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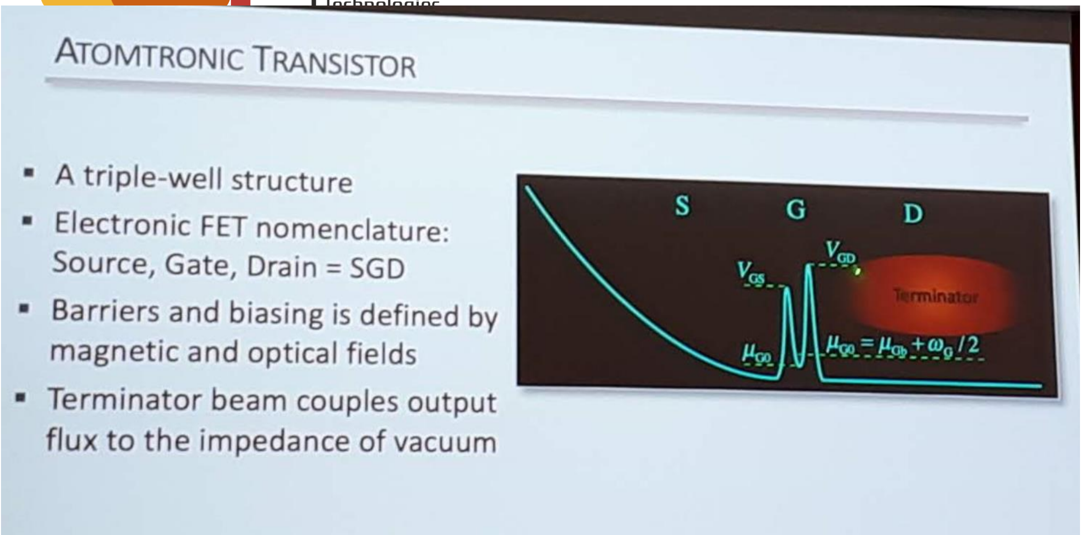
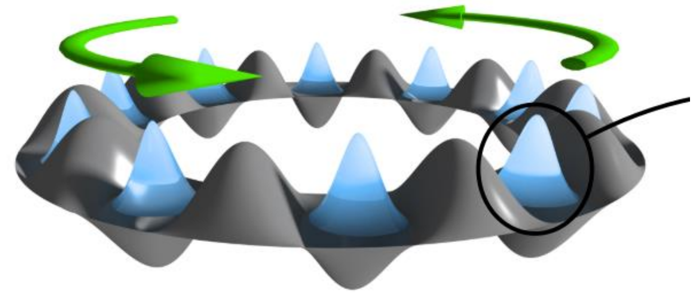
Topological pumping in Aharonov-Bohm rings

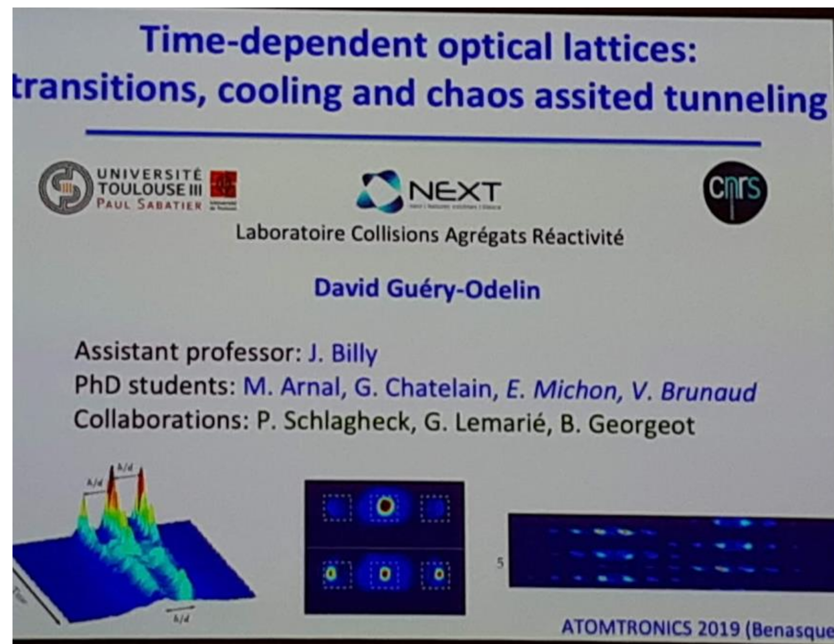
arXiv:1810.08525

Tobias Haug, Rainer Dumke, Leong-Chuan Kwek, Luigi Amico

06.05.2019



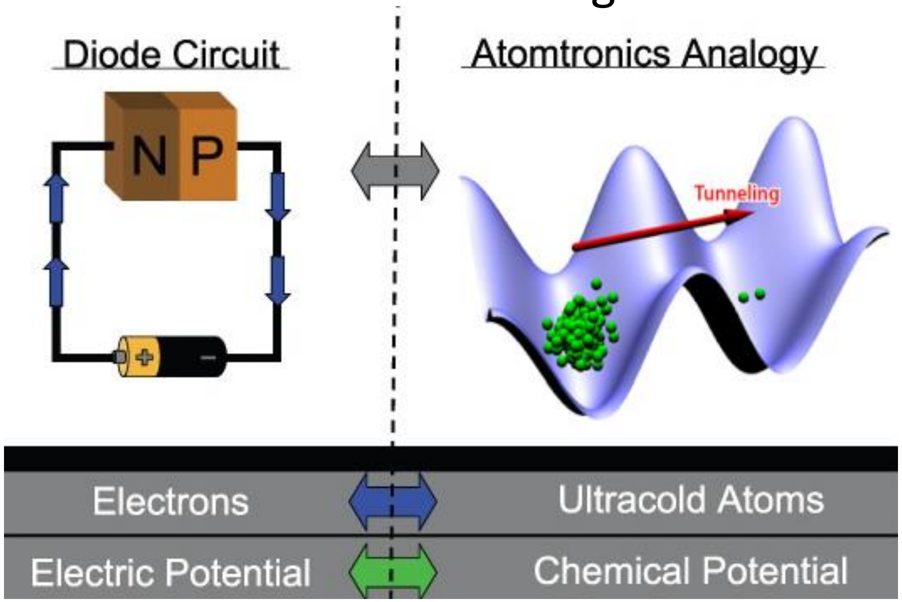


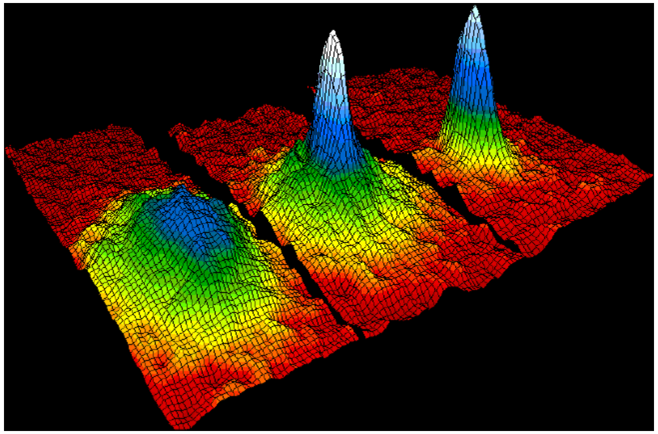


- Transistors/Lead-system dynamics
- Time dependent lattices
- Ring with flux

Atomtronics

Atomtronics: Cold atoms are analog to electronics





Opportunities

- Improve cold atom ***quantum simulators***
- Bridging **mesoscopic** and cold-atoms physics
- New quantum **devices**/Quantum **sensing**

Advantages: - Neutral atoms →No charge and long coherence (~1 minute)

- Flexible trapping with light

Seaman, B. T., et al. "Atomtronics: Ultracold-atom analogs of electronic devices." *Phys, Rev, A* 75.2 (2007)

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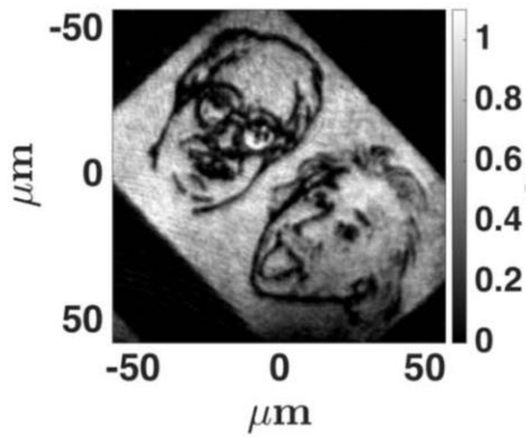
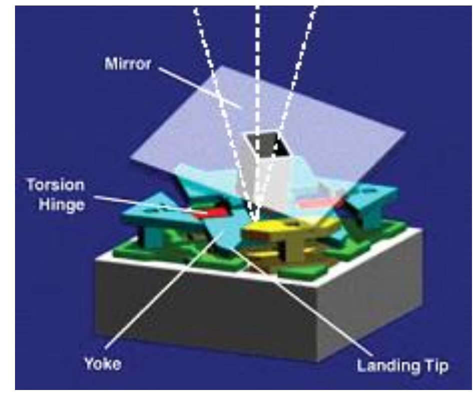
Light shaping techniques

- Digital micromirror device (DMD) for arbitrary light potentials

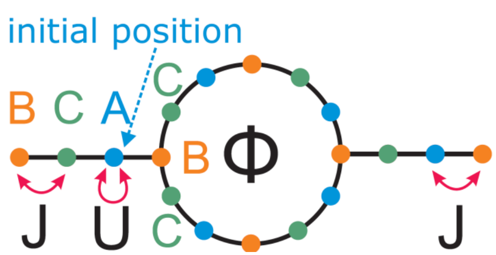
Laser field

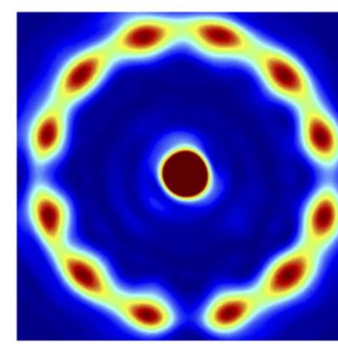
Actual trapped atoms



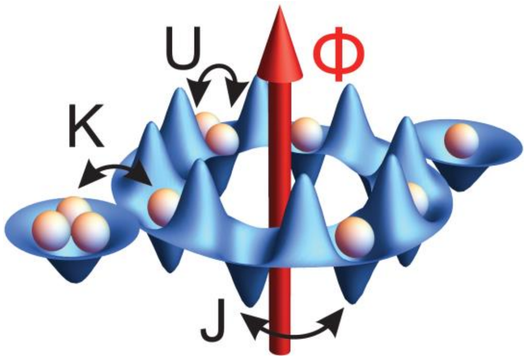


- Possible to create potentials for complex circuits
- Repetition rate ~100μs →Modulate potential in time during experiment to change local potential energy





Gauthier, G., et al. *Optica* 3.10 (2016)
L. Amico, D. Aghamalyan, F. Auksztol, H. Crepaz, R. Dumke, L.C. Kwek *Scientific reports 4* (2014)

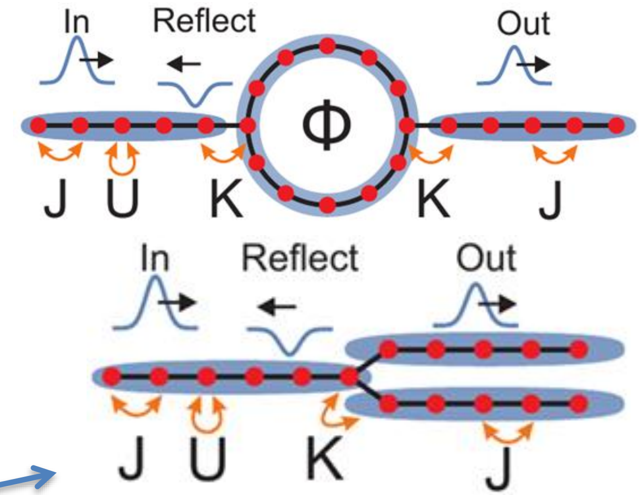


Aharonov-Bohm effect

TH, H. Heimonen, R. Dumke, L.-C. Kwek, L. Amico
arXiv:1706.05180

Fragmented states

N. Victorin, TH, L.-C. Kwek, L. Amico, A. Minguzzi
Phys. Rev. A ***99****, 033616*
arXiv:1810.03331



Transport

TH, R. Dumke, L.-C. Kwek, L. Amico
arXiv:1807.03616

Cold atoms + potential shaping+ control currents

Quantum phases

TH, L. Amico, R. Dumke, L.-C. Kwek
Quantum Sci. Technol. (2018)
arXiv:1612.09109

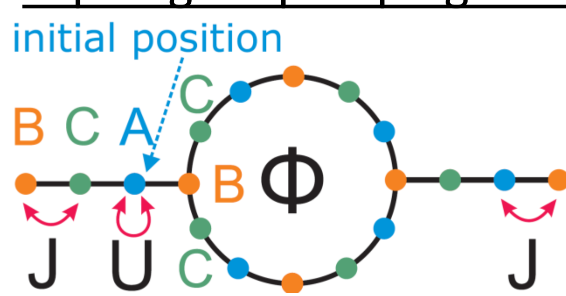
AQUID read-out

TH, J. Tan, M. Theng, R. Dumke, L.C. Kwek, L. Amico
Phys. Rev. A 97 (2018)
arXiv: 1707.09184

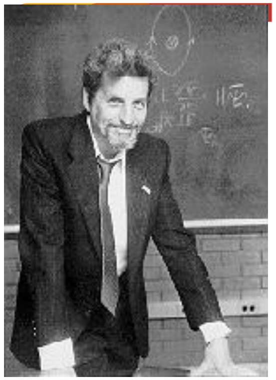
Topological pumping with spin dualities

TH, L. Amico, L.-C. Kwek, W.J. Munro, V.M. Bastidas
Soon on arXiv

Topological pumping in rings



TH, R. Dumke, L.-C. Kwek, L. Amico
arXiv:1810.08525

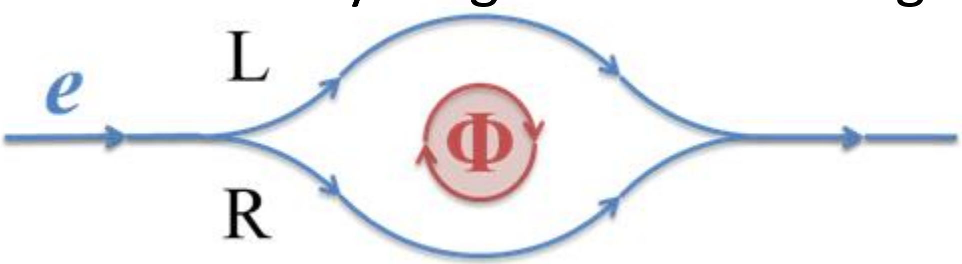


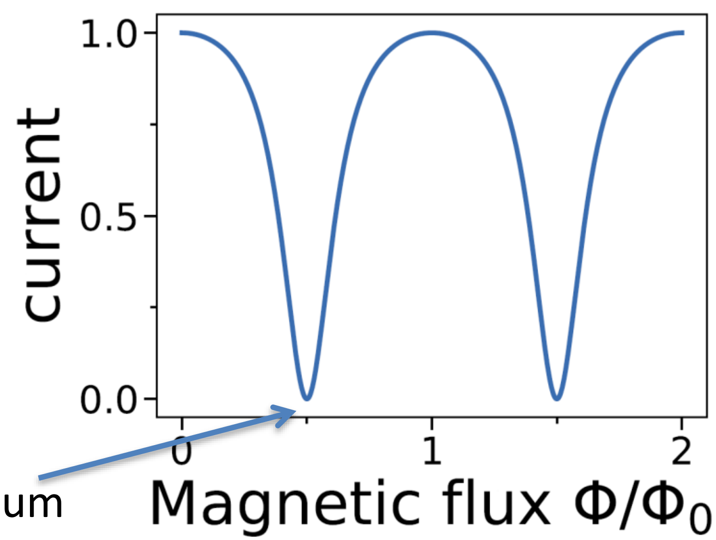

Aharonov-Bohm effect

- Charged particle enclosing a region with magnetic field

$$\Delta\phi = \frac{e}{\hbar}\oint_C \mathbf{A}(\mathbf{r})\mathrm{d}\mathbf{r} \propto \Phi$$

- Phase shift by magnetic field changes interference pattern/current

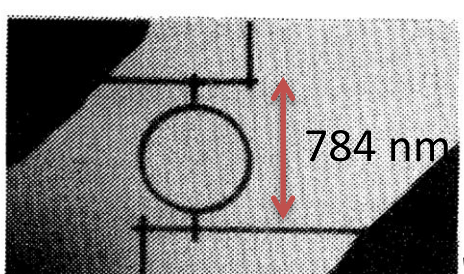




½ flux quantum

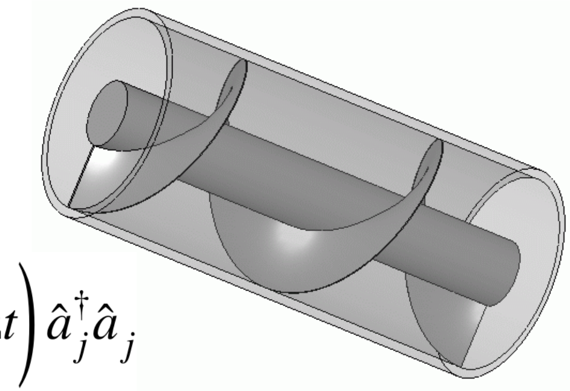
- Minimal current at

  $\Phi/\Phi_0 = 1/2$ (destructive interference)



Washburn Web 1986

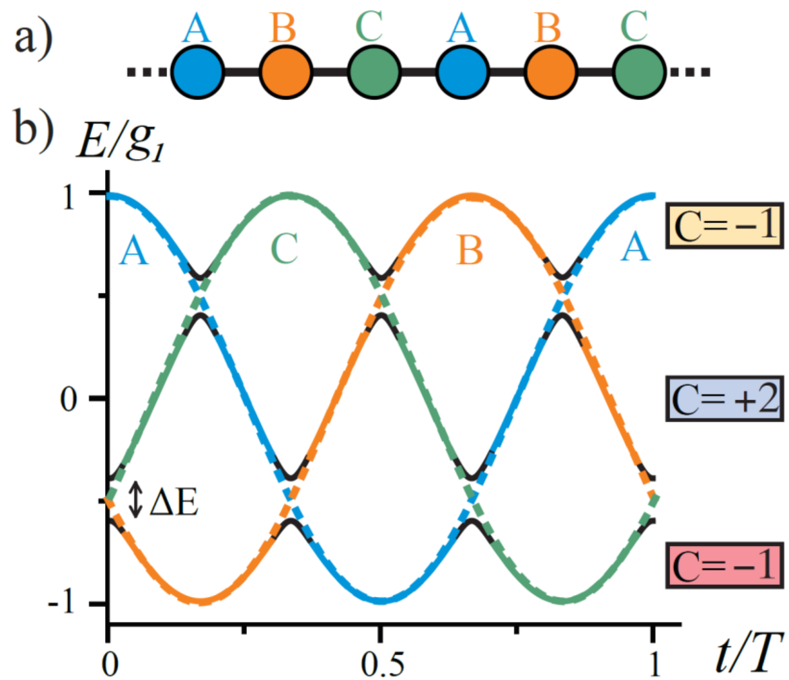
Topological pumping



$$H(t) = -J\sum_j\left[\hat{a}_j^\dagger\hat{a}_{j+1} + \hat{a}_{j+1}^\dagger\hat{a}_j\right] + P\sum_j\cos\left(\frac{2\pi j}{3} - \Omega t\right)\hat{a}_j^\dagger\hat{a}_j$$

- on-site energy modulated in space (A,B,C) with period T
- J=0 disconnected (dashed)
- With J>0, three bands form (solid)

- Adiabatic modulation: Transport
- Speed of band depends on number of anti-crossings (Chern number **C**)
- Robust to random disorder if smaller than energy gap ΔE



nature physics

ARTICLES

PUBLISHED ONLINE: 14 DECEMBER 2015 | DOI: 10.1038/NPHYS3584

A Thouless quantum pump with ultracold bosonic atoms in an optical superlattice

M. Lohse[1,2]*, C. Schweizer[1,2], O. Zilberberg[3], M. Aidelsburger[1,2] and I. Bloch[1,2]

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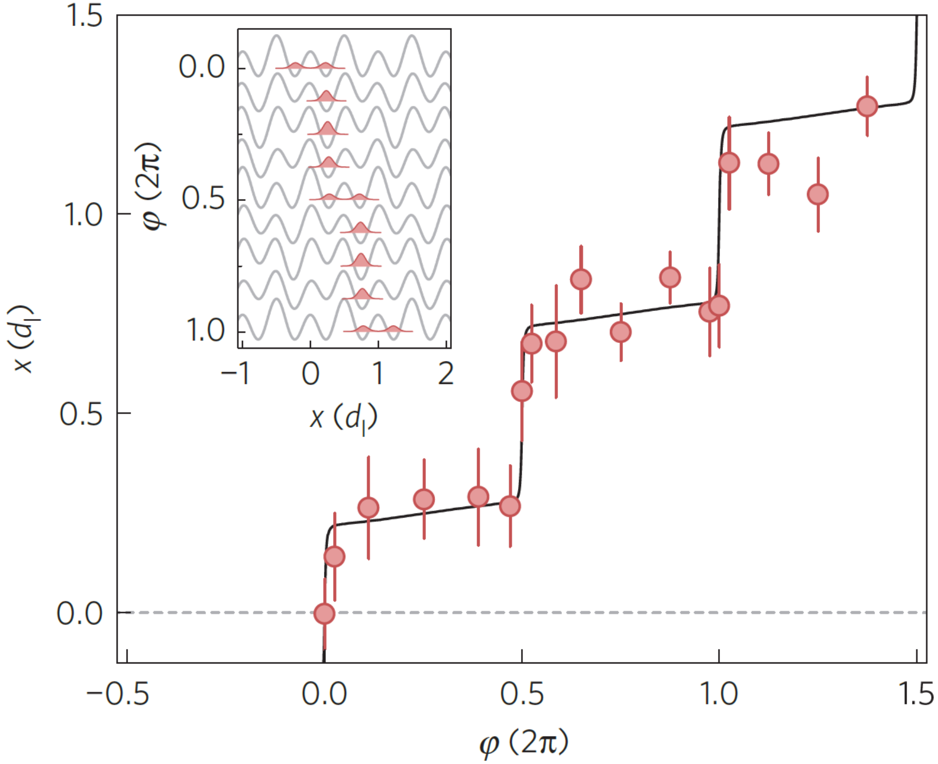
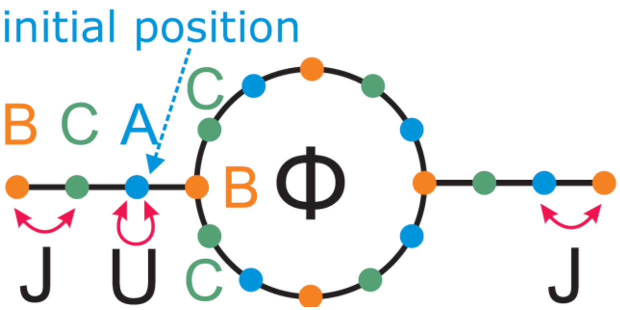
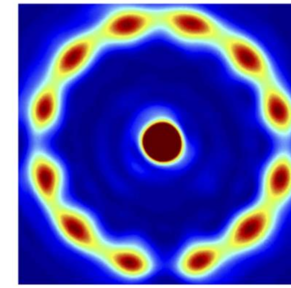


Topological Pumping in ring-lead system





$$H = H_R + H_S + H_D + H_L + H_P$$

$$H_R = -\sum_{j=1}^{L_R} (J e^{i2\pi\Phi} \hat{a}_j^\dagger \hat{a}_{j+1} + HC) + U/2 \sum_{j=1}^{L_R} \hat{n}_j^a (\hat{n}_j^a - 1)$$

$$H_S = -\sum_{j=1}^{L_R} (J \hat{s}_j^\dagger \hat{s}_{j+1} + HC) + U/2 \sum_{j=1}^{L_R} \hat{n}_j^s (\hat{n}_j^s - 1)$$

$$H_D = -\sum_{j=1}^{L_R} (J \hat{d}_j^\dagger \hat{d}_{j+1} + HC) + U/2 \sum_{j=1}^{L_R} \hat{n}_j^d (\hat{n}_j^d - 1)$$

$$H_L = -J(\hat{a}_0^\dagger \hat{s}_0 + \hat{a}_{L_r/2}^\dagger \hat{d}_0 + HC)$$

$$H_P(t) = P_0 \sum_j \cos\left(\frac{2\pi j}{3} - \phi_0 - \Omega t\right) \hat{n}_j$$

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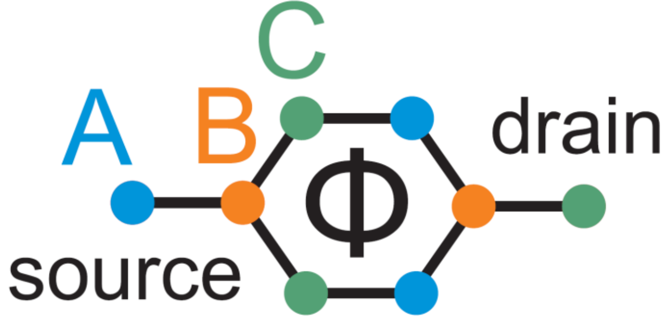
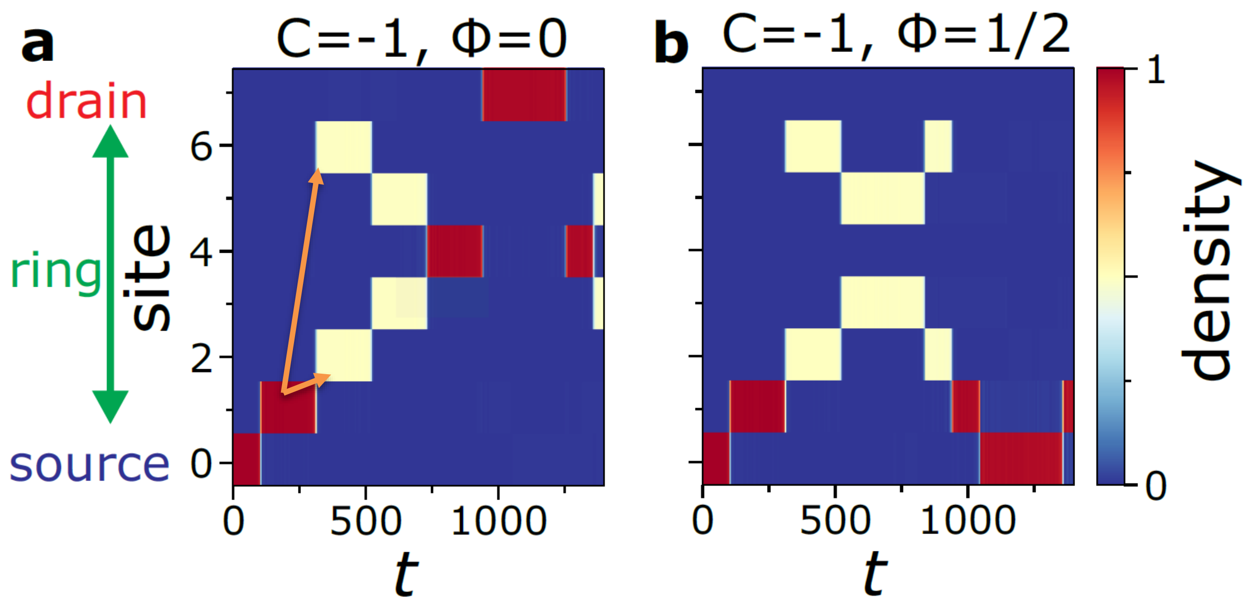
Single atom dynamics



- Prepare in bottom band (Chern number -1)
- Φ phase shift between upper and lower path
- Total transmission for Φ=0, total reflection for Φ=1/2
- Reflected atom moves twice as fast in band with Chern number 2→AB reflection occur via transitions to band with Chern number of opposite sign!



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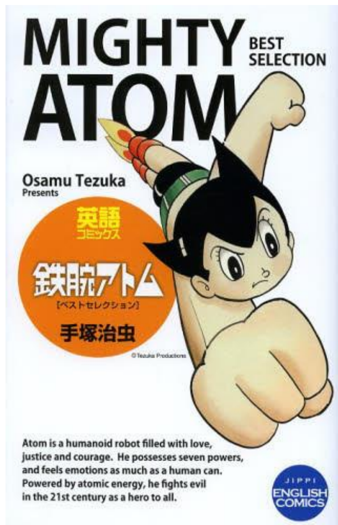
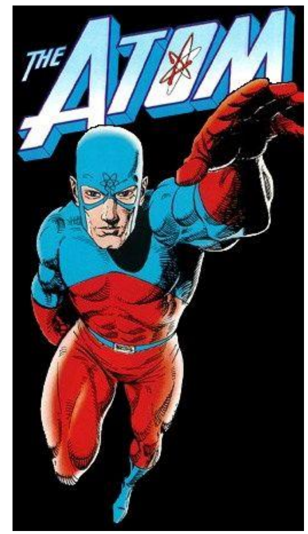
Interaction and pumping

- Topology is property of non-interacting bands
- How does it fare with interacting atoms?



VS



- Interaction → Topological pumping can break down
- However: Highly localized states of many particles (=bound states) behave similar to free particles →Pumping survives

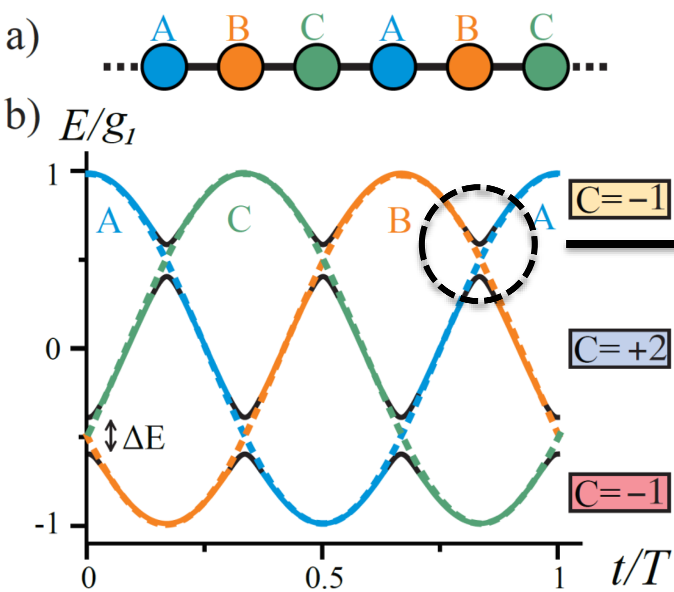
→can generate **entanglement** and modify energy gaps

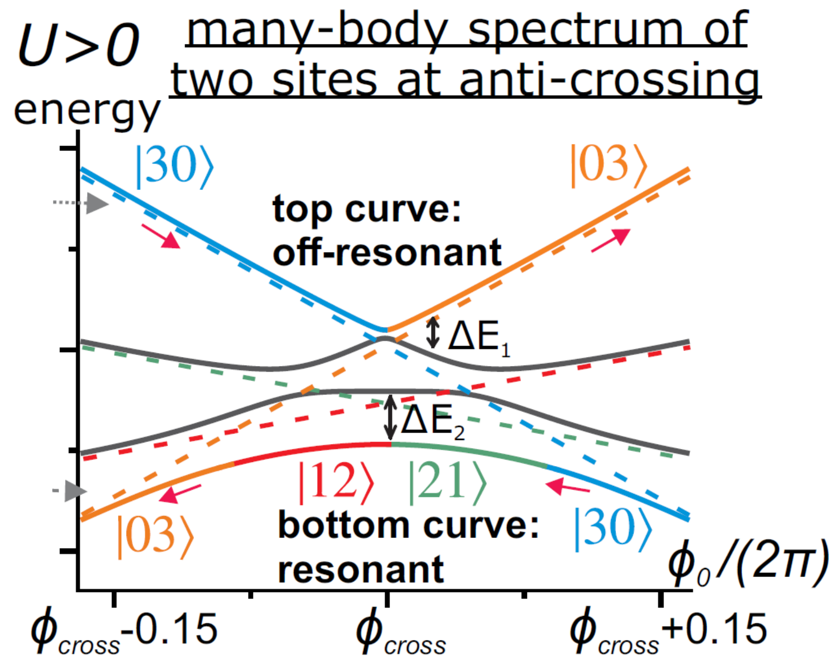
Nakagawa, Masaya, et al. Physical Review B 98.11 (2018): 115147

J. Tangpanitanon, V. M. Bastidas, S. Al-Assam, P. Roushan, D. Jaksch, and D. G. Angelakis, PRL. 117, 213603 (2016).

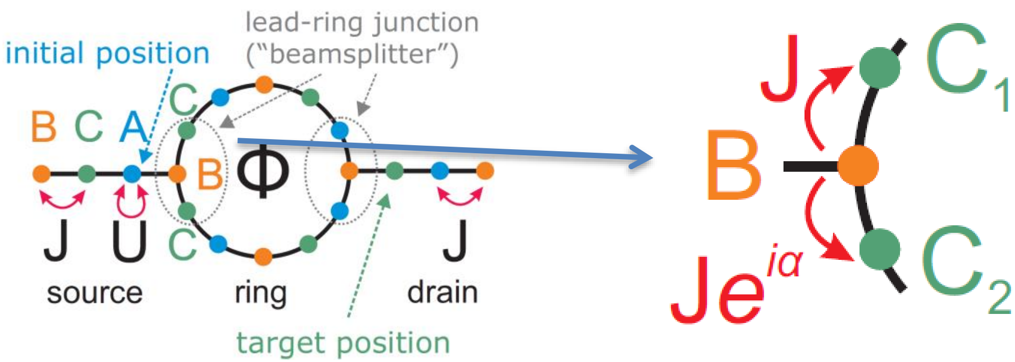
Effect of interaction

- Gap without interaction U: $\Delta E = 2J$
- *U* creates asymmetry in upper&lower path in anti-crossing
- Top band: Off-resonant coupling, all particles tunnel as a whole $\Delta E_1 \propto J^N / U^{N-1}$
- Bottom band: Resonant coupling, single particles tunnel one after the other $\Delta E_2 = 2\sqrt{N}J$





Effect of interaction at ring-lead interface



- Top band: NOON states
  - Enhanced AB phase ~N

Initial Fock state *Final Fock state*

$$|3\rangle_B \otimes |00\rangle_{C_1C_2} \longrightarrow |0\rangle_B \otimes |30\rangle_{C_1C_2} + e^{i3\alpha}|0\rangle_B \otimes |03\rangle_{C_1C_2}$$

$$|4\rangle_B \otimes |00\rangle_{C_1C_2} \longrightarrow |0\rangle_B \otimes |40\rangle_{C_1C_2} + e^{i4\alpha}|0\rangle_B \otimes |04\rangle_{C_1C_2}$$

- Bottom band: Bell-like states
  - Even number of atoms: absence of AB phase

$$|3\rangle_B \otimes |00\rangle_{C_1C_2} \longrightarrow |0\rangle_B \otimes |21\rangle_{C_1C_2} + e^{i\alpha}|0\rangle_B \otimes |12\rangle_{C_1C_2}$$

$$|4\rangle_B \otimes |00\rangle_{C_1C_2} \longrightarrow |0\rangle_B \otimes |22\rangle_{C_1C_2}$$

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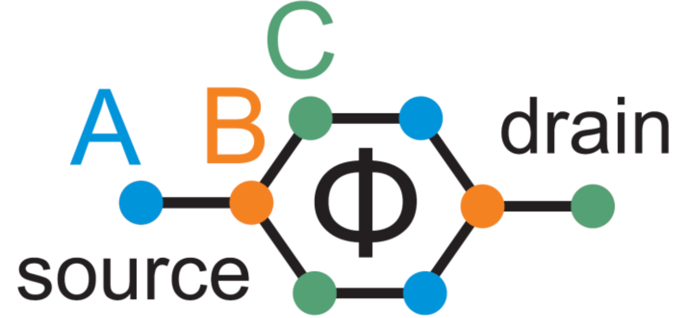
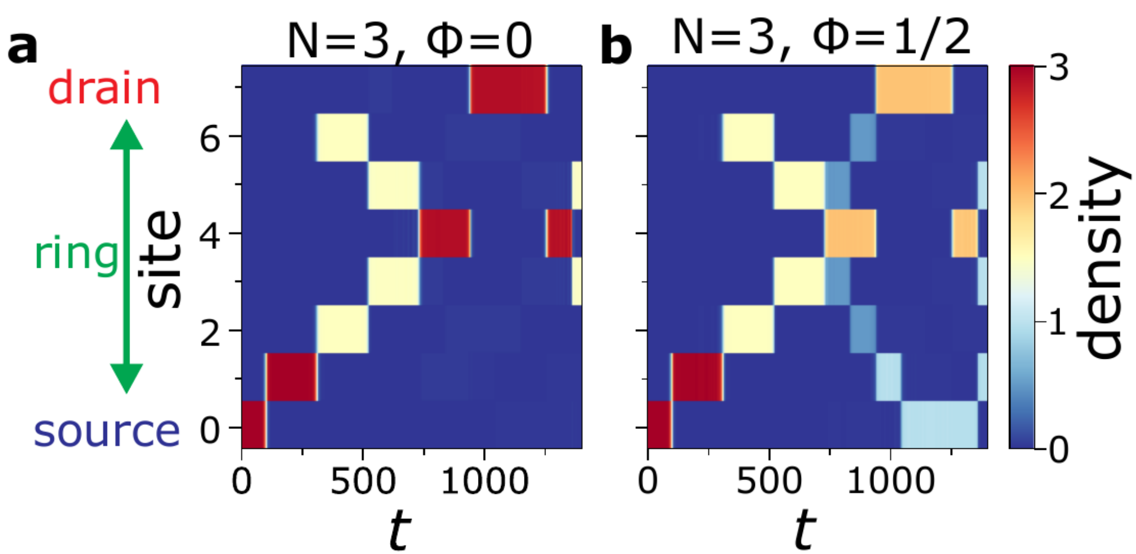
Many-atom dynamics



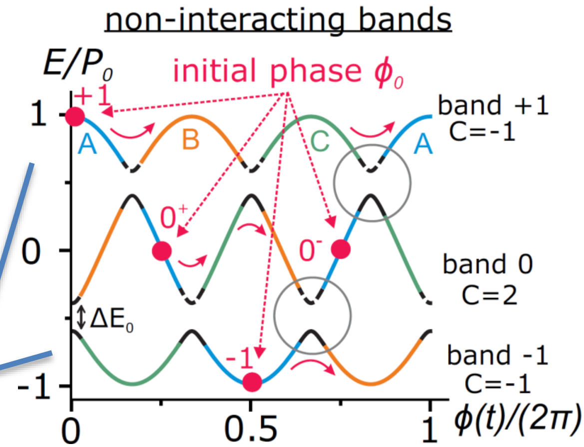
- Prepare N atoms in bottom band (Chern number -1)
- Odd N:
  - Φ=0: Total transmission
  - Φ=1/2: one atom reflected, N-1 transmitted
- Even N:
  - Always total transmission for any Φ

$$|3\rangle_B \otimes |00\rangle_{C_1C_2} \longrightarrow |0\rangle_B \otimes |21\rangle_{C_1C_2} + e^{i\alpha}|0\rangle_B \otimes |12\rangle_{C_1C_2}$$

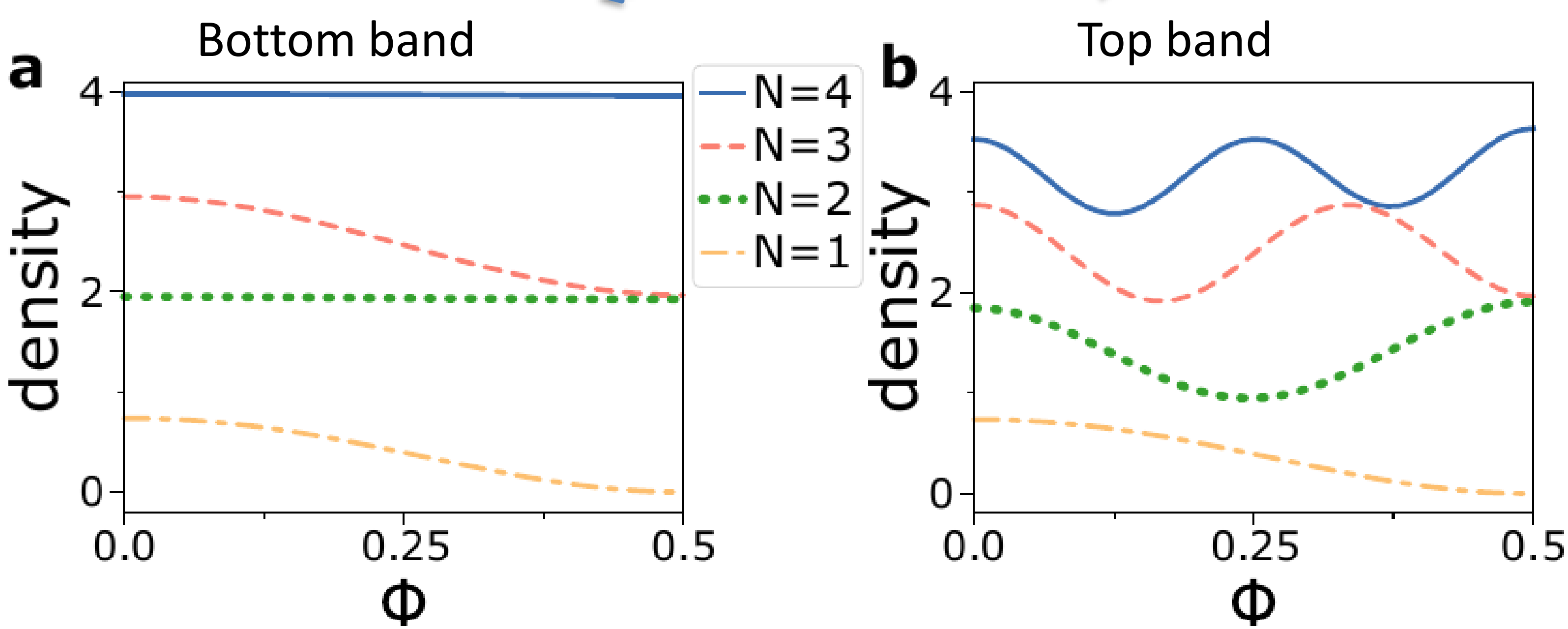
$$|4\rangle_B \otimes |00\rangle_{C_1C_2} \longrightarrow |0\rangle_B \otimes |22\rangle_{C_1C_2}$$



AB transmission



- Density pumped into the drain (transmission) depends on flux



- Parity effect: Even and odd number of particles N behave differently

- Periodicity of flux 1/N
- NOON states in ring

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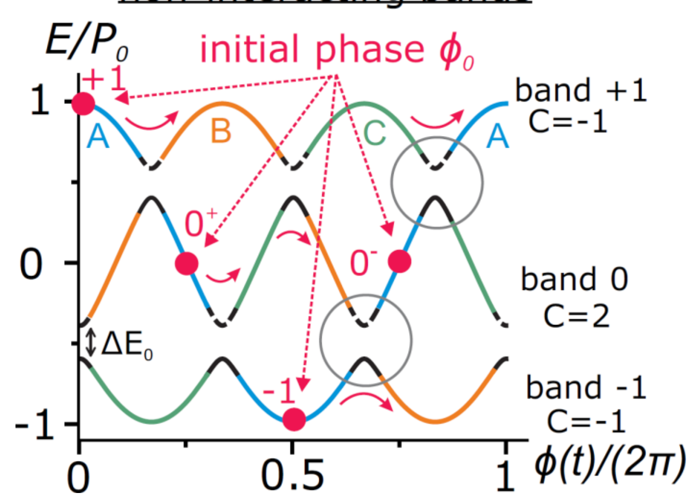
Topological pumping and Aharonov-Bohm

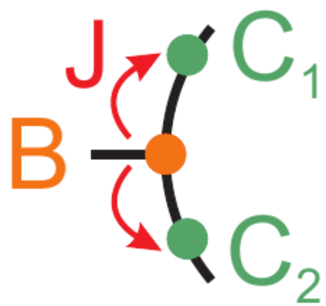
band $U>0$	ring length L_R	transmission N even $T_{\mathrm{even}}(\Phi,N)$	transmission N odd $T_{\mathrm{odd}}(\Phi,N)$	Chern number	ϕ_0	AB period Φ_0	parity effect	state in ring	band gap ΔE
+1	$2n$	$N-1+\cos^2(\pi\Phi N)$	$N-1+\cos^2(\pi\Phi N)$	-1	0	$1/N$	no	NOON type	J^N/U^{N-1}
0^+	$4n+2$	$N-1+\cos^2(\pi\Phi N)$	$N-1+\cos^2(\pi\Phi N)$	2	$\pi/2$	$1/N$	no	NOON type	J^N/U^{N-1}
0^+	$4n$	$\sin^2(\pi\Phi N)$	$\cos^2(\pi\Phi N)$	2	$\pi/2$	$1/N$	yes	NOON type	J^N/U^{N-1}
0^-	$4n$	0	$\cos^2(\pi\Phi)$	2	$-\pi/2$	1	yes	varies	J^N/U^{N-1}
0^-	$4n+2$	N	$N-1+\cos^2(\pi\Phi)$	2	$-\pi/2$	1	yes	varies	J^N/U^{N-1}
-1	$2n$	N	$N-1+\cos^2(\pi\Phi)$	-1	π	1	yes	varies	$2\sqrt{N}J$
$U=0$ all bands	$2n$	$N\cos^2(\pi\Phi)$	$N\cos^2(\pi\Phi)$			1	no	superposition	$2J$

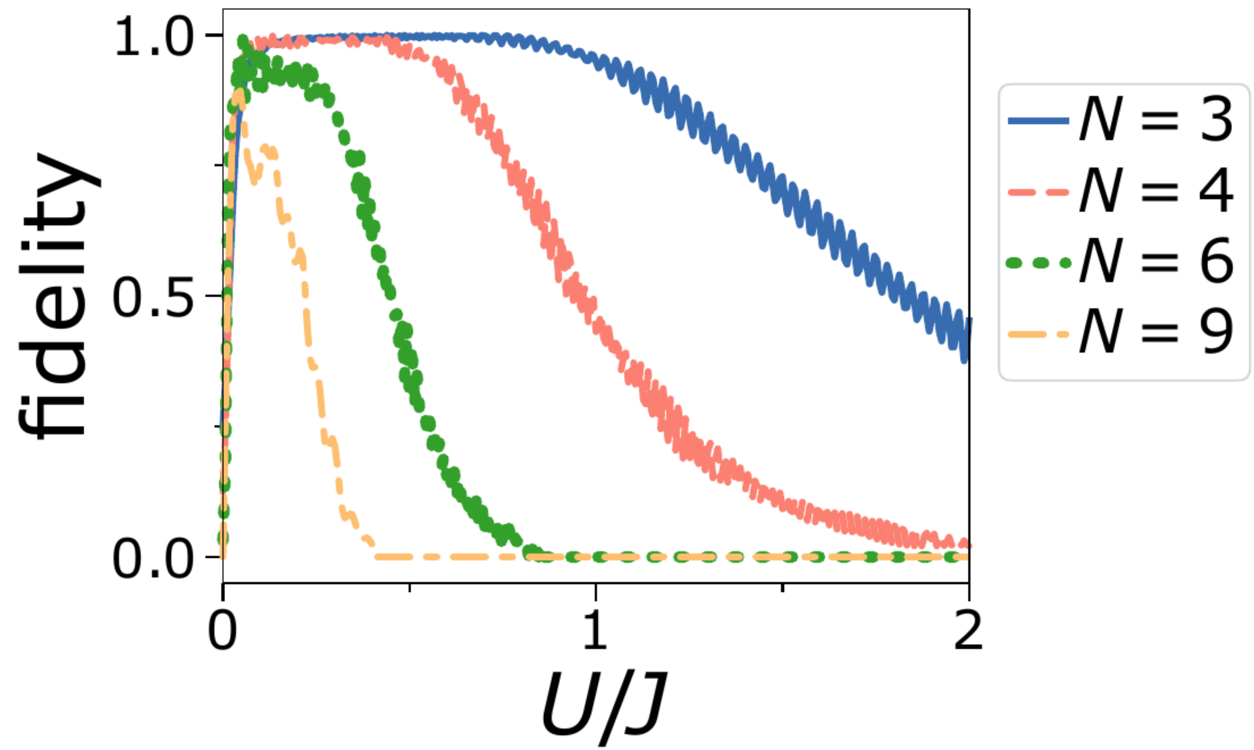
non-interacting bands



Fidelity to generate NOON state

- Consider lead-ring junction only
- Fidelity of adiabatically generating a NOON state for N particles for interaction U $F = |\langle \Psi_{\mathrm{NOON}} | \Psi \rangle|^2$





Conclusions

- Topological pumping and topological AB phase interact in a non-trivial way
- AB reflection occur by transfer to different band with Chern number of opposite sign
- Can engineer highly entangled NOON states for quantum information or sensing
- Realize using time-dependent laser potentials for cold atoms