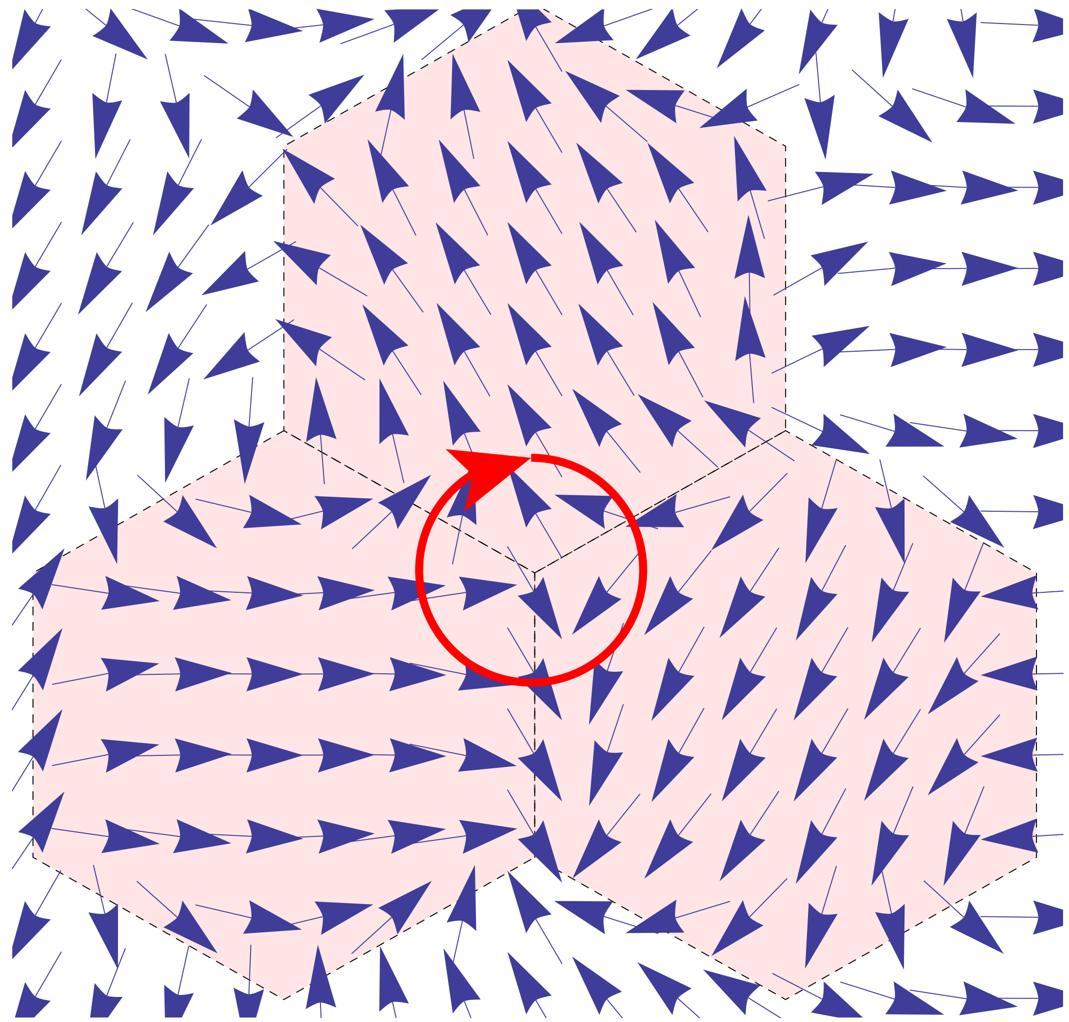
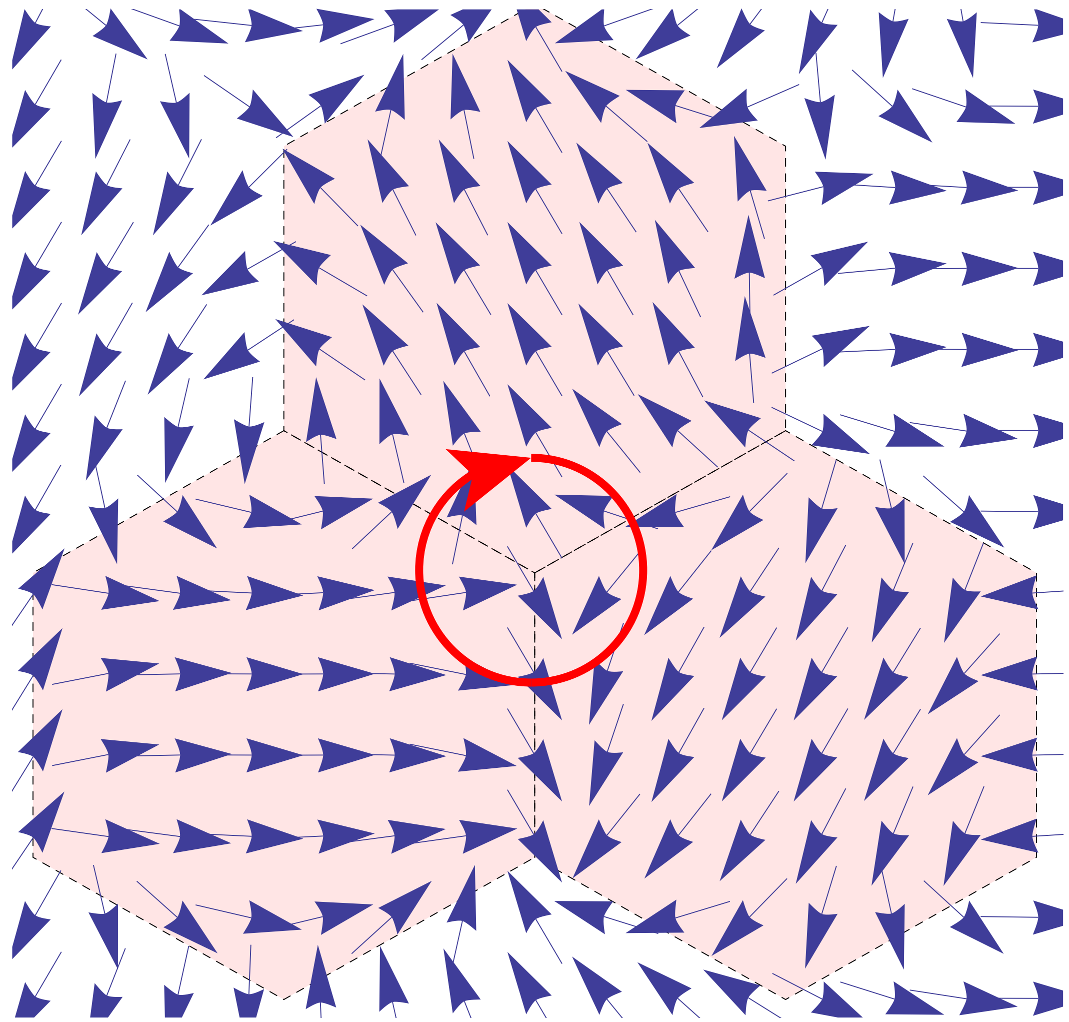


$$\Delta\phi = \pi$$

Naive measurement



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Problem with this naive approach

1. Trajectory is curved and complicated.

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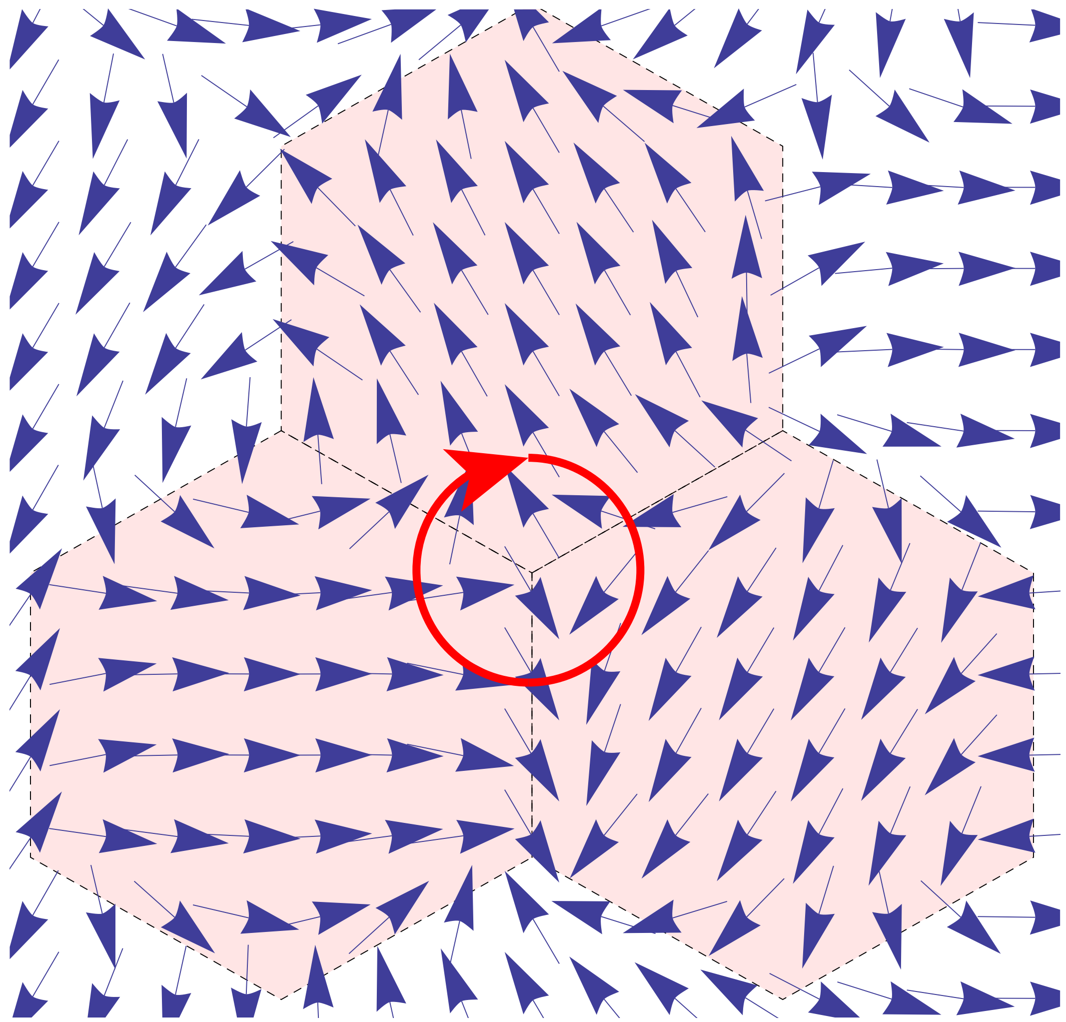

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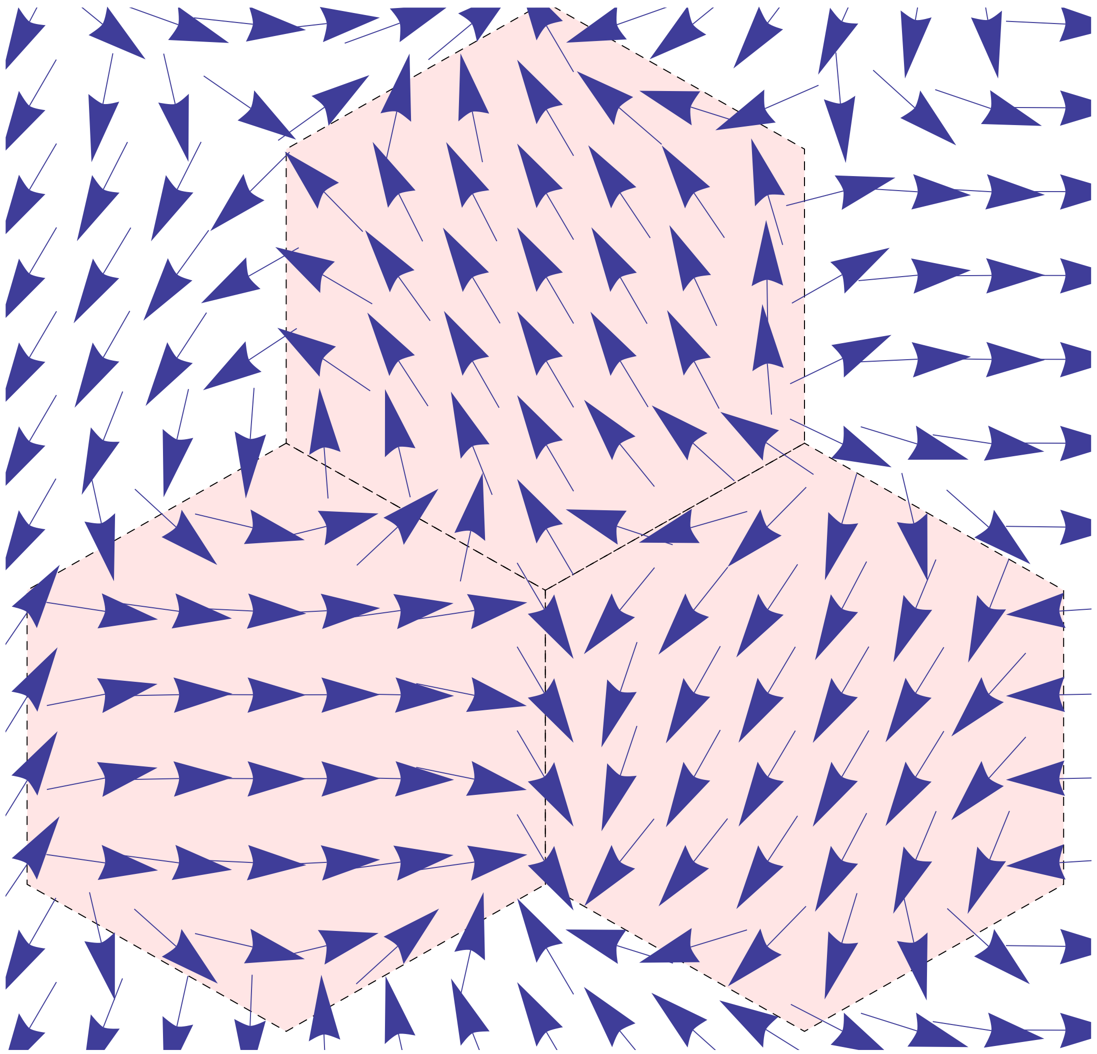
Problem with this naive approach

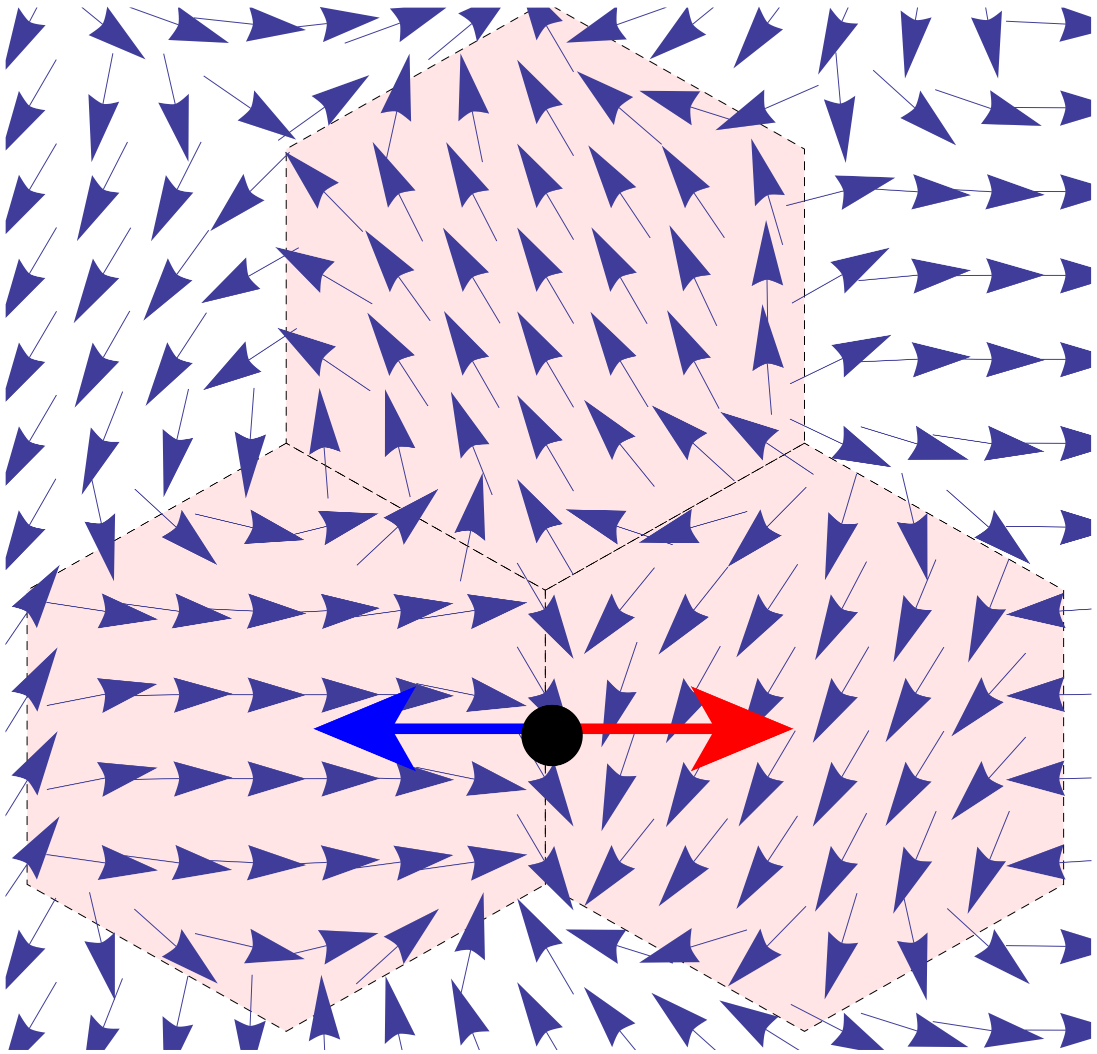
1. Trajectory is curved and complicated.
2. Need to separate dynamical phase from Berry phase

Measurement with Ramsey-type interferometer



Measurement with Ramsey-type interferometer

Use two hyperfine states



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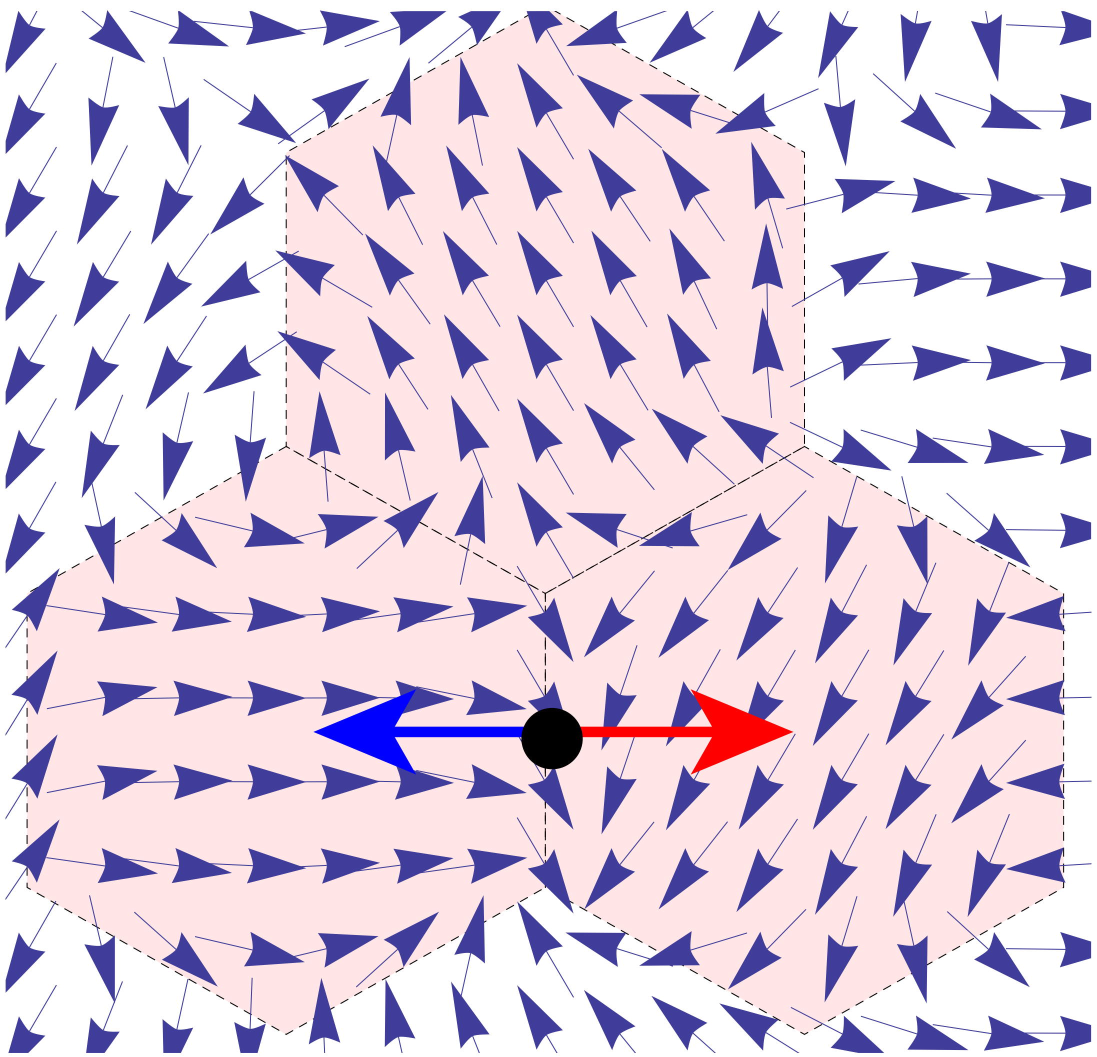

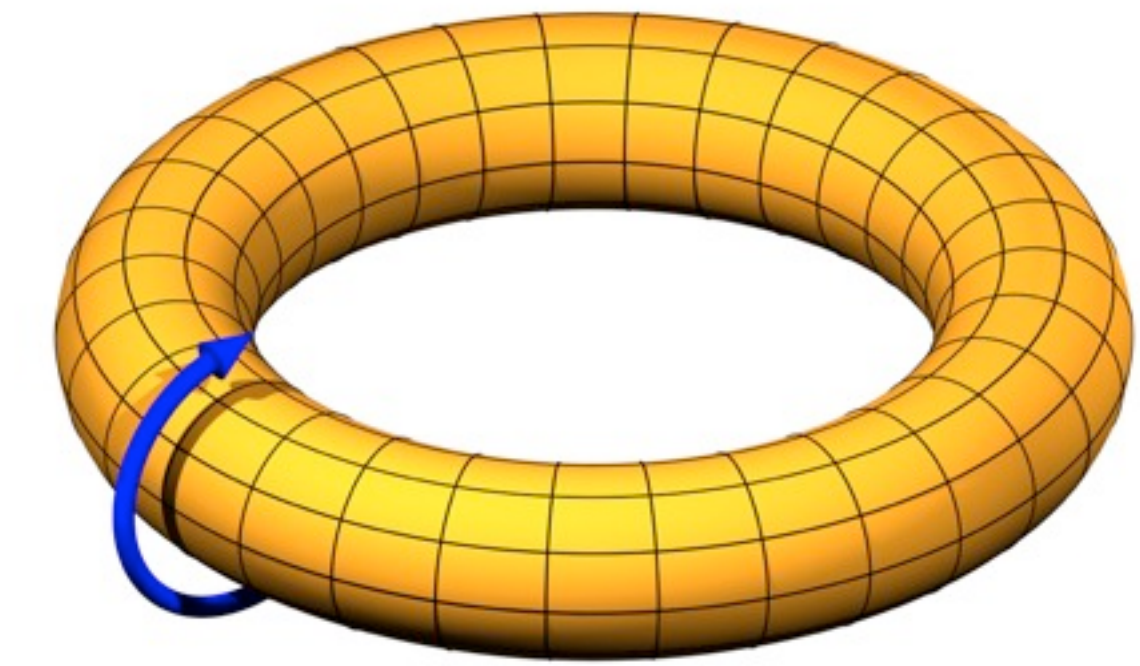

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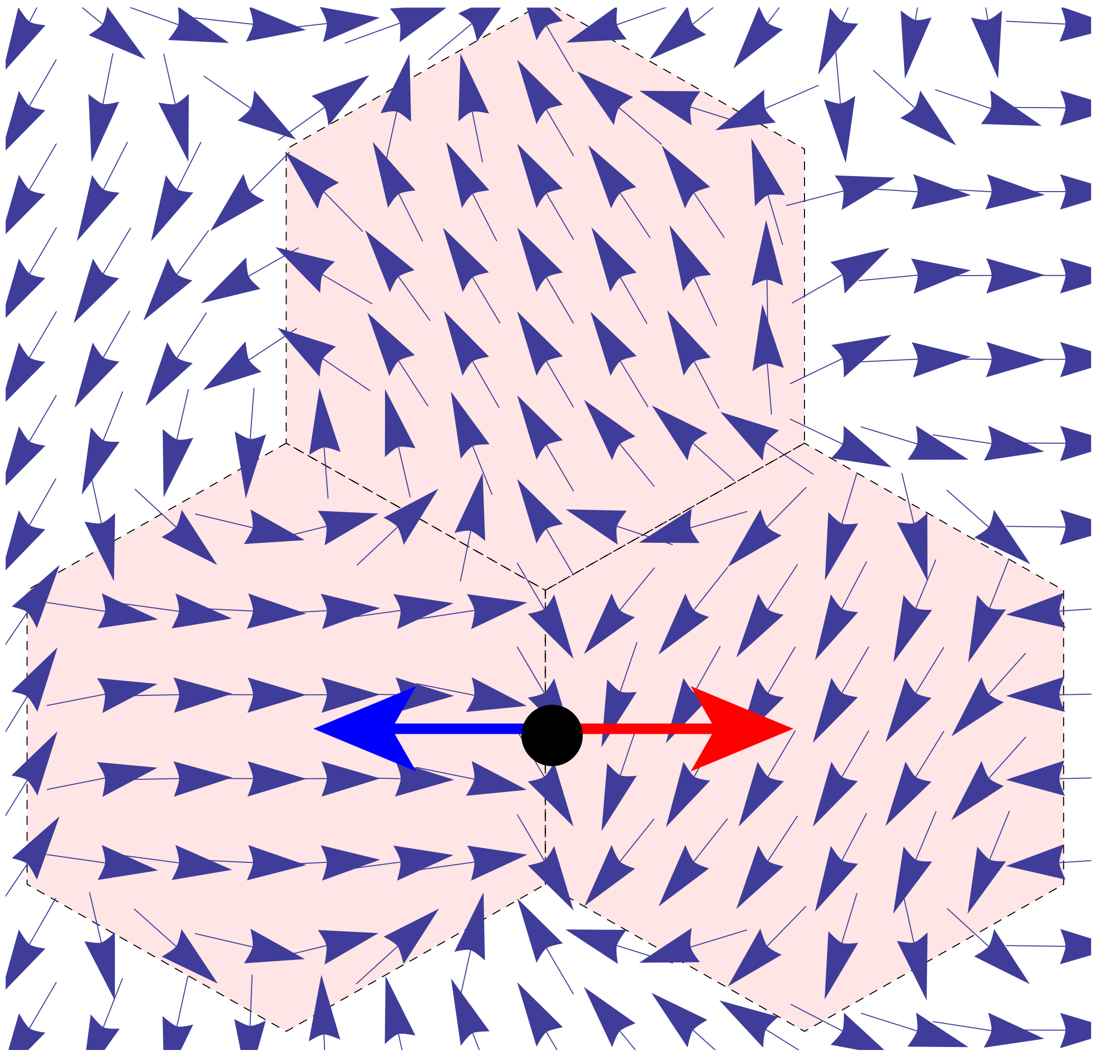

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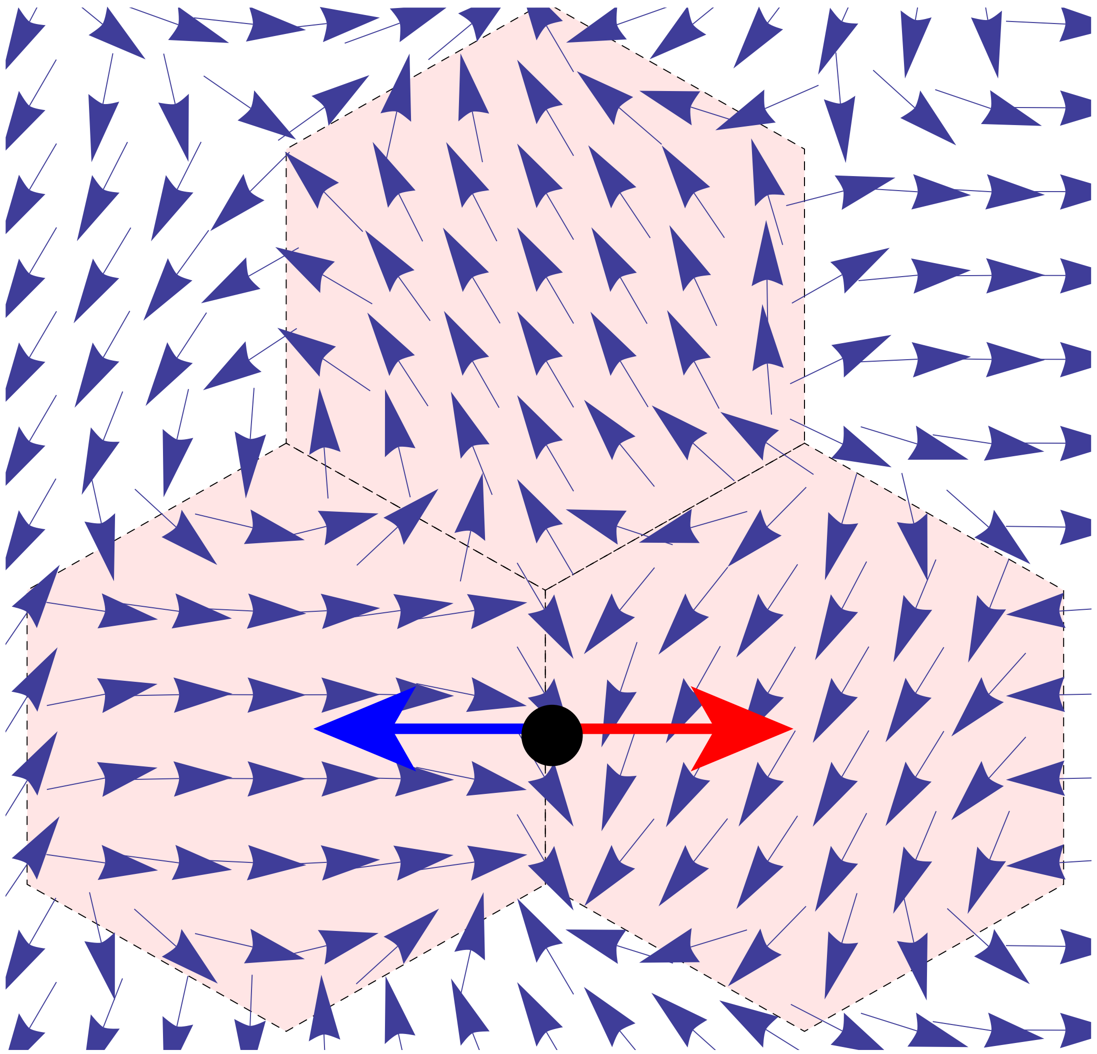

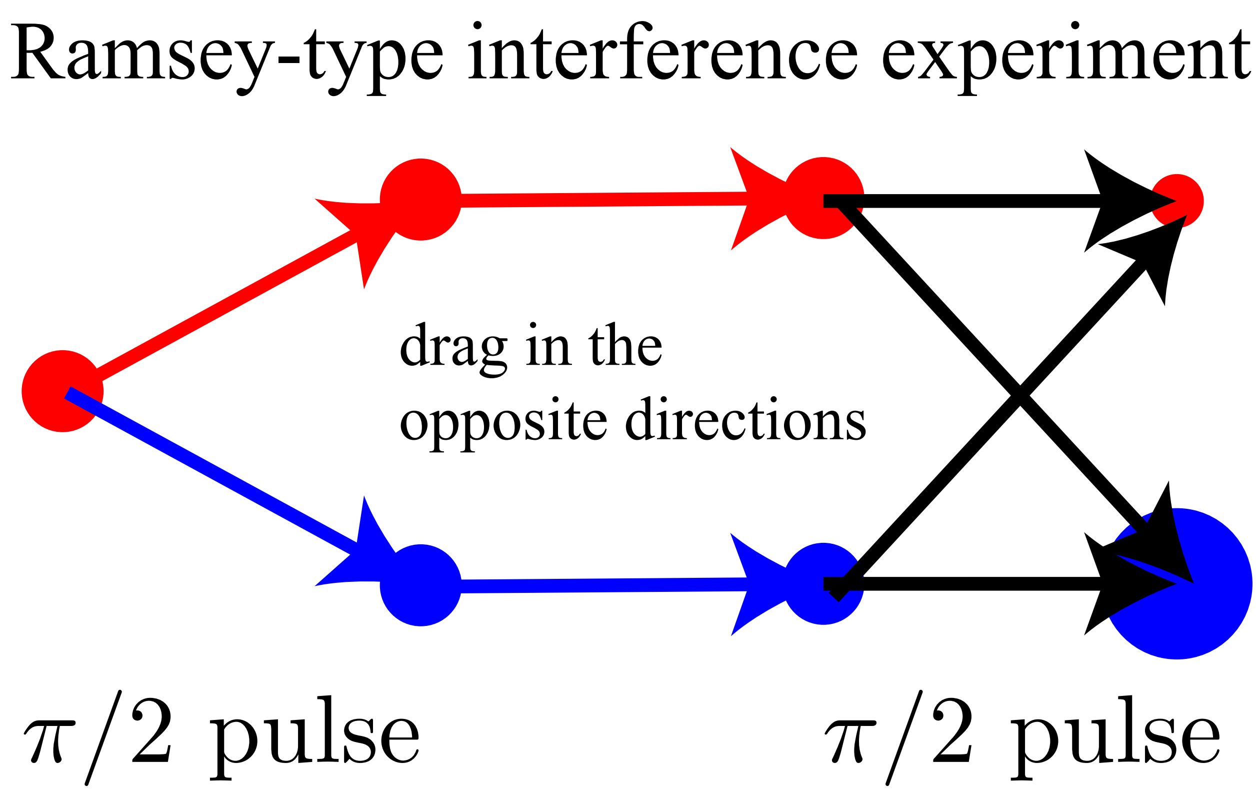

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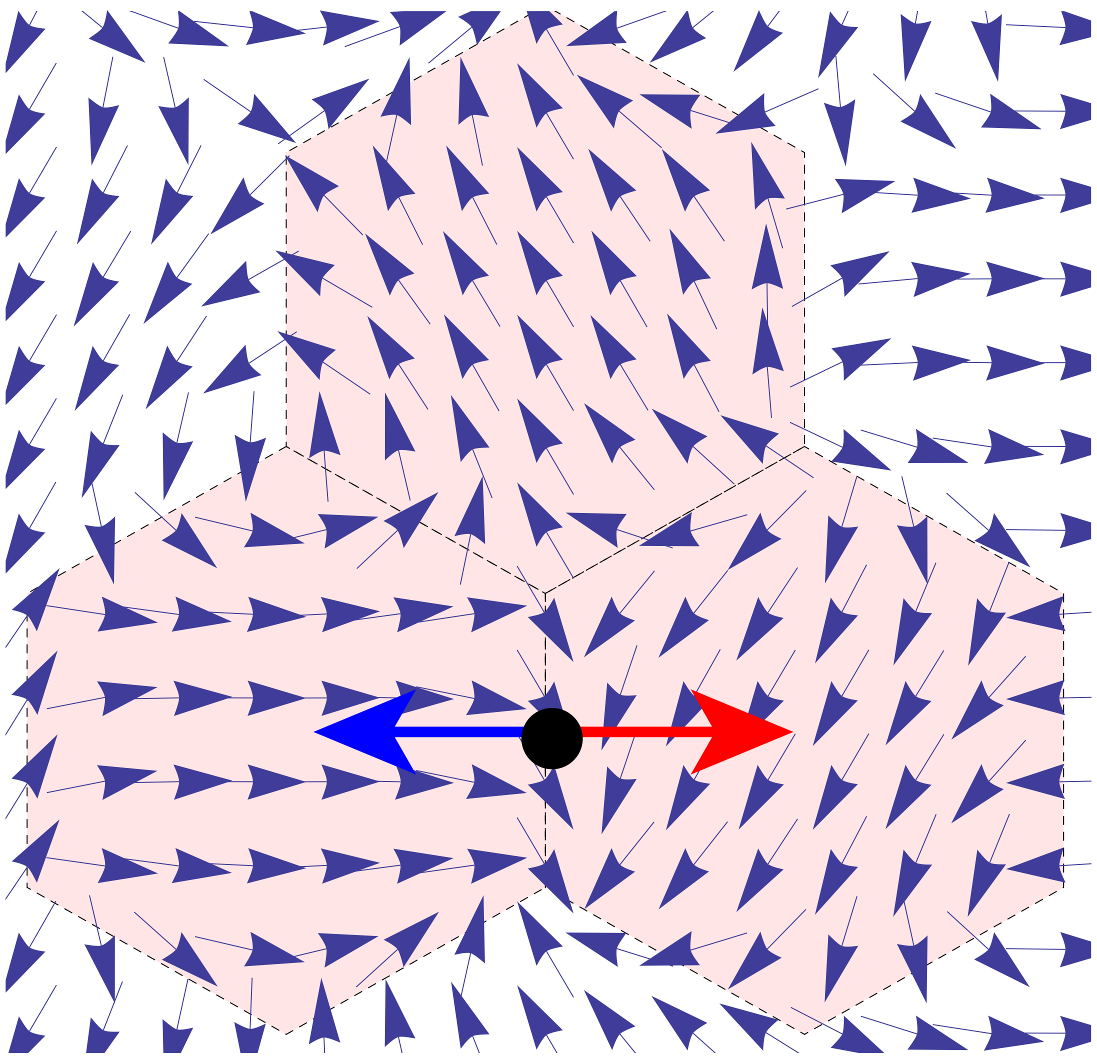
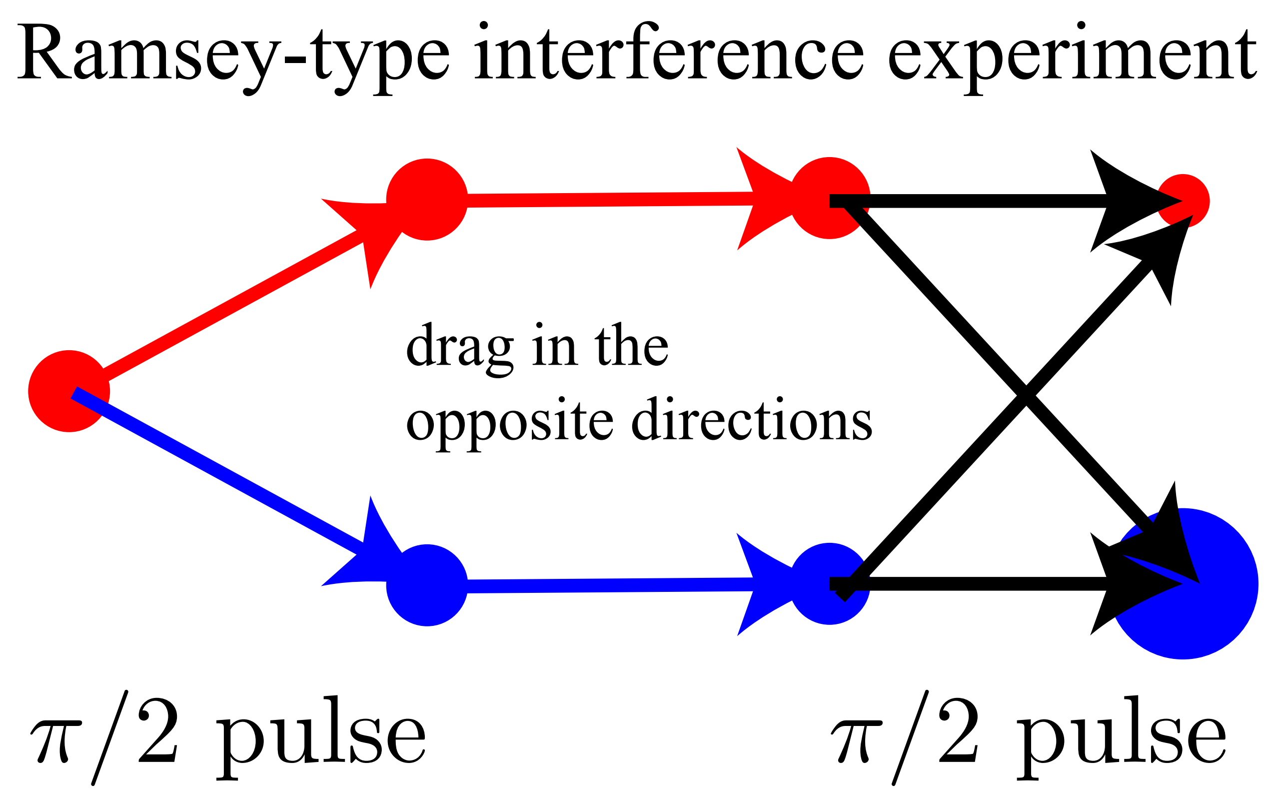




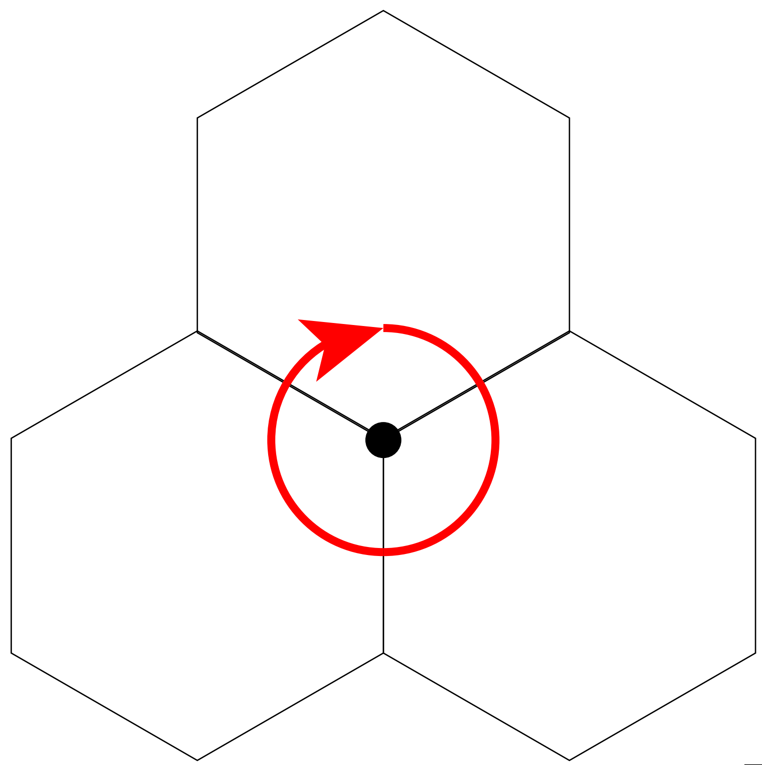
Solves the problems

1. Only requires straight-line trajectory
2. Dynamical phase will cancel between the two trajectory

Zak phase under Bloch oscillations

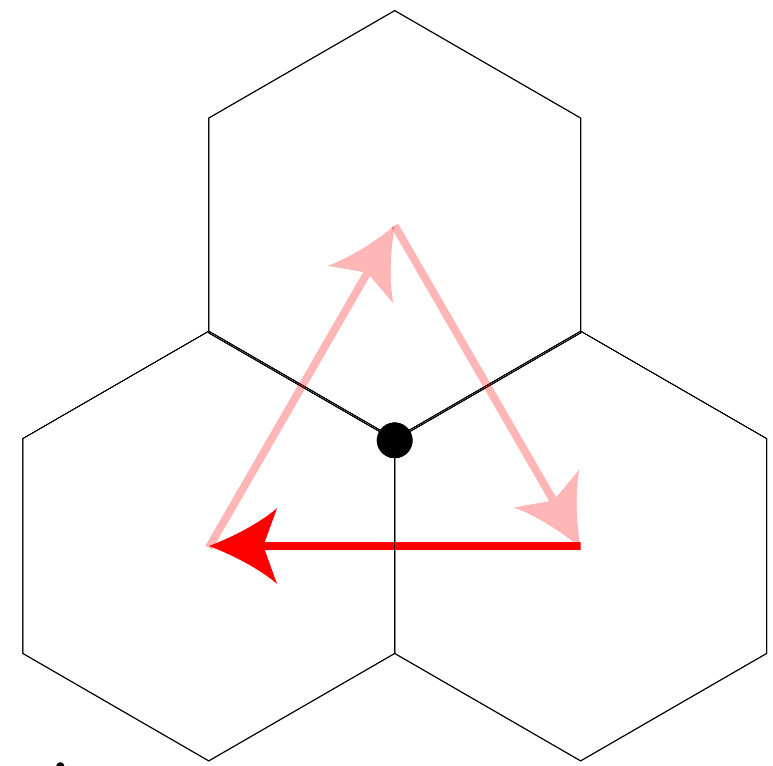
This scheme measures the phase accumulation under Bloch oscillation

Berry phase



$\Delta\phi = \pi$

Zak phase



● Dirac point

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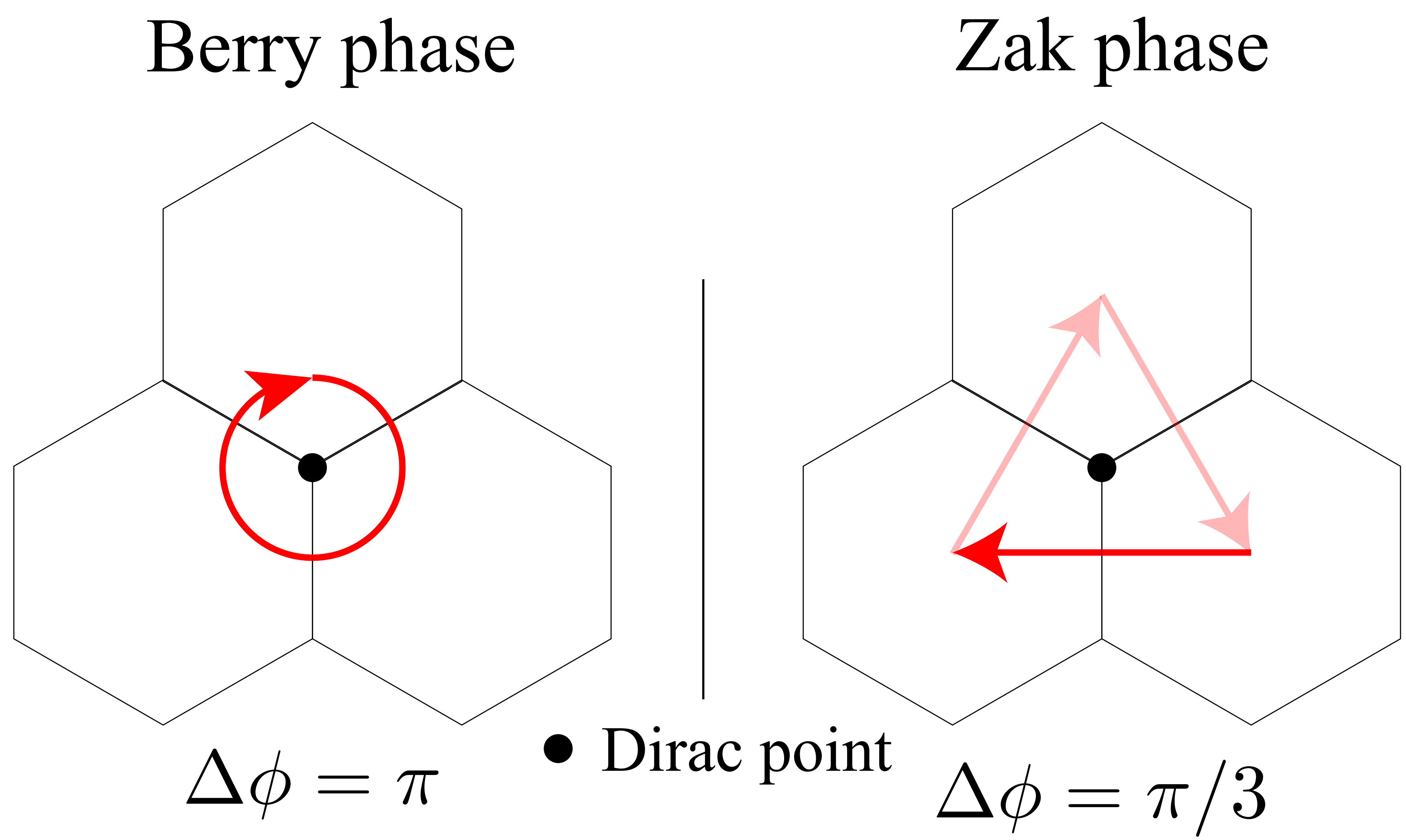

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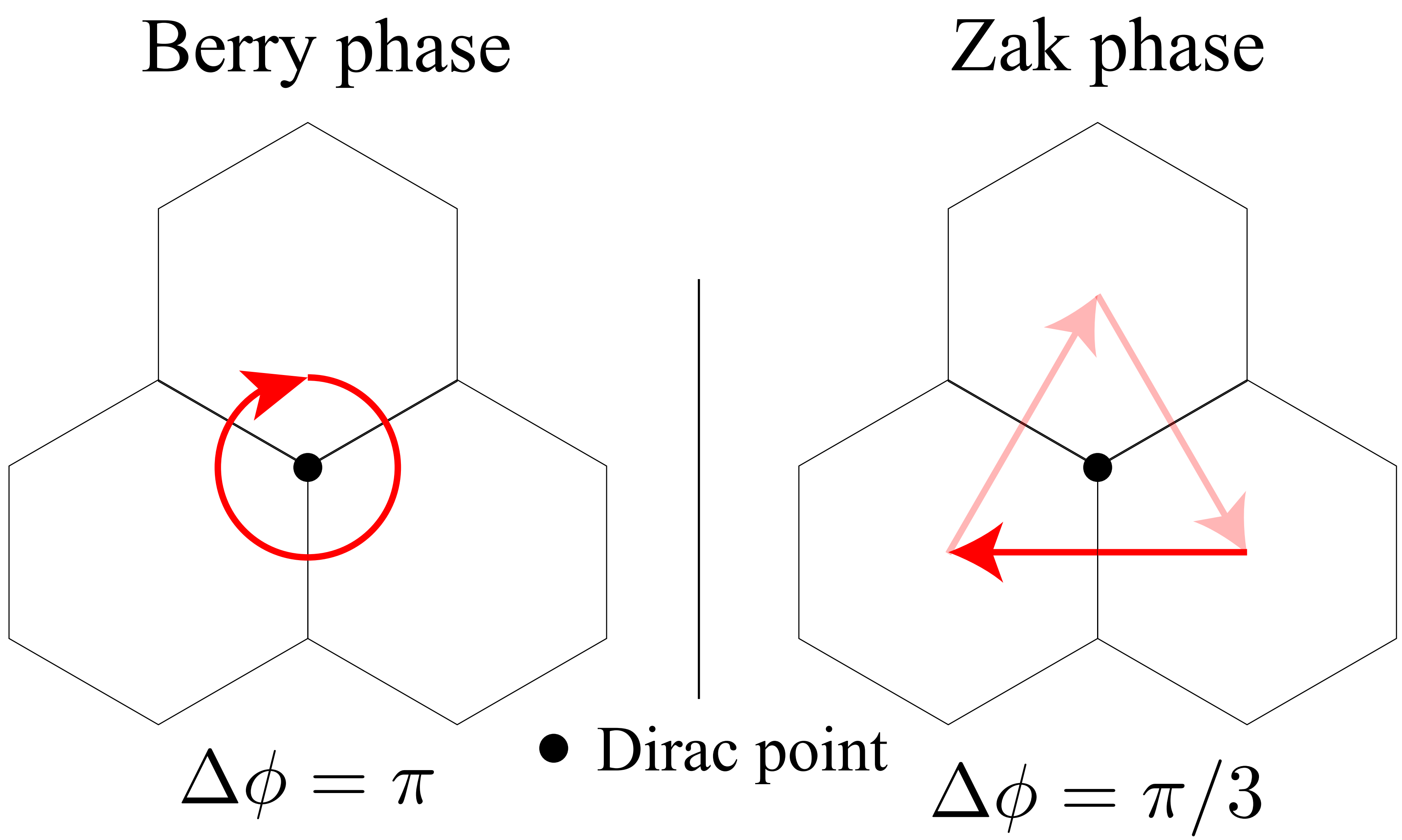
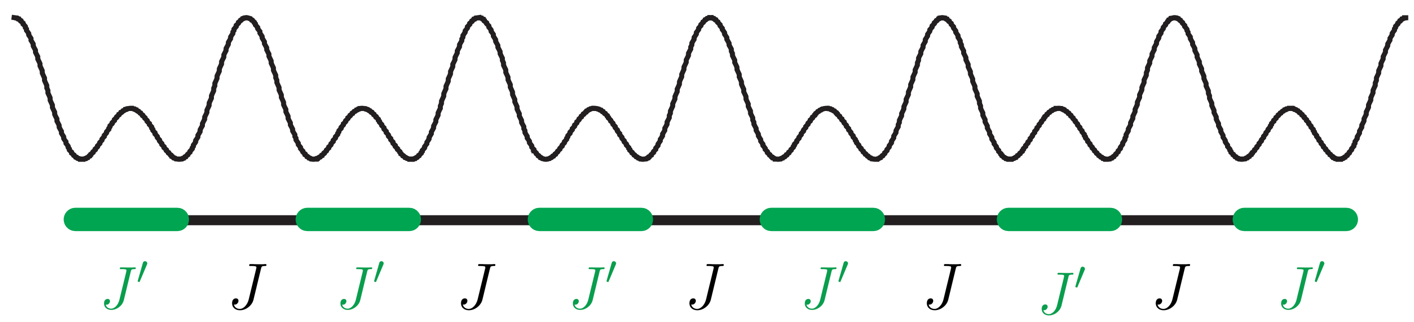
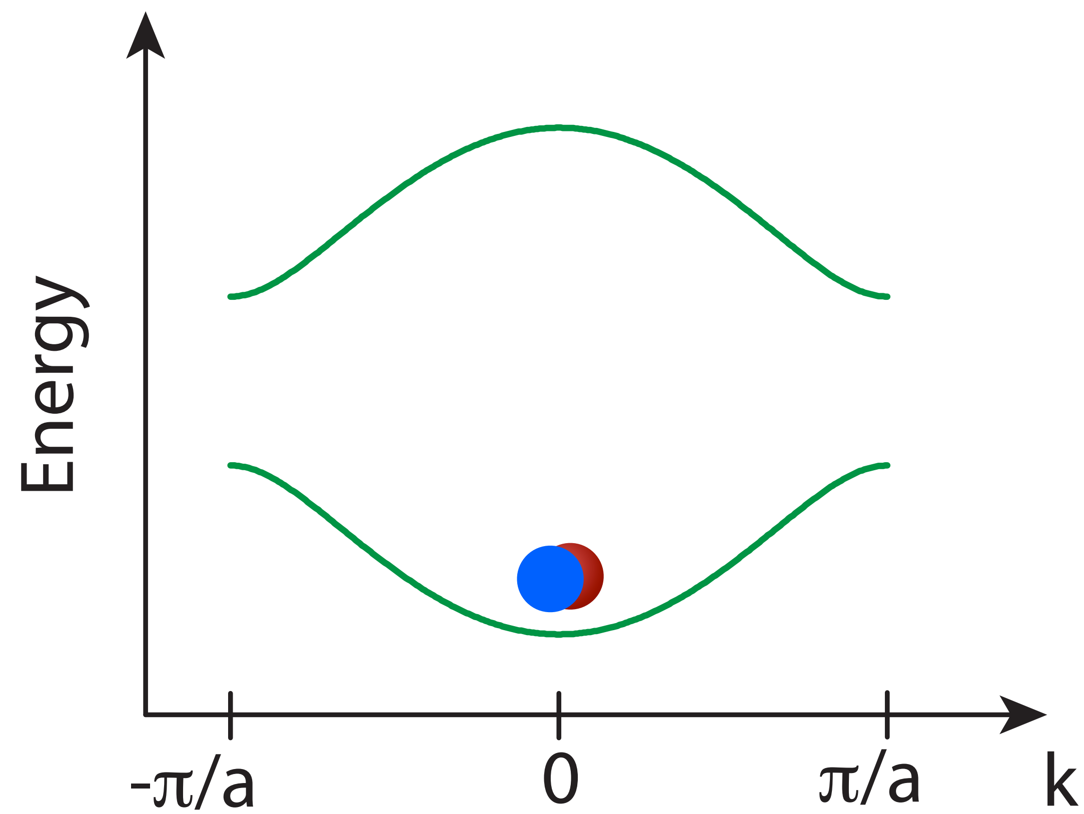


Zak phase is related to Berry phase through a geometrical symmetry of the lattice!

Measurement of Zak phase for SSH phase

Dimerized-Lattice Model (SSH model)





Experiment: M. Aidelsburger, M. Atala, J. Barreiro, I. Bloch

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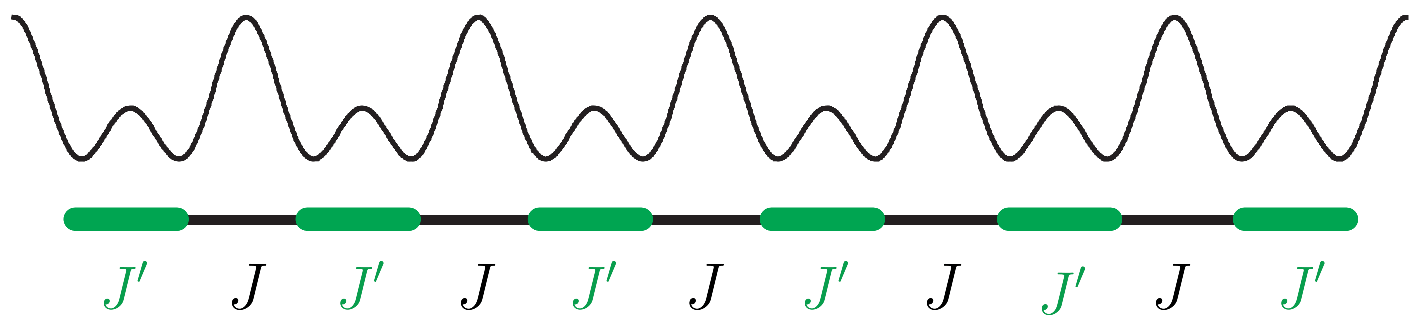

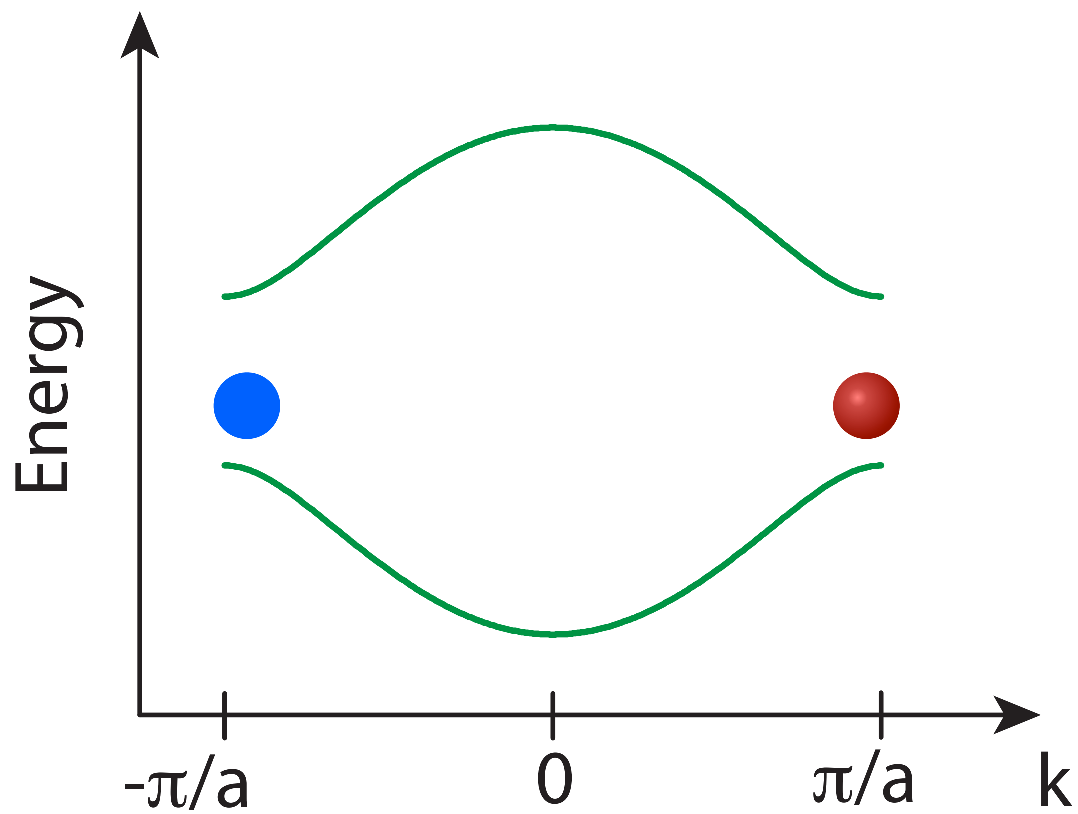

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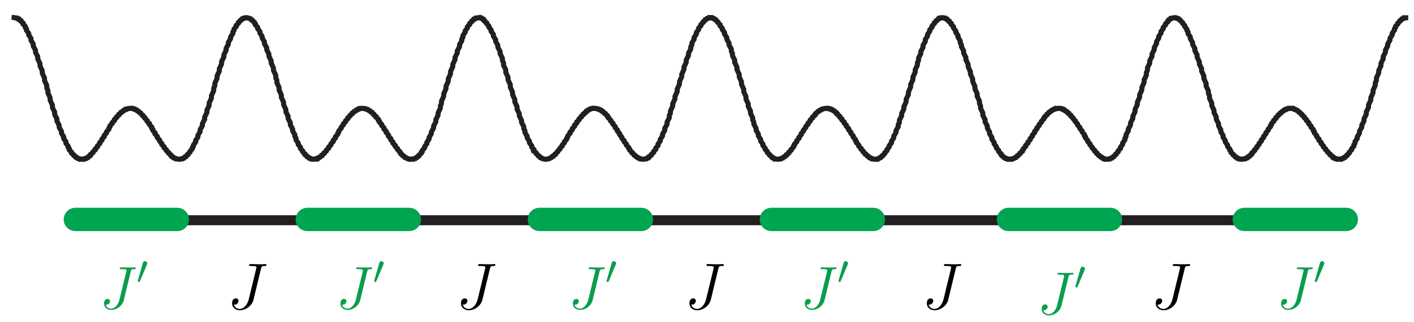

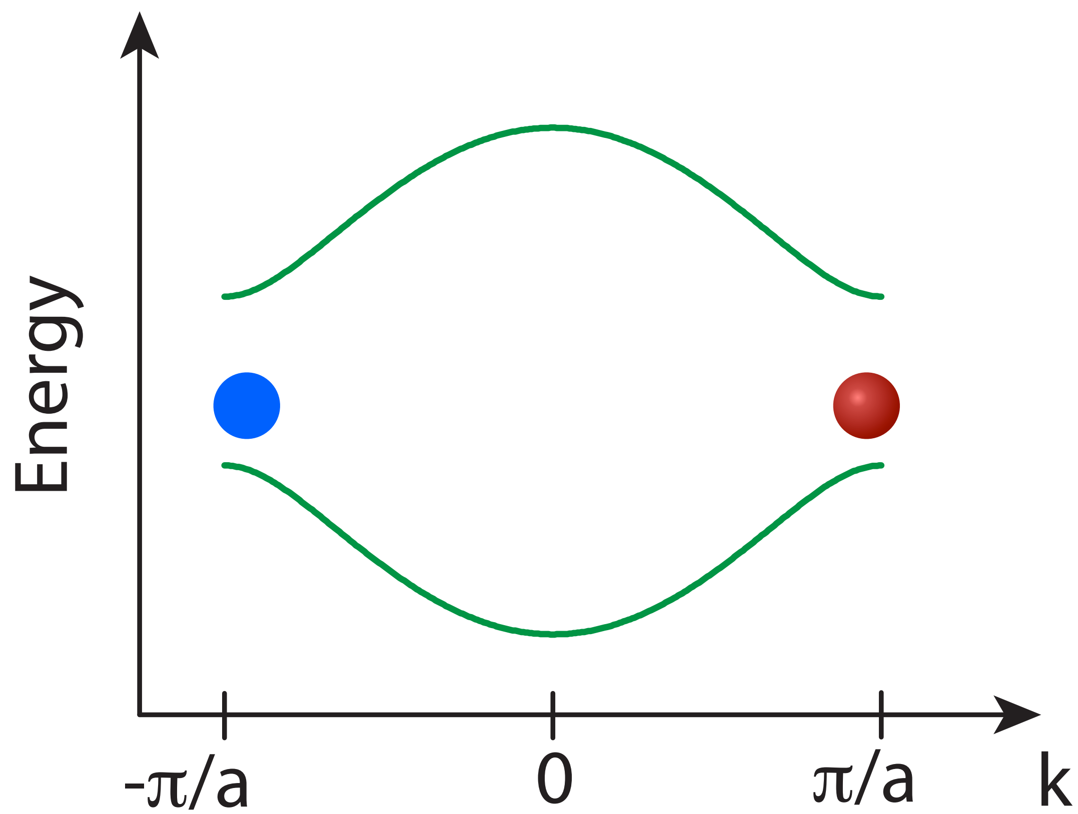

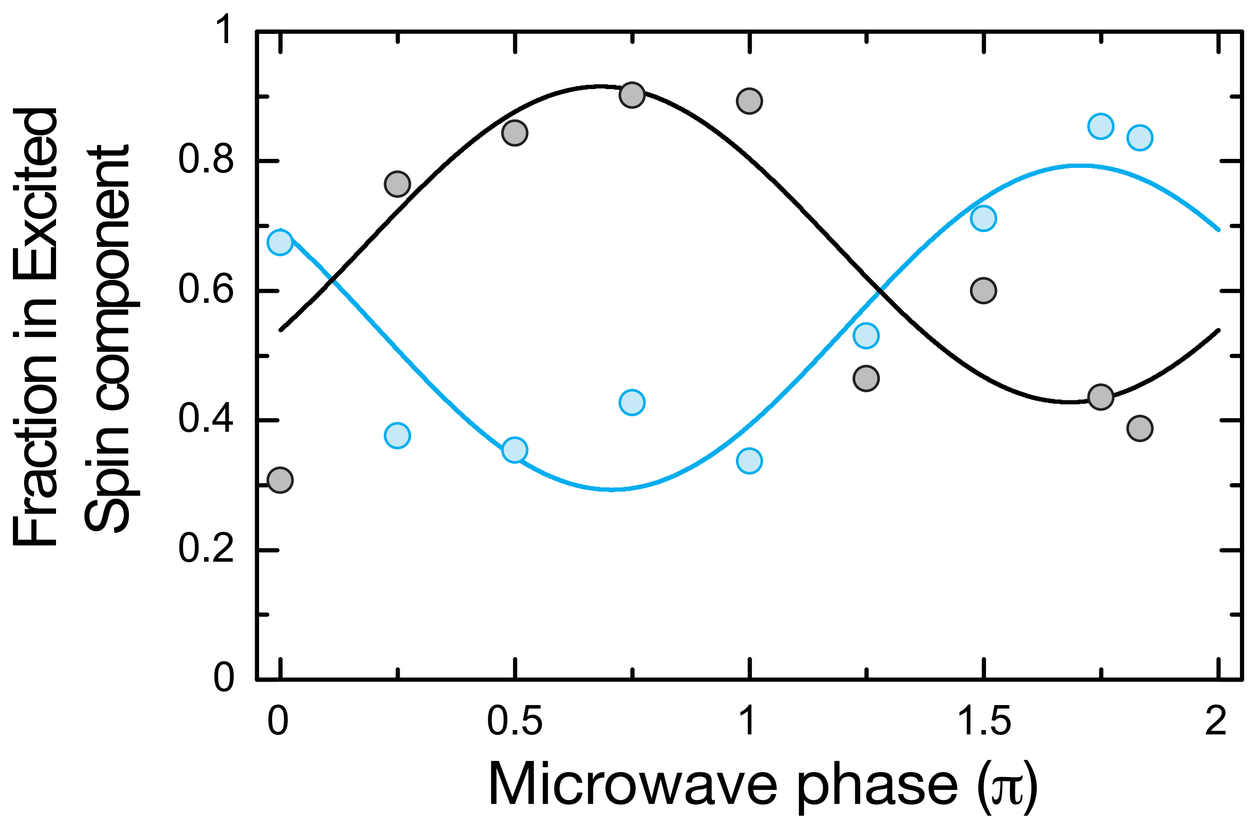

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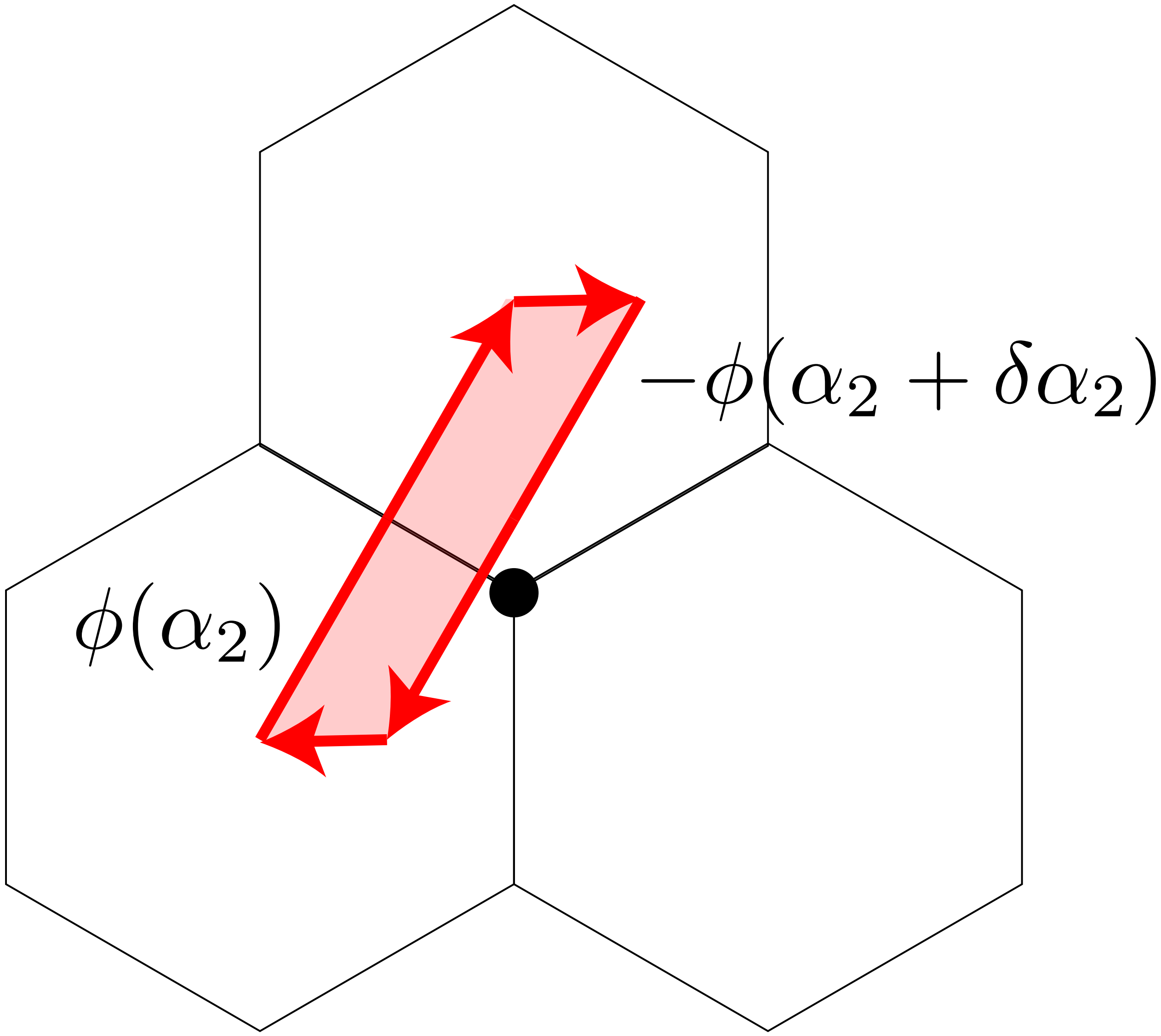
Relation between Zak phase and Chern number

Measurement of (integrated) local Berry curvature from Zak phase



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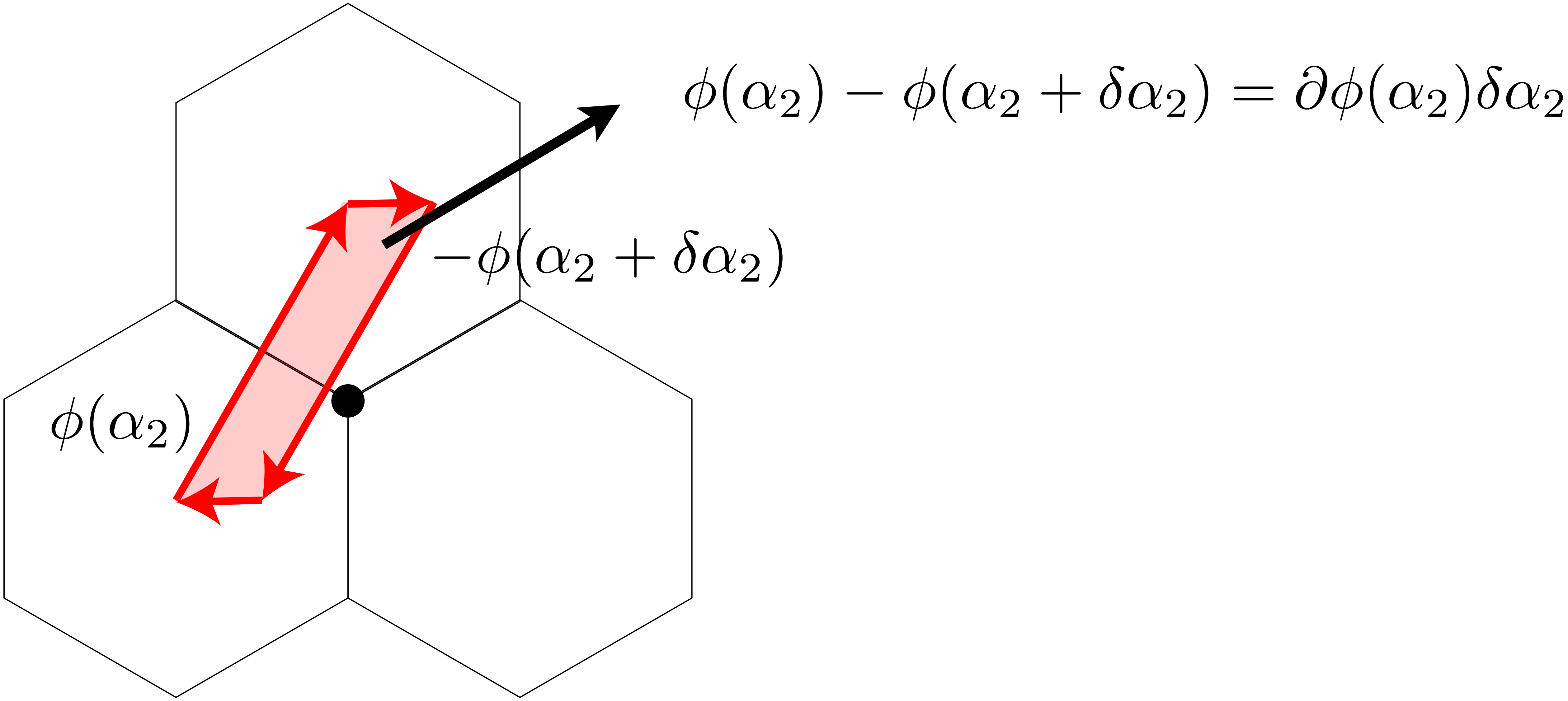
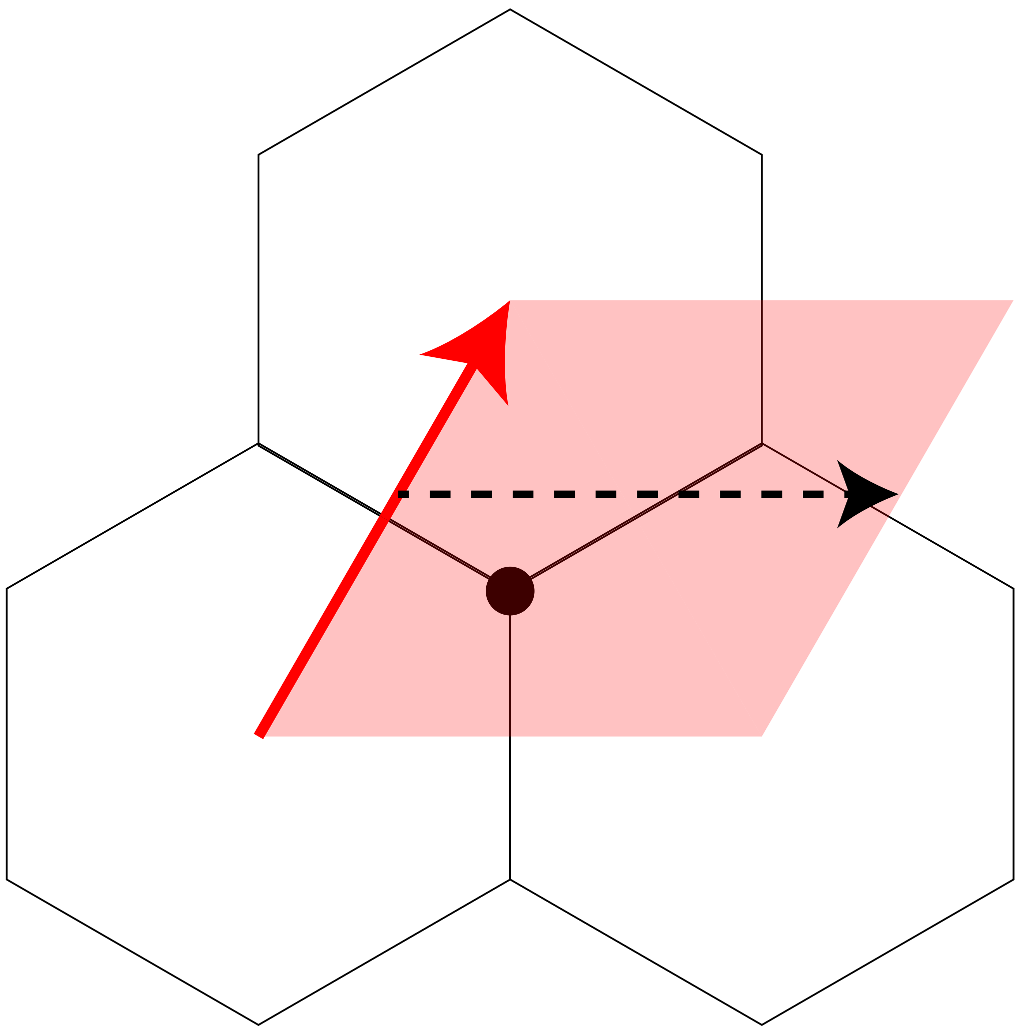


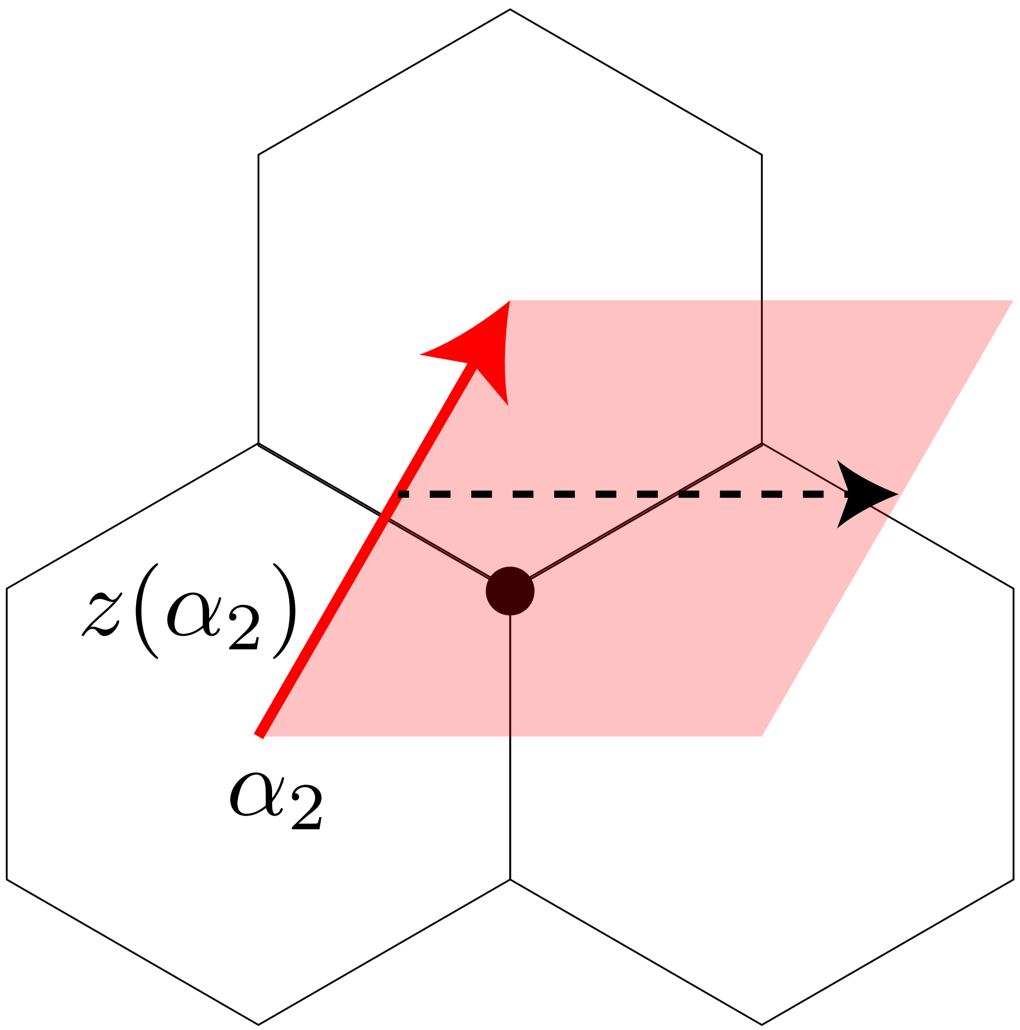
Relation between Zak phase and Chern number

Zak phase



Relation between Zak phase and Chern number

Zak phase

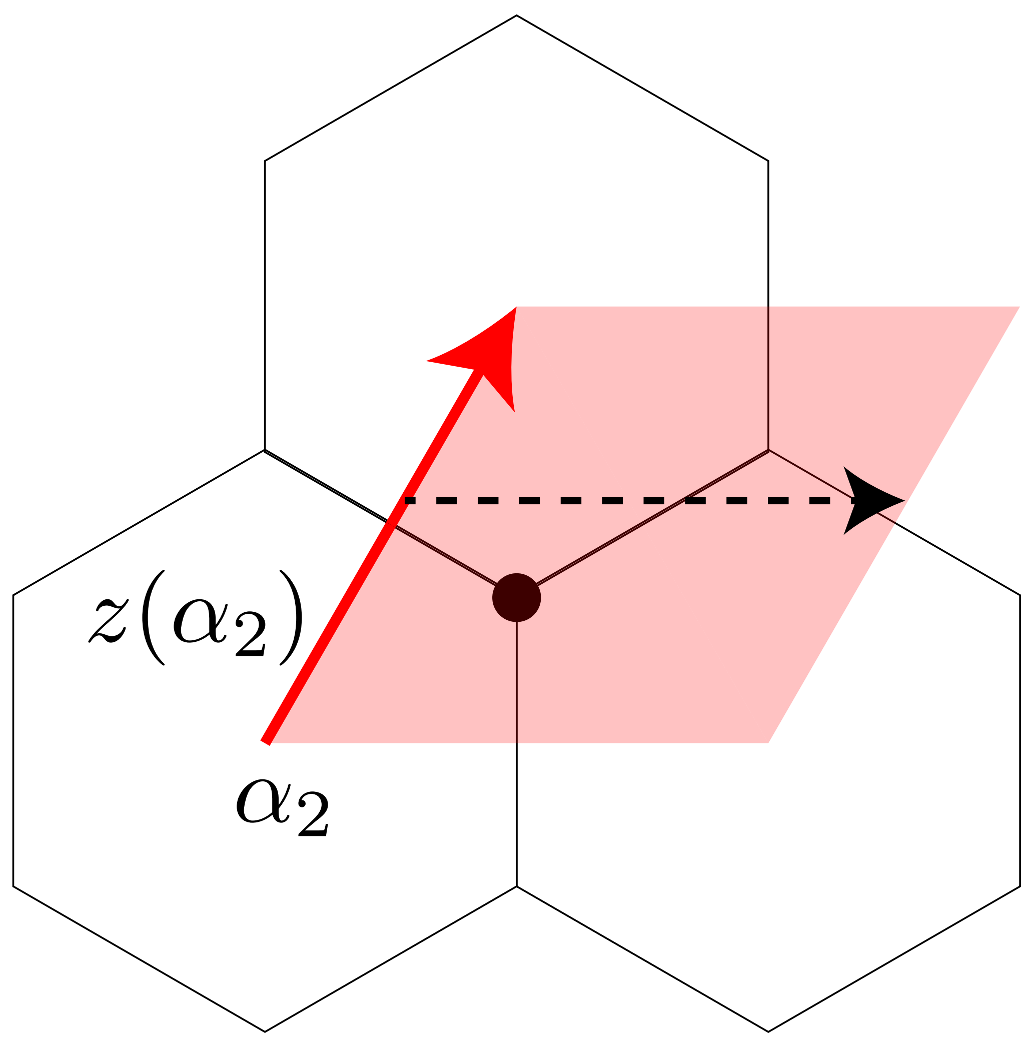


Measure Zak phase for different initial points in the primitive cell

$$z(\alpha_2) = e^{-i\varphi_{\rm B}(\alpha_2)}$$

Relation between Zak phase and Chern number

Zak phase



Measure Zak phase for different initial points in the primitive cell

$$z(\alpha_2) = e^{-i\varphi_{\mathrm{B}}(\alpha_2)}$$

Chern number

$$c = -\frac{i}{2\pi}\int_0^1 d\alpha_2 \bar{z}(\alpha_2)\partial_{\alpha_2} z(\alpha_2)$$

Outline

1. Overview of topological phases
2. Topology of periodically driven systems
   a. Design of static topology through driving

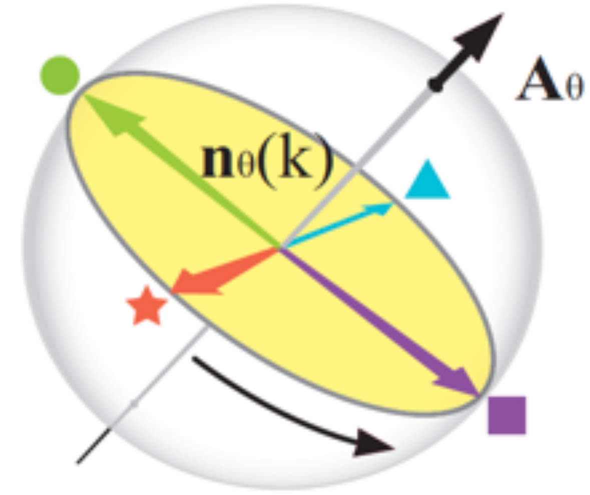
3. Examples from driven hexagonal lattice system;
Graphene under circularly polarized light

4. Detection scheme of topological band

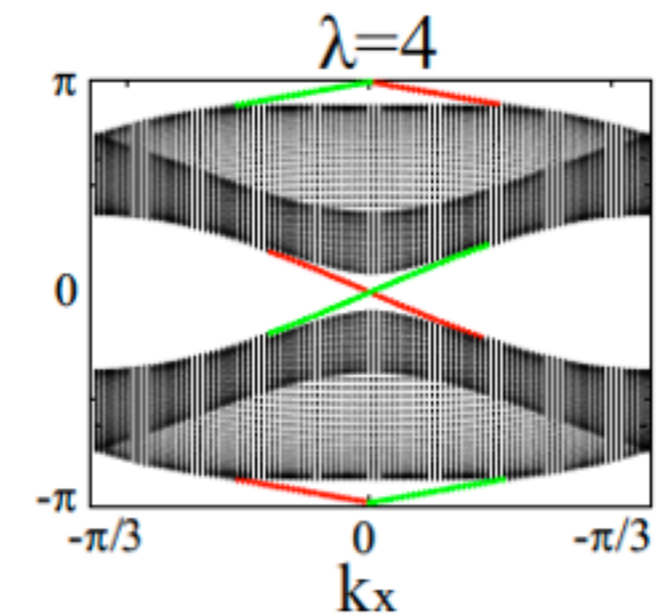
5. Conclusion

Conclusion

1. Rich and unique topological behaviors exist for periodically driven systems

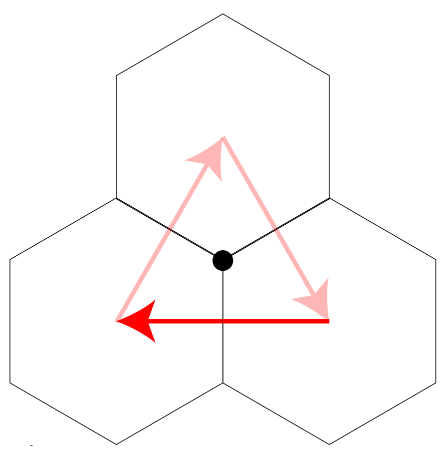


2. Examples of such non-equilibrium topological phenomena are abundant in quantum optics, cold atoms and condensed matter systems.



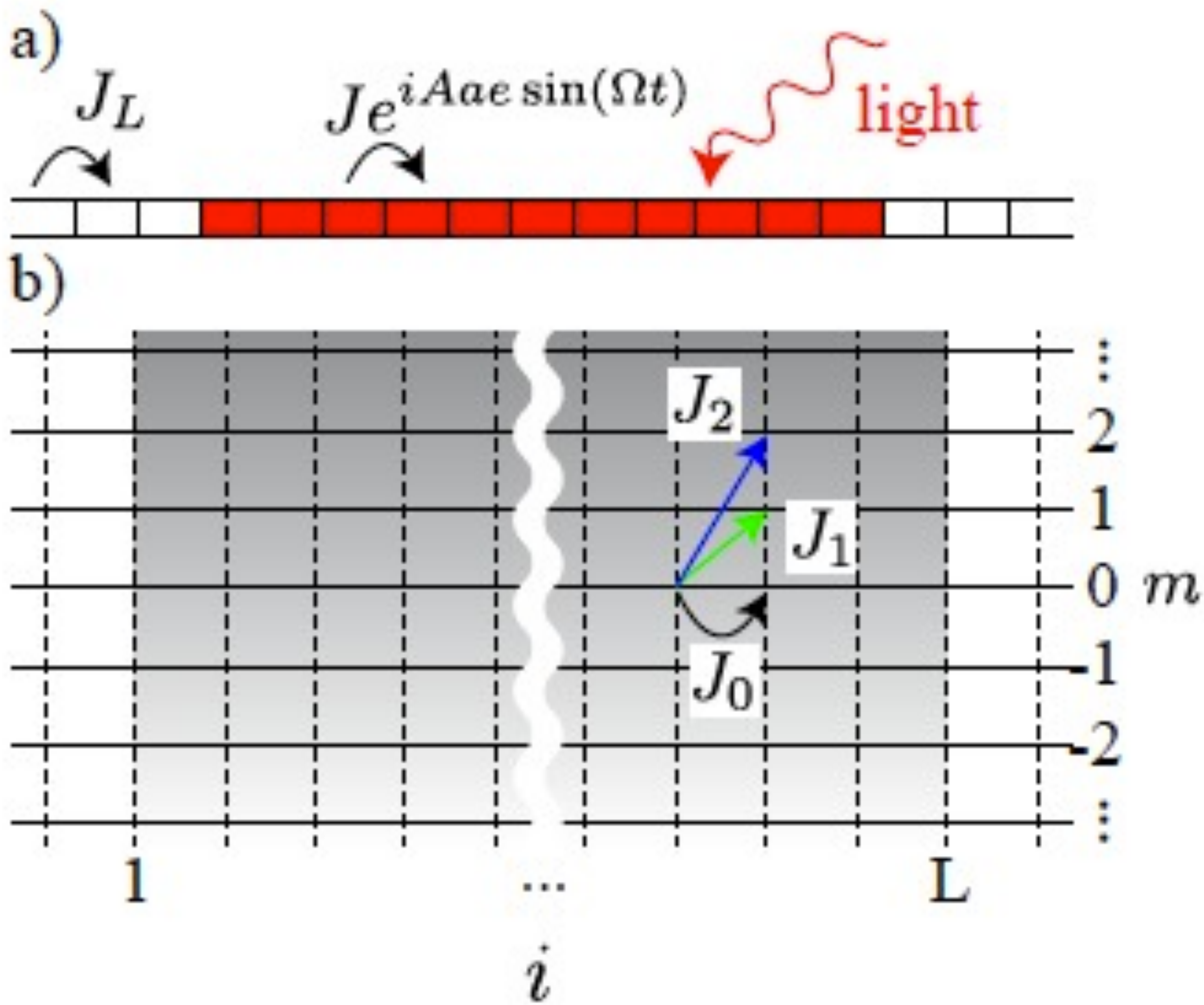
3. Band Topology can be directly measured through a combination of Bloch oscillation and Ramsey interferencce in atomic phyiscs.

Zak phase



Further work

Dimension increase from light application



Further work

Dimension increase from light application