Synthetic Topological Matter

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Joint Quantum Institute (JQI)
Joint Center for Quantum Information and Computer Science (QuICS)
NIST and University of Maryland

Postdoctoral and graduate fellowships at JQI and QuICS offered annually!

KITP
September 20, 2019

Synthetic Topological Matter

Overview

Focus on atomic, molecular, optical systems

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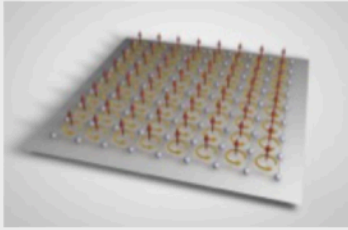
Interacting Topological Matter: Atomic, Molecular and Optical Systems

Coordinators: Monika Aidelsburger, Georg Bruun, Victor Gurarie, and Pietro Massignan

Topological quantum matter is a vibrant area of research of theoretical condensed matter physics. Starting with the explanation of integer and fractional quantum Hall effect, with subsequent breakthroughs of the prediction of topological insulators, classifying symmetry protected topological states starting with lower dimensional systems, and continuing with the elucidation of the concept of topological order, including the recent discovery of the fractonic topological order, the field is rapidly covering an increasingly broad ground. Many of the proposed topological states require interactions for their existence and yet so far much of the experimental progress has occurred for non-interacting topological states, such as topological insulators.

This program aims to advance the field by exploring realistic models of interacting topological quantum matter, which rely on interactions accessible with AMO tools or other engineered quantum systems. Those tools include optical lattices, interactions tunable by Feshbach resonances, low- and mixed-dimensional systems, Bose and Fermi mixtures, periodically-driven systems, systems with dissipation, local control with quantum gas microscopes, as well as optomechanical devices and other tools for engineering quantum systems. The relevant models can be addressed analytically within some corner of their phase diagram, numerically for a broader range of their parameters and conceptually by matching them against the broader classification schemes already developed or whose development is in progress. Detection and “smoking-gun” signatures of these topological states will also be explored.



DATES

Jun 1, 2021 - Aug 13, 2021

INFORMATION

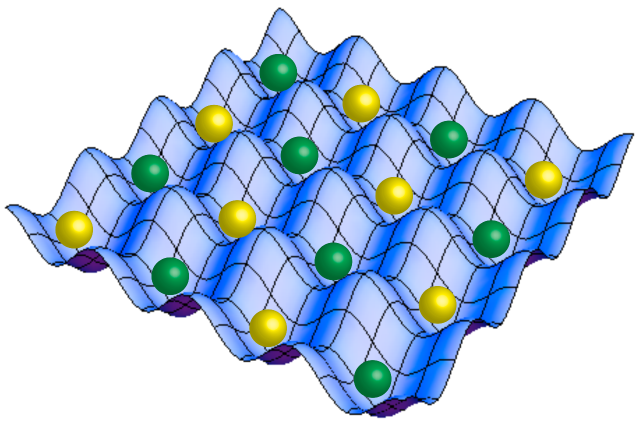
Apply

Application deadline is:
Dec 8, 2019.
Primary deadline above date.

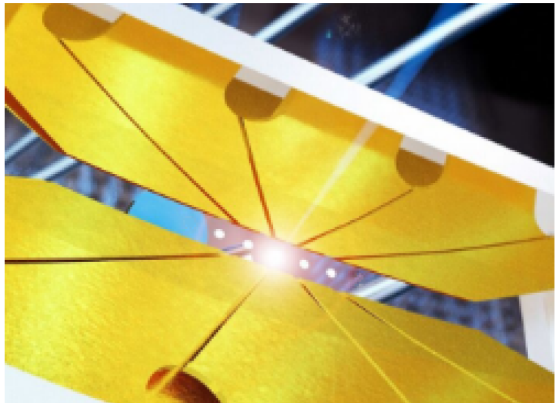
Rolling admissions after until the program is filled.

Atomic, molecular, and optical (AMO) systems

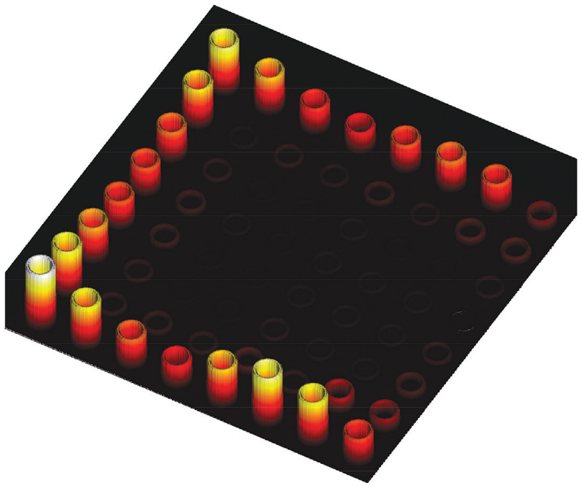
neutral atoms



trapped ions



optical photons



Other (including AMO-like systems): polar molecules, microwave photons, superconducting qubits, implanted solid-state defects,…

- can be cleaner & more tunable than condensed matter
- can be more coherent => long-time non-equilibrium dynamics
- easy access to a variety of bosons, fermions, spins
- prepared & probed differently

=> new avenues for studying strongly-interacting topological systems

Outline

Topological phases with

- ultracold atoms
- photons
- spins

(not exhaustive, e.g. optomechanics, …)

Effective gauge fields for ultracold atoms

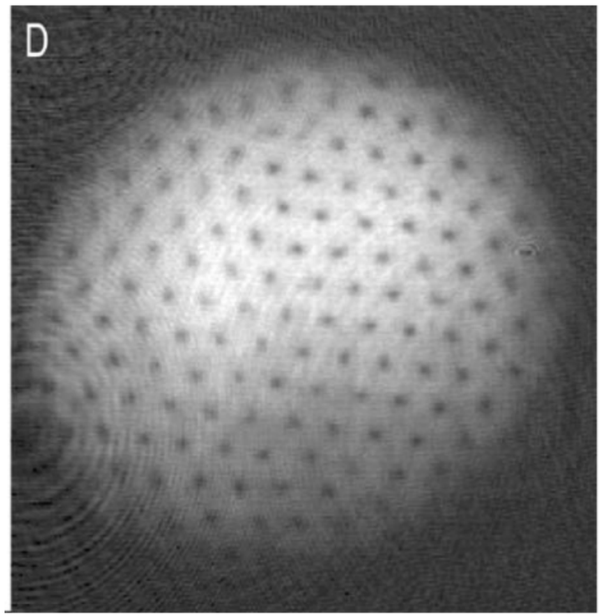
Reviews: Dalibard, Gerbier, Juzeliunas, Ohberg, RMP 83, 1523 (2011)
Goldman, Juzeliunas, Ohberg, Spielman, Rep. Prog. Phys. 77, 126401 (2014)
Zhang et al, Adv. Phys., 67, 253 (2018) <= 150 pages, 570 refs
Galitski, Spielman, Juzeliunas, Physics Today 72, 1, 38 (2019)
Cooper, Dalibard, Spielman, RMP 91 015005 (2019) <= 50 pages, 260 refs

- will focus on 2D topological matter
- will not focus on spin-orbit coupling

Spin-orbit reviews: Galitski, Spielman, Nature 494, 49 (2013)
Zhang, Yi, Sa de Melo, Synthetic Spin-Orbit Coupling in Cold Atoms (2018)

Effective magnetic fields in rotating quantum gases

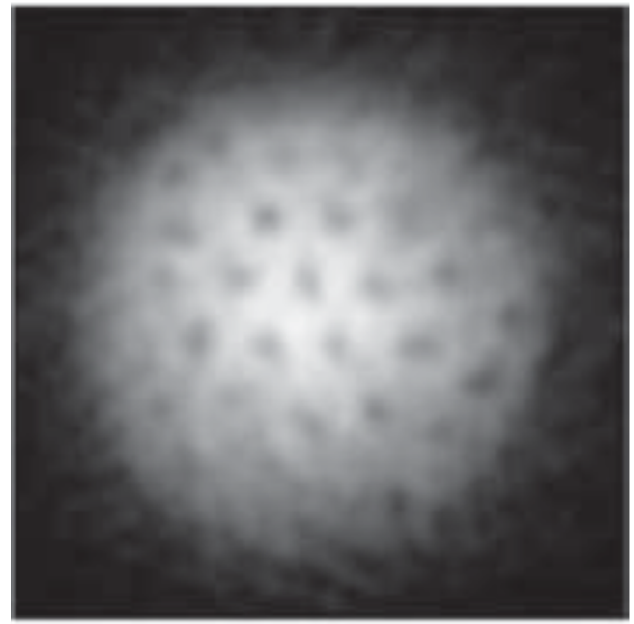
Coriolis force ~ Lorentz force



vortex lattice in a BEC

Ketterle group (2001)

Dalibard group (2000)



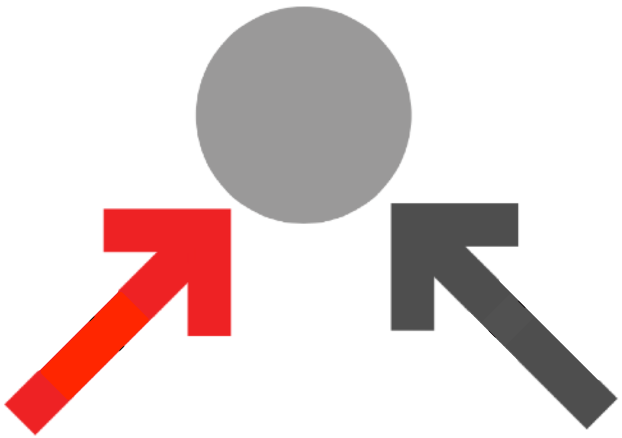
vortex lattice in strongly interacting Fermi gas

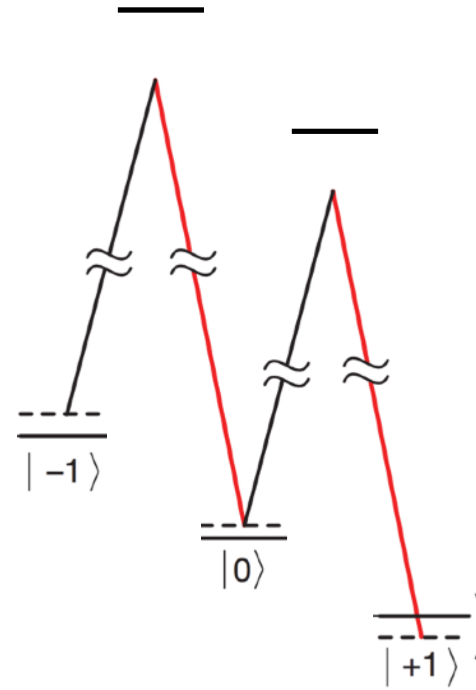
Ketterle group (2005)

vortex ~ magnetic flux

due to technical limitations: fields << one flux (vortex) per atom

Light-induced effective magnetic field



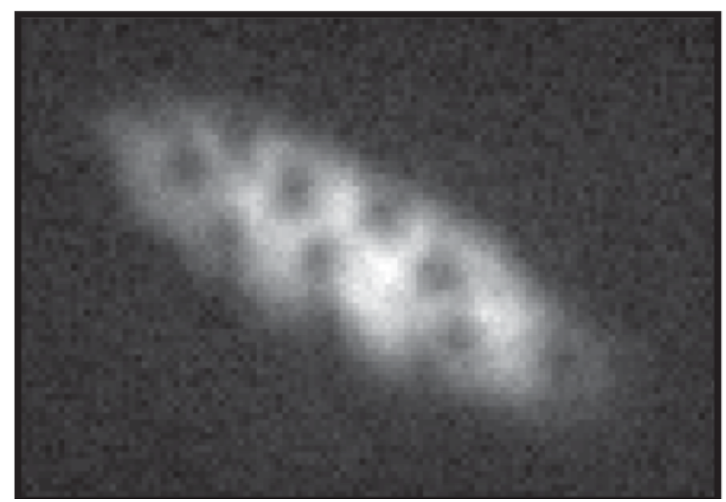


lowest dressed state

$$|d(\mathbf{r})\rangle = c_{\text{-}1}(\mathbf{r})|\text{-}1\rangle + c_0(\mathbf{r})|0\rangle + c_1(\mathbf{r})|1\rangle$$

experiences effective magnetic field

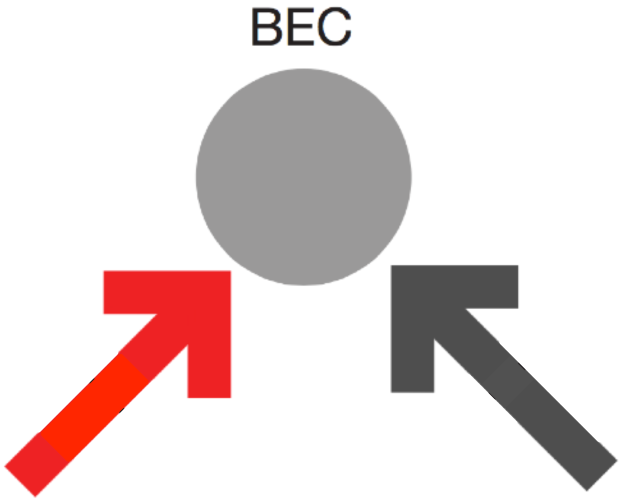
- can get large magnetic field
- only over a narrow strip
- spontaneous emission

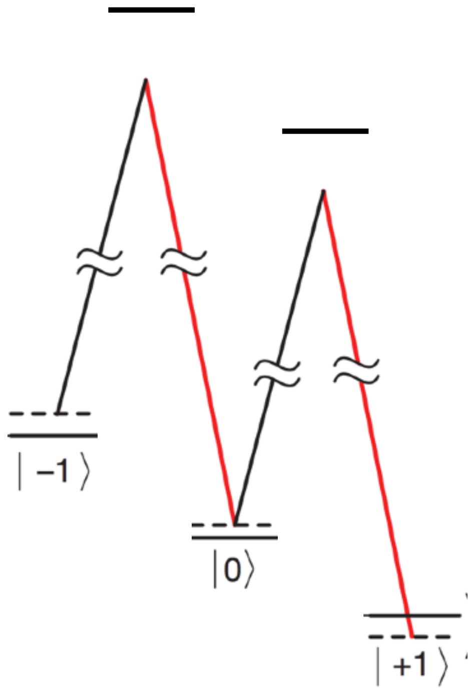


vortices in a BEC

Lin, Compton, Jimenez-Garcia, Porto, Spielman, Nature 462, 628 (2009)

Light-induced effective magnetic field





lowest dressed state

$$|d(\mathbf{r})\rangle = c_{-1}(\mathbf{r})|-1\rangle + c_0(\mathbf{r})|0\rangle + c_1(\mathbf{r})|1\rangle$$

experiences effective magnetic field

- can get large magnetic field
- ~~only over a narrow strip~~
- spontaneous emission

Cooper, PRL 106, 175301 (2011)

optical flux lattices

NOT in tight-binding limit

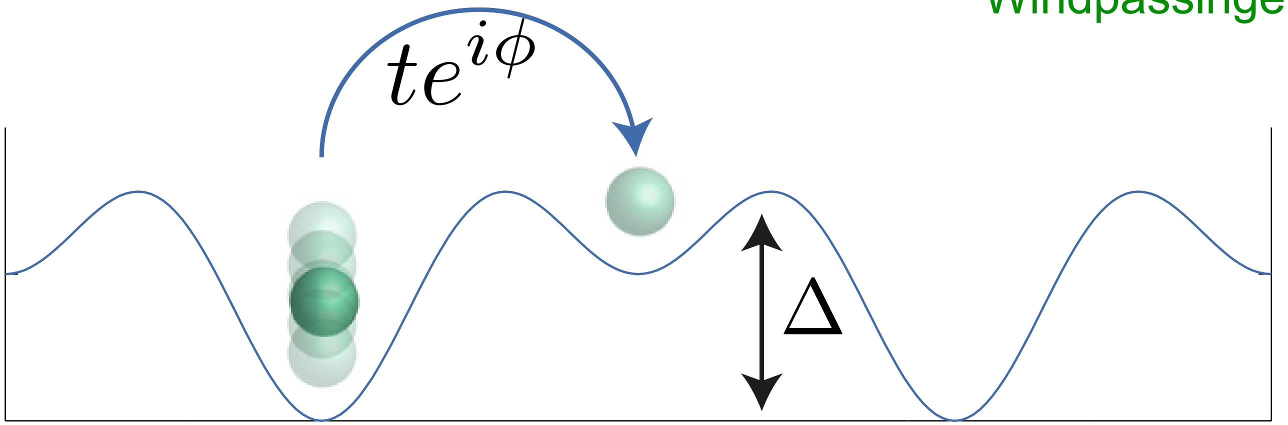
related expt: Sun et al (Pan), PRL 121, 150401 (2018)

Lin, Compton, Jimenez-Garcia, Porto, Spielman, Nature 462, 628 (2009)

Gauge fields in optical lattices

- shaking with momentum transfer

e.g. Struck,…, Lewenstein, Sengstock, Windpassinger, PRL (2012)

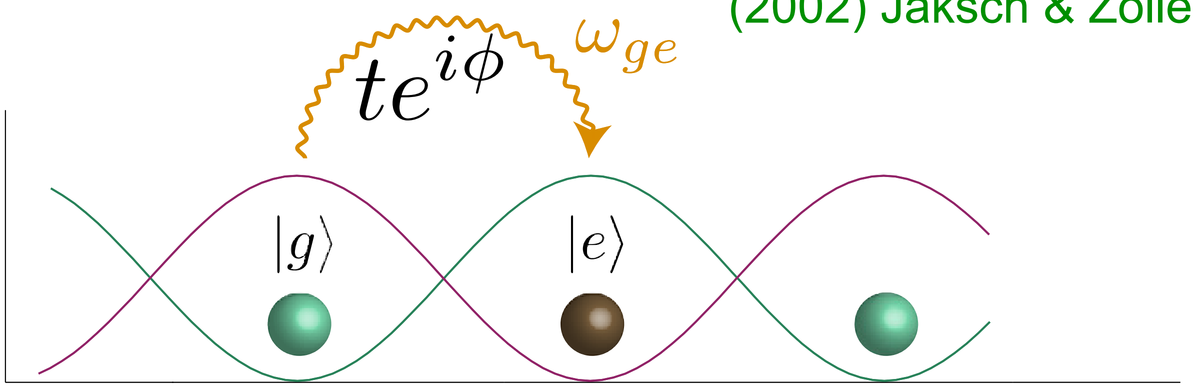


2D => magnetic field

Issue: heating, esp. with interactions ☹

- laser-assisted tunneling

Ruostekoski, Dunne, Javanainen PRL (2002) Jaksch & Zoller NJP (2003)



Issue: spontaneous emission ☹

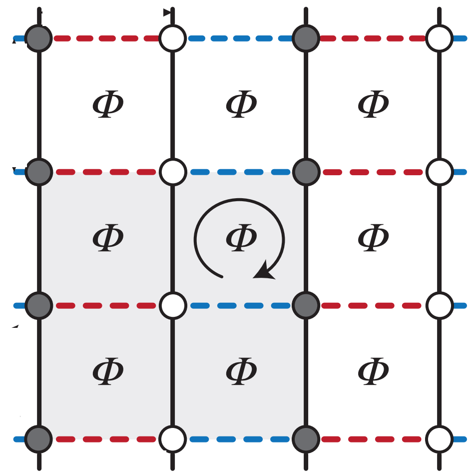
Experiments: Bloch, Spielman, Sengstock, Ketterle, Esslinger, Greiner, etc…

Review: Goldman, Juzeliunas, Ohberg, Spielman, Rep. Prog. Phys. 77, 126401 (2014)

Examples of lattices with topological bands

Hofstadter square lattice

Hofstadter PRB (1976)



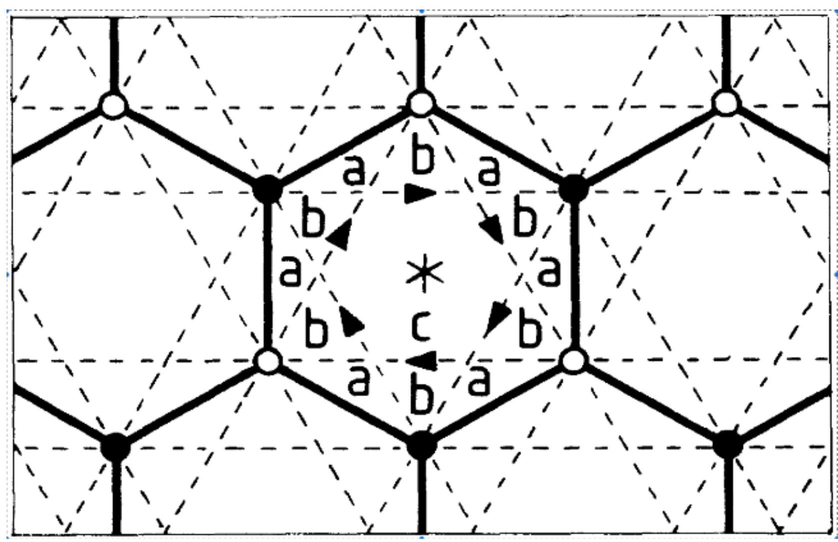
bosons, using laser-assisted tunneling

Aidelsburger, …, Cooper, Bloch, Goldman, Nature Phys. 11, 162 (2015) $(\Phi = \pi/2)$

Kennedy, Burton, Chung, Ketterle, Nature Phys. (2015) $(\Phi = \pi)$

Haldane model

Haldane PRL (1988)



fermions, using shaking

Jotzu, …,Esslinger, Nature 515, 237 (2014)

Measuring topological invariants (Bloch group)

- measure Chern number in Hofstadter band

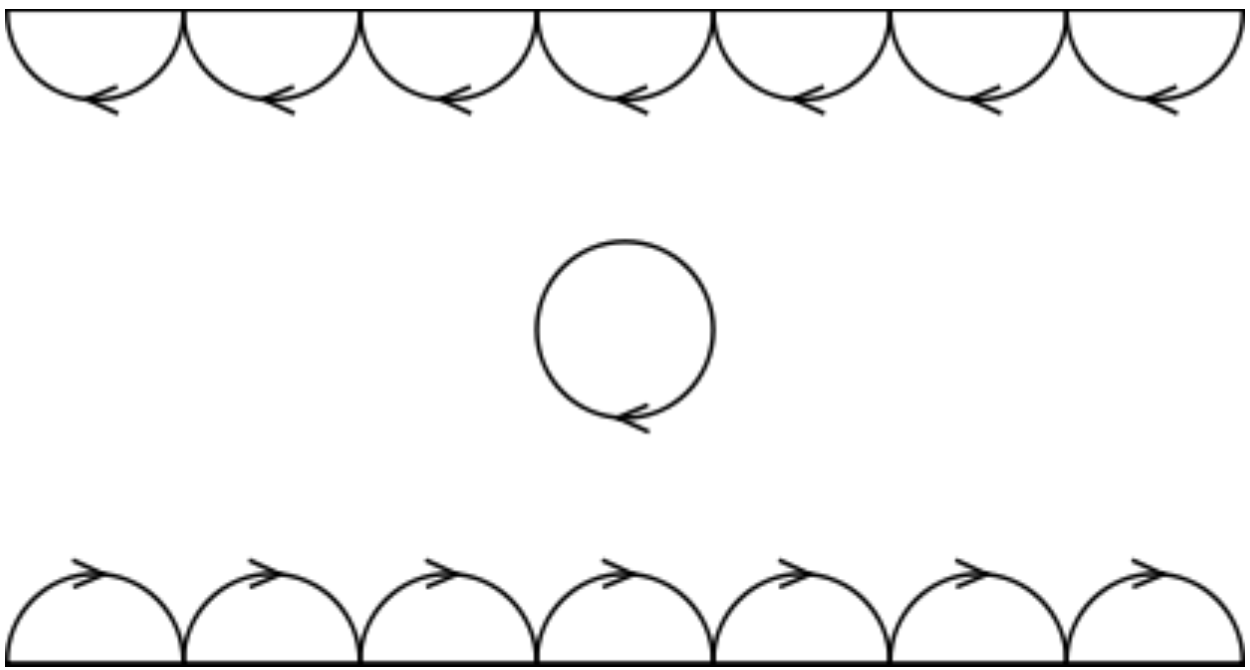
  Aidelsburger, …, Cooper, Bloch, Goldman, Nature Phys. 11, 162 (2015)

- measure Berry flux over entire Brillouin zone (hex. lattice)

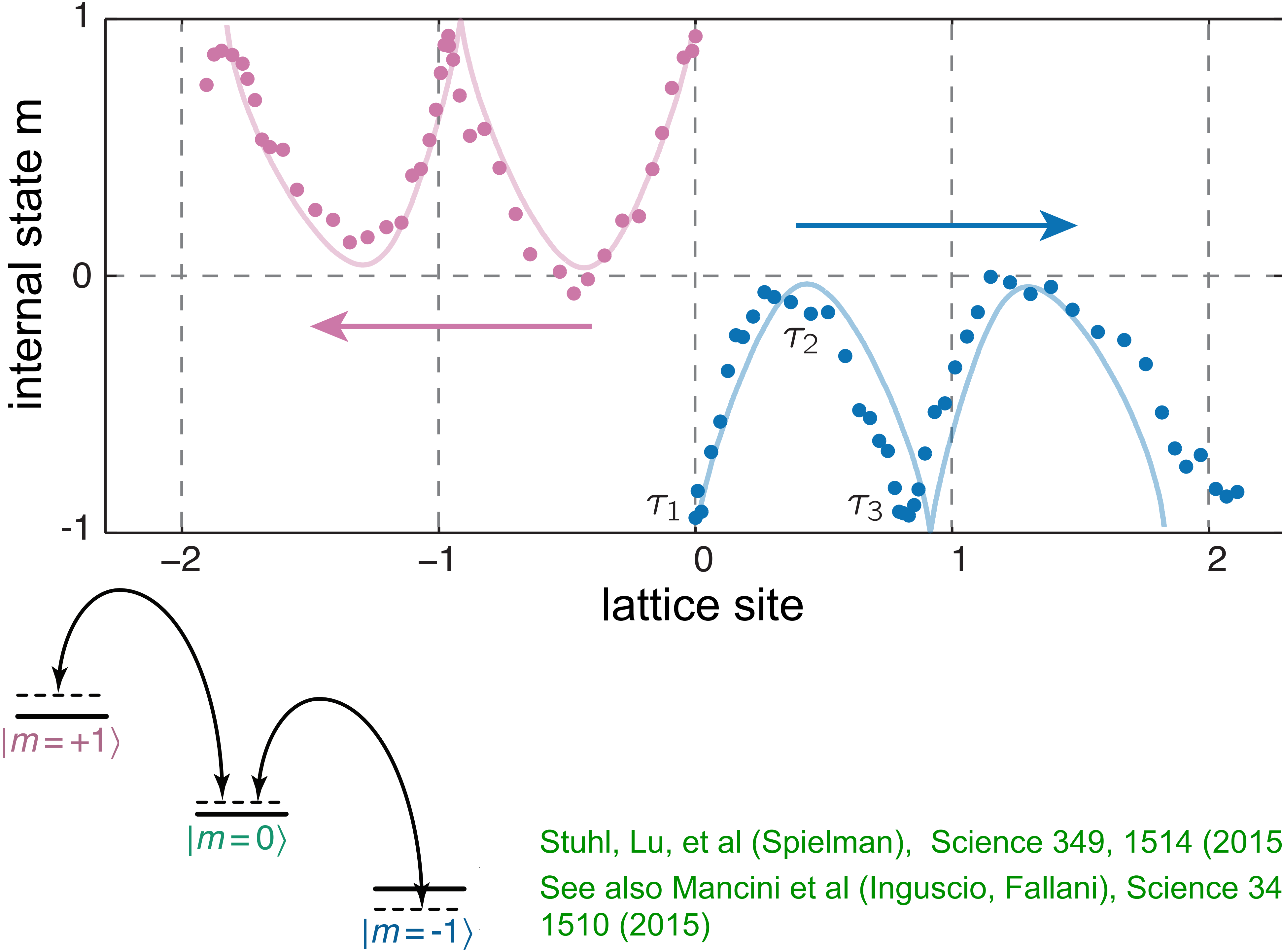
  Duca, …,Bloch, Schleier-Smith, Schneider, Science 347, 288 (2015)

- …

Skipping orbits



Skipping orbits with synthetic dimension

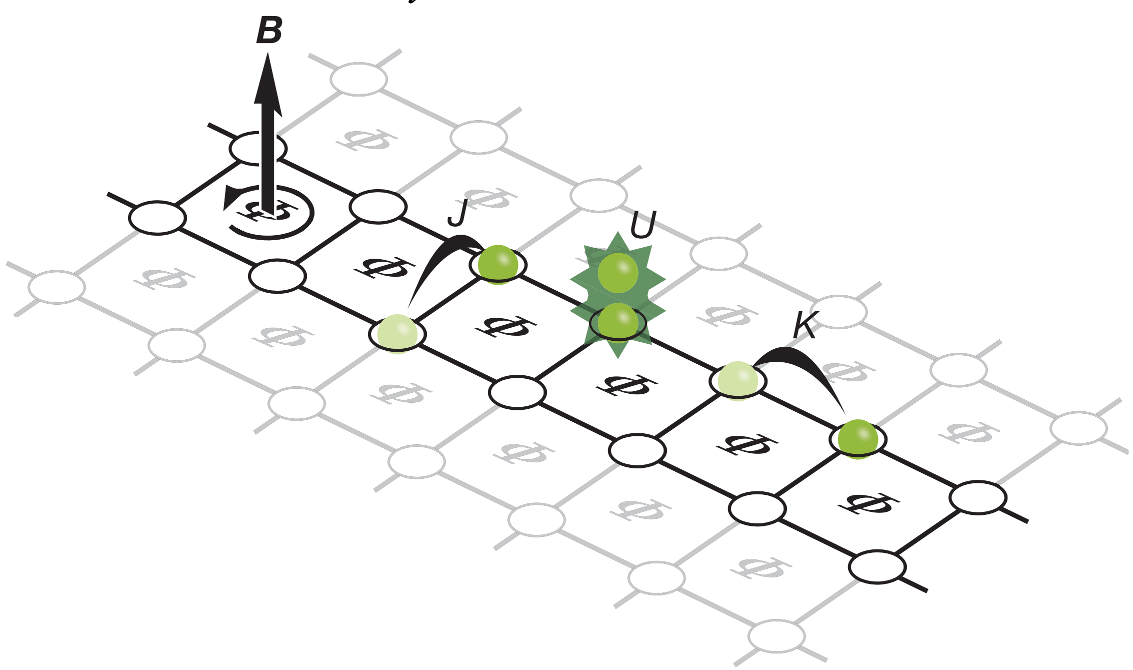


Stuhl, Lu, et al (Spielman), Science 349, 1514 (2015)

See also Mancini et al (Inguscio, Fallani), Science 349, 1510 (2015)

Interacting Harper-Hofstadter model in the two-body limit

$$\mathcal{H} = \frac{U}{2}\sum_{i,j} \hat{n}_{i,j}(\hat{n}_{i,j}-1) - \sum_{i,j}\left(K e^{-i\phi_{i,j}}\hat{a}^{\dagger}_{i+1,j}\hat{a}_{i,j} + J\hat{a}^{\dagger}_{i,j+1}\hat{a}_{i,j} + \text{h.c.}\right)$$



- 2 bosons on a ladder; using shaking
- K/h = 10 Hz, J/h = 30 Hz, U/h = 130 Hz
- actively pursuing FQH, but heating is an issue…

Tai et al (Greiner), Nature 546, 519-523 (2017)

Effective gauge fields for ultracold atoms

Outlook

- no IQH or FQH yet
- in principle, native weak 2-body interactions enough for FQH
  - e.g. Laughlin (Abelian), Moore-Read (Ising)

    Cooper, Dalibard PRL (2013), Sterdyniak, Bernevig, Cooper, Regnault (2015)

(• can engineer tunable 3-body interactions => tune Haldane pseudopotentials => exotic FQH states:

Graß et al (AVG), PRL 121, 253403 (2018))

- several groups actively pursuing FQH
  - challenges: heating and/or spontaneous emission
- preparation (esp for FQH) is non-trivial

  (- our work: scale-invariant cMERA for IQH

  Chu et al (AVG), PRL 122, 120502 (2019))

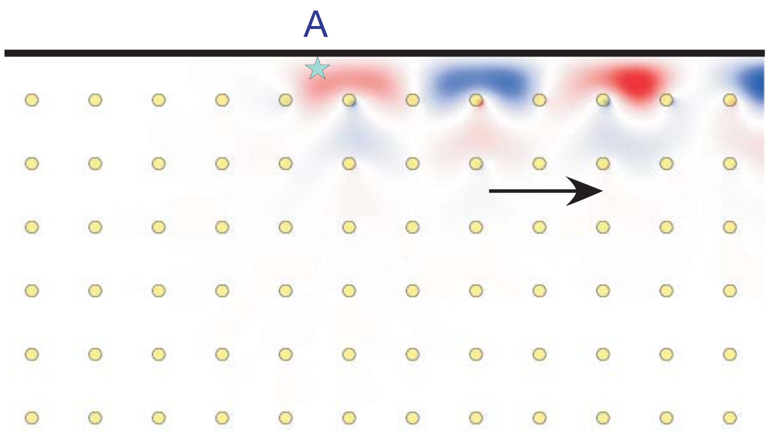
Topological photonic systems

Reviews: Hafezi, Taylor, Physics Today 67(5), 68 (2014)
Lu, Joannopoulos, Soljacic, Nature Photonics 8, 821 (2014)
Mittal, DeGottardi, Hafezi, Optics and Photonics News 29, 36 (2018)
Ozawa et al, Rev. Mod. Phys. 91, 015006 (2019)

Topological bands with microwave photons

• use photonic crystals

• chiral edge states

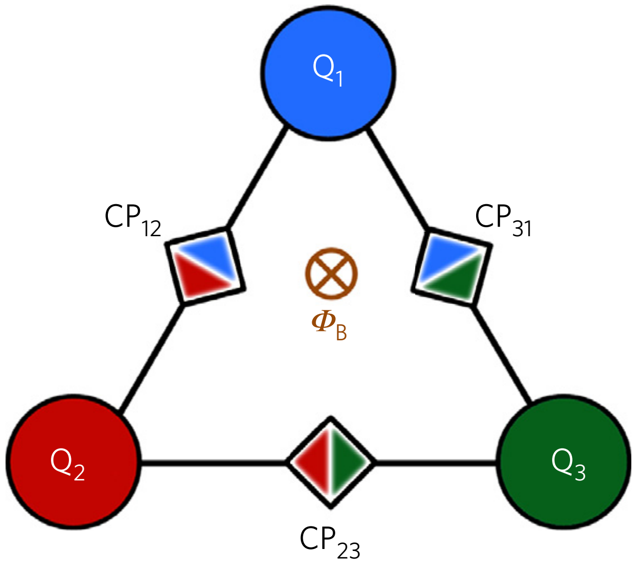


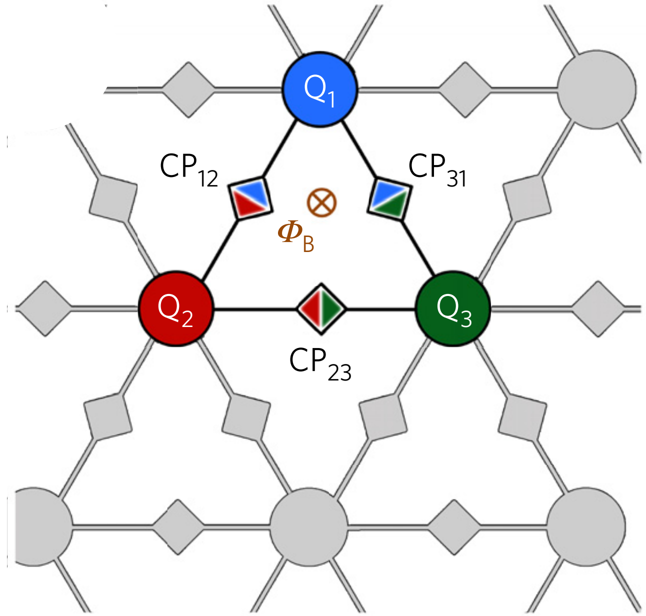
• lossy unless in superconducting circuits

Wang, Chong, Joannopoulos, Soljacic, Nature 461, 772 (2009)

See also: Ningyuan, Owens, Sommer, Schuster, Simon, PRX 5, 021031 (2015)
(Hofstadter model with radio-frequency photonic circuits)
Cheng, Jouvaud, Ni, Mousavi, Genack, Khanikaev, Nat. Mater. 15, 542 (2016)

Interacting microwave photons in a synthetic magnetic field



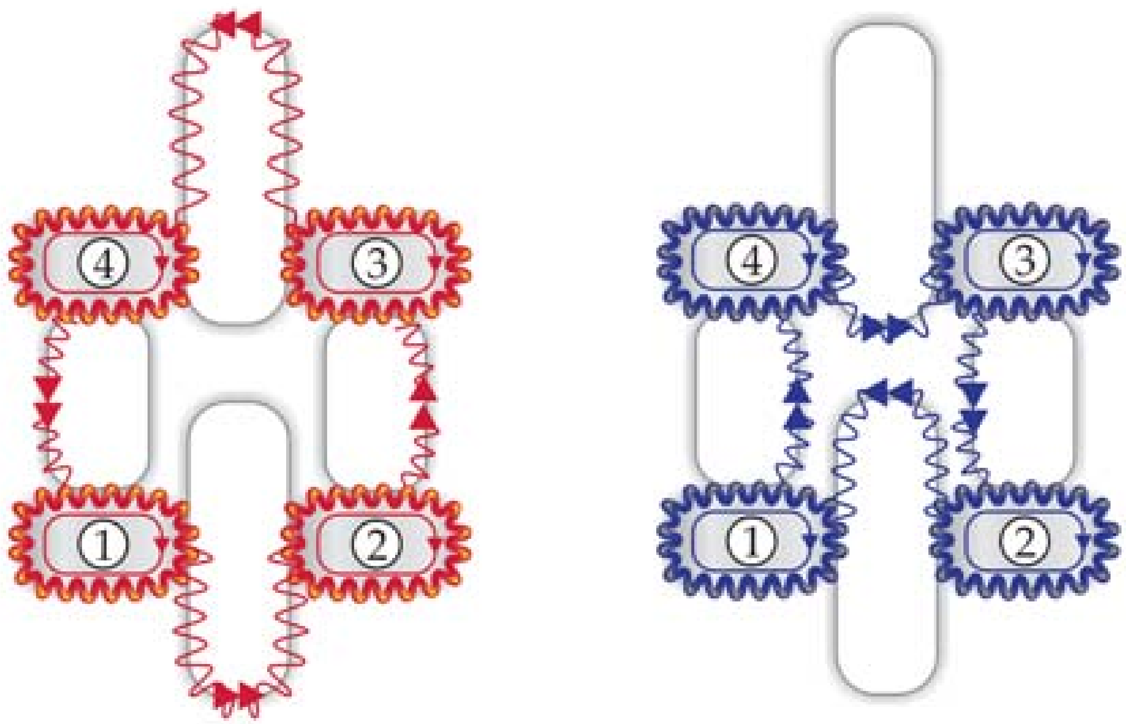


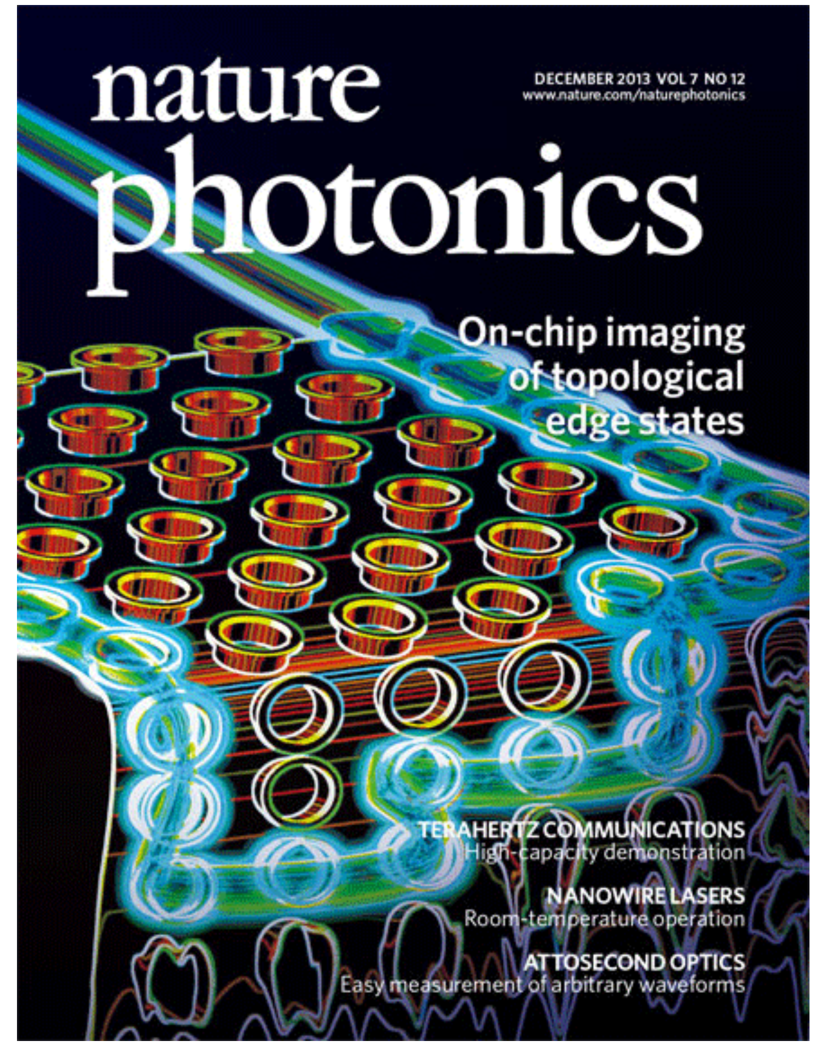
- 3 bosonic modes (microwave photons in a superconducting circuit)
- engineer flux by periodically modulating the coupling
- interactions = non-linearity due to Josephson junctions
- extension to lattice seems promising

Roushan et al (Martinis), Nature Physics 13, 146-151 (2017)

Topological bands with optical photons

- use ring resonators





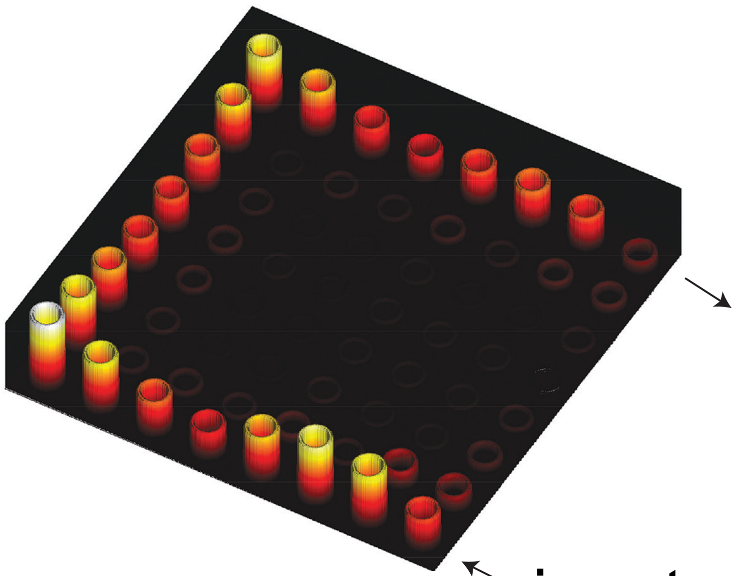
Hafezi, Mittal, Fan, Magdall, Taylor, Nat Photon. 7, 1001 (2013)

Also: Tzuang, Fang, Nuseenzveig, Fan, Lipson, Nat Photon. 8, 701 (2014)

Rechtsman, …,Segev, Szameit, Nature 496, 196 (2013)

Topological bands with optical photons

Simulation



Hafezi, Mittal, Fan, Magdall, Taylor, Nat Photon. 7, 1001 (2013)

Also: Tzuang, Fang, Nuseenzveig, Fan, Lipson, Nat Photon. 8, 701 (2014)
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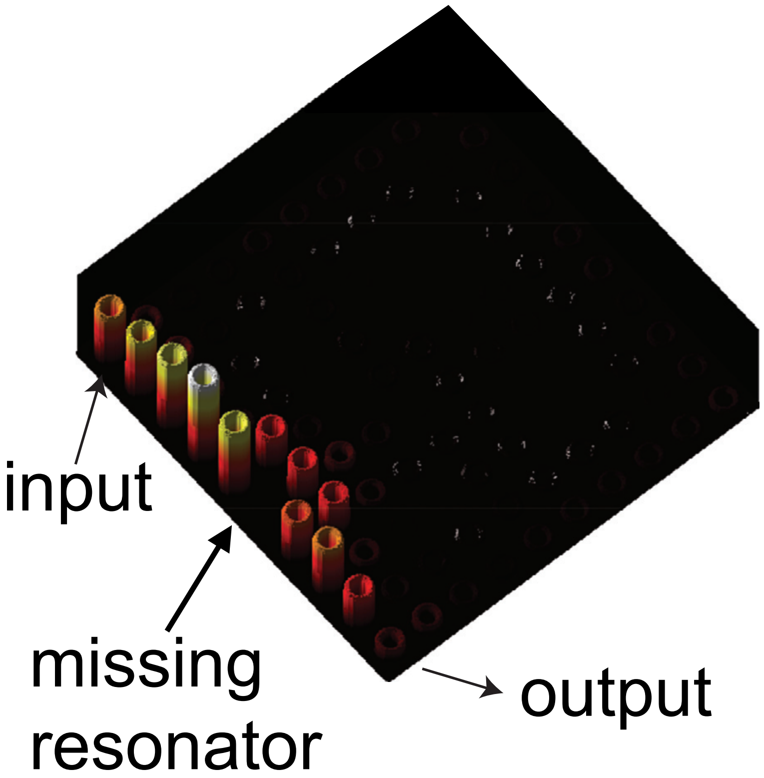
Topological bands with optical photons

Simulation



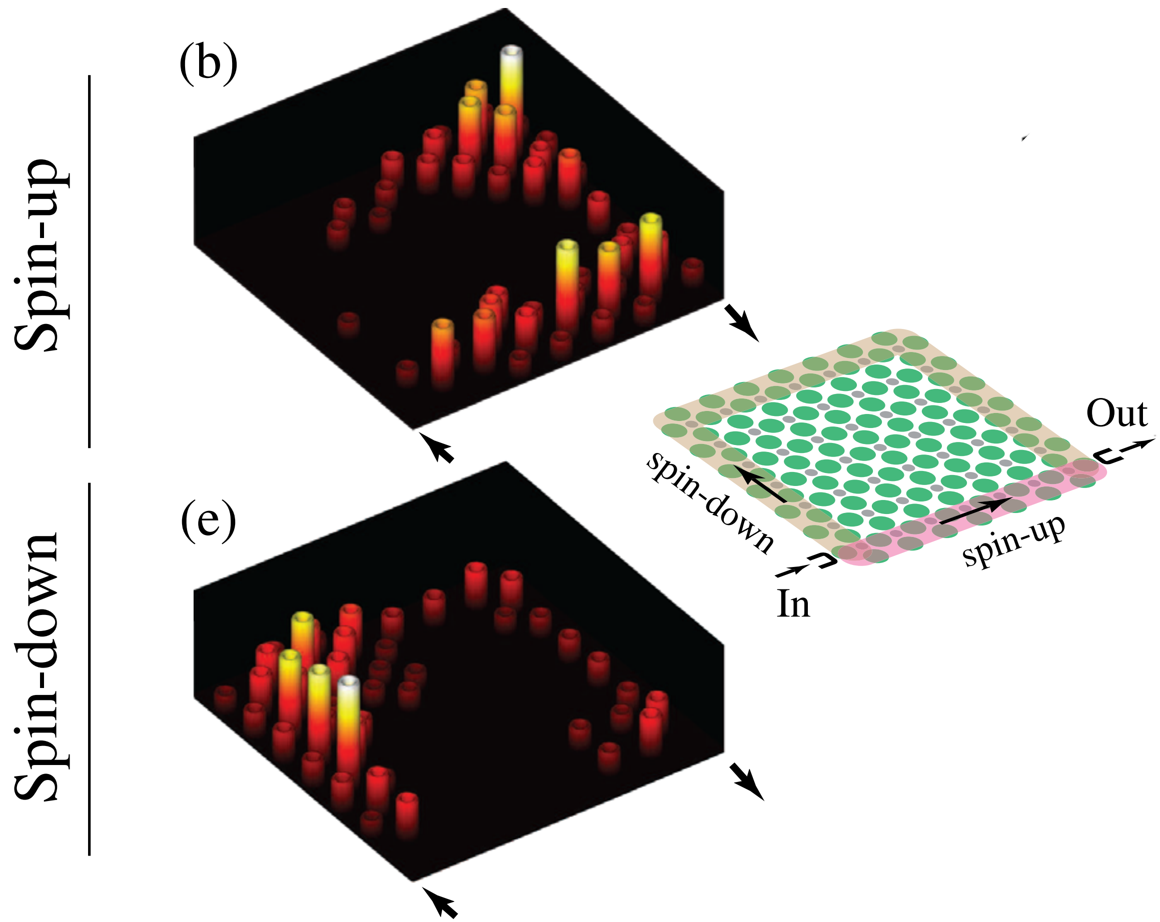
- invariant measured: Mittal et al (Hafezi), Nature Photonics 10, 180 (2016)

Hafezi, Mittal, Fan, Magdall, Taylor, Nat Photon. 7, 1001 (2013)

Also: Tzuang, Fang, Nuseenzveig, Fan, Lipson, Nat Photon. 8, 701 (2014)
Rechtsman, …,Segev, Szameit, Nature 496, 196 (2013)

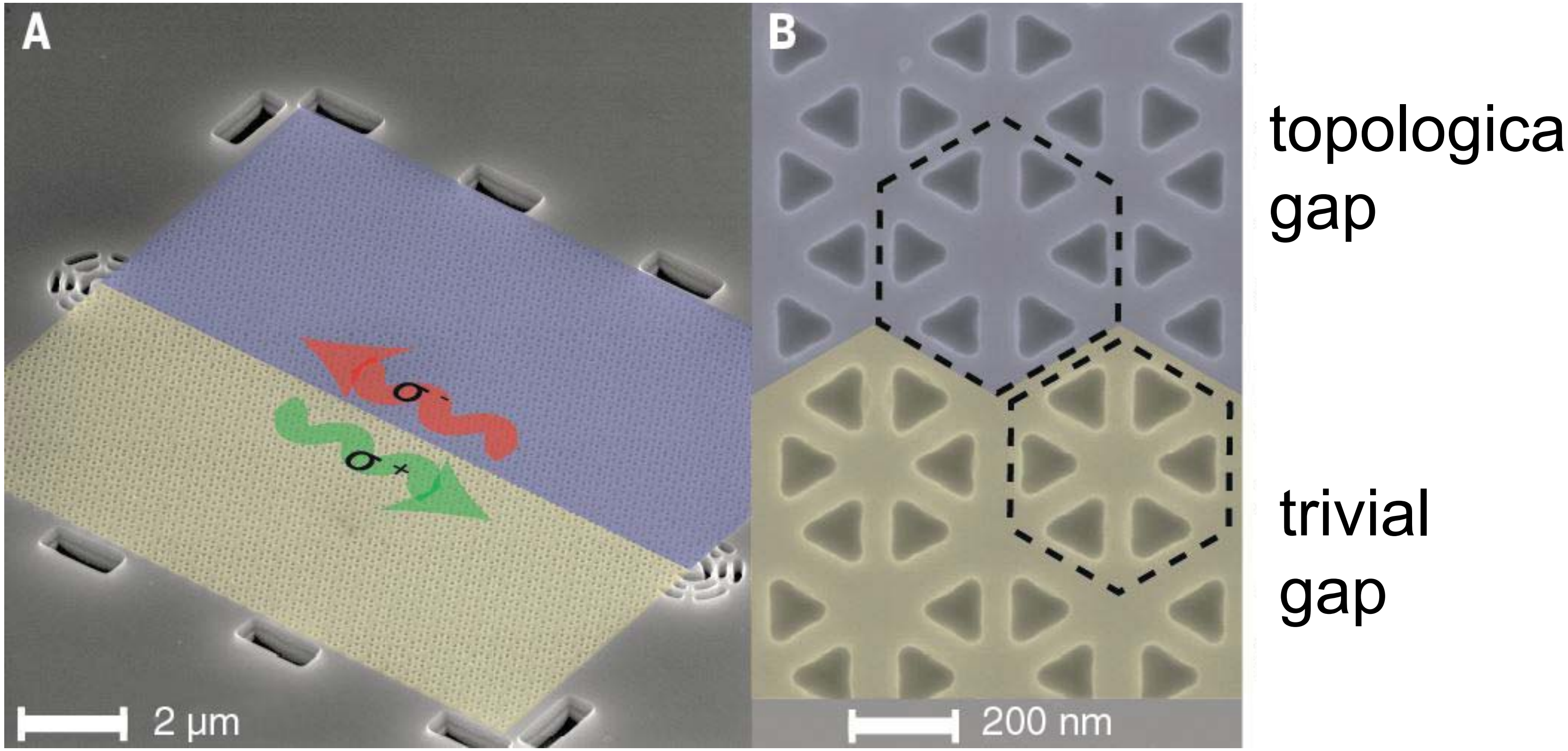
Topological bands with optical photons

Photonic Anomalous Quantum Hall Effect



Mittal, Orre, Leykam, Chong, Hafezi, Nat Photon. 7, 1001 (2013)

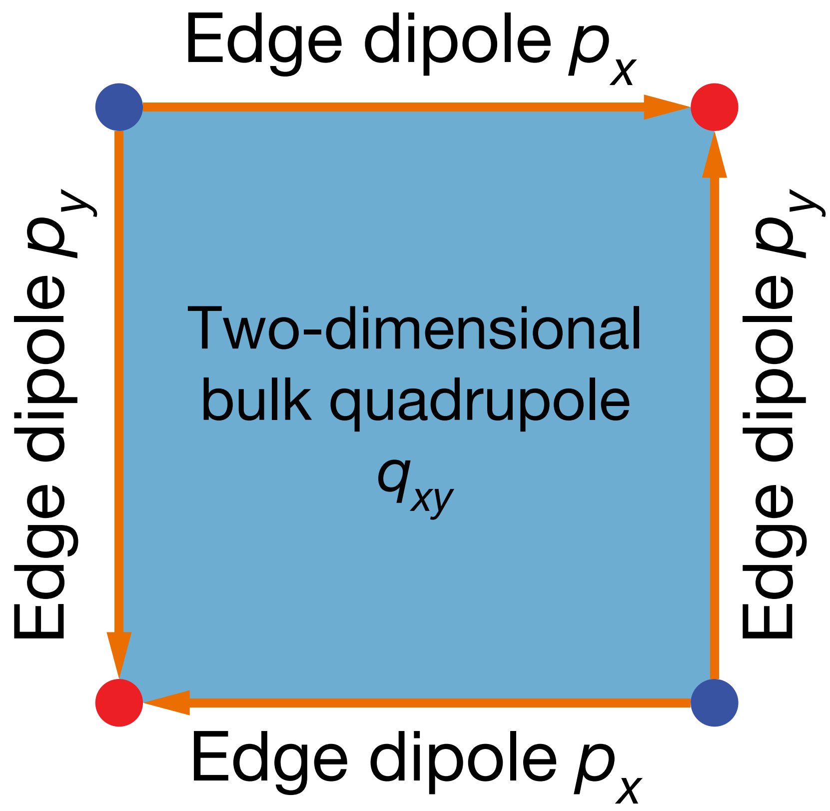
Topological bands with optical photons



- GaAs photonic crystal
- coupled one quantum dot to edge
- promising to couple many dots to get FQH-like physics

Barik et al (Hafezi, Waks), Science 359, 666 (2018)
Barik, Karasahin, Mittal, Waks, Hafezi, arXiv:1906.11263

Photonic quadrupole topological phases



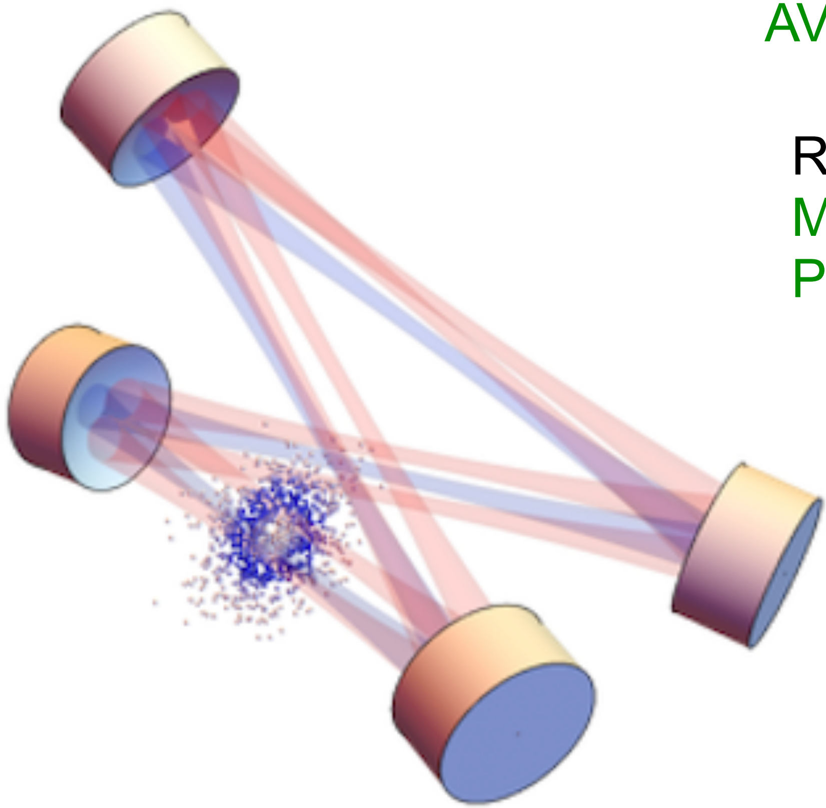
Microwave photons: - Peterson, Benalcazar, Hughes, Bahl, Nature (2018)
- Imhof et al (Molenkamp, Kiessling, Schindler, Lee, Greiter, Neupert, Thomale), Nature Phys (2018)

Optical photons: - Mittal et al (Hafezi), Nature Photonics (2019)

Observation of Laughlin states made of light

- Laughlin state for N=2 bosons
- gauge field: twisting an optical resonator
- interactions: dressing photons with Rydberg atoms

AVG et al, PRL 107, 133602 (2011)



Related theory - FQH states of Rydberg polaritons:
Maghrebi, Yao, Hafezi, Pohl, Firstenberg, AVG, PRA 91, 033838 (2015)

Engineering 3-body interactions:
Gullans et al (AVG), PRL 117, 113601 (2016)
Jachymski, Bienias, Büchler, PRL 117, 053601 (2016)

Clark, Schine, Baum, Jia, Simon, arXiv:1907.05872 (2019)
Clark, Jia, Schine, Baum, Georgakopoulos, Simon, Nature 571, 532 (2019)
Schine, Chalupnik, Can, Gromov, Simon, Nature 565, 173 (2019)
Schine, Ryou, Gromov, Sommer, Simon, Nature 534, 671 (2016)

Topological photonic systems

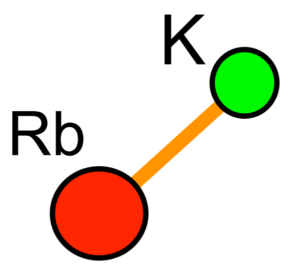
Outlook

- optical:
  - Simon’s Rydberg polariton approach promising
  - Hafezi-Waks photonic crystal approach promising
  - challenges: loss of photons, preparation, …
- microwave:
  - superconducting approach (Martinis experiment) promising
  - disorder an issue?
  - essentially qubits (spins)

Topological lattice-spin models

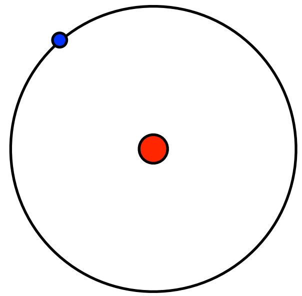
Lattice of dipoles

Electric



polar molecules

[Ye, Weidemuller, Inouye, Nagerl, Zwierlein, …]



Rydberg atoms

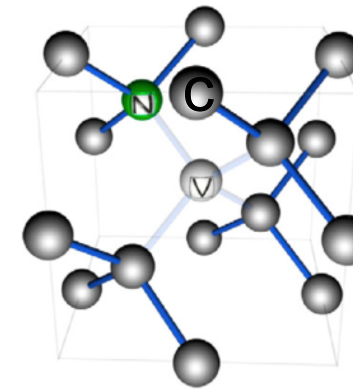
[Grangier, Saffman, Pfau, Weidemuller, Bloch, Lukin, Vuletic, Browaeys, etc…]

Magnetic

large electronic angular momentum J

magnetic atoms (e.g. Dy, Er, Cr)

[Lev, Ferlaino, Pfau, Laburthe-Tolra, etc...]



[drawn by Wrachtrup et al.]

NV centers

[Wrachtrup, Jelezko, Lukin, etc...]

- lots of topological proposals (Zoller, Buchler, Jaksch, Pupillo, Fleischhauer, Martin-Delgado, Yao, Hazzard, Lukin, AVG, etc…)

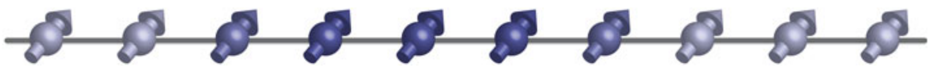
Some of our work:
- $\nu = 1/2$ Laughlin Yao et al, PRL 110, 185302 (2013)
- Kitaev honeycomb AVG et al, Mol. Phys. 111, 1908 (2013)
- bilayer FQH Yao et al, PRA 92, 033609 (2015)

- Rydberg experiments most advanced

Rydberg atoms in lattices

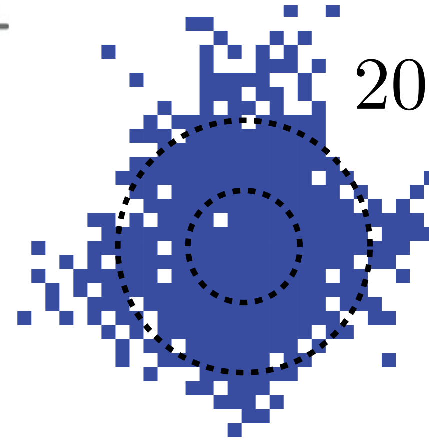
$$H = \sum_i (\Omega \sigma_i^x - \delta n_i) + \sum_{i \neq j} \frac{C_6}{2 r_{ij}^6} n_i n_j$$

10



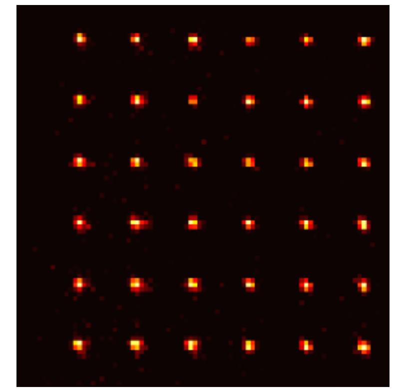
$$H = \sum_{i<j} \frac{J_0}{1 + r_{ij}^6 / R_c^6} \sigma_i^z \sigma_j^z$$

Zeiher et al (Bloch, Gross), PRX 2017



200

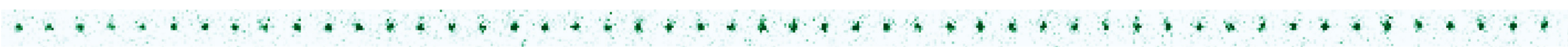
Guardado-Sanchez et al (Bakr), PRX 2018



36

Lienhard et al (Browaeys), PRX 2018

51

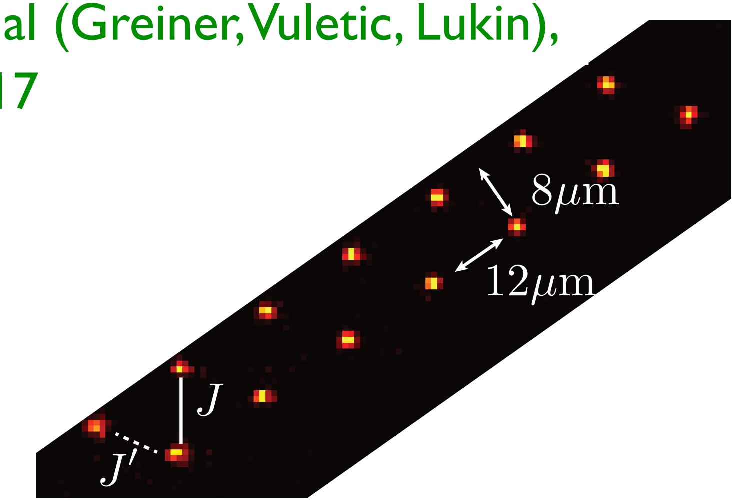


$$H = \sum_i (\Omega \sigma_i^x - \Delta n_i) + \sum_{i<j} \frac{C_6}{r_{ij}^6} n_i n_j$$

Bernien et al (Greiner, Vuletic, Lukin), Nature 2017

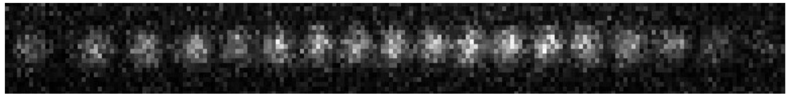
SSH with hardcore bosons on N = 14 sites

Léséleuc et al (Browaeys), Science 365, 775 (2019)



Spin models in ion crystals

chains



Monroe et al

$$H = B\sum_i \sigma_i^x + \sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$$

$$J_{i,j} \sim \frac{1}{|i-j|^\alpha} \quad 0 \le \alpha \le 3$$

- other spin-1/2 models (theory)

  Porras, Cirac, PRL 92, 207901 (2004)

- arbitrary $J_{i,j}$ (theory)

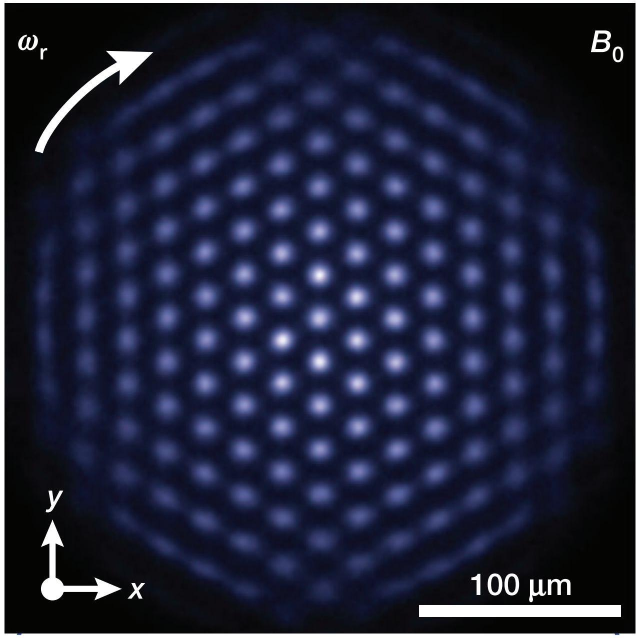
  Korenblit,…, Monroe, NJP 14, 095024 (2012)

- spin-1 (experiment)

  Senko,…, Monroe, PRX 5, 021026 (2015) [Theory: Retzker et al]

- topo theory papers: Porras, Cirac, Solano, Hauke, Grass, AVG,…

2D crystals



Britton, …, Bollinger, Nature 484, 489 (2012)

$$H = B\sum_i \sigma_i^x + \frac{1}{2}\sum_{i\neq j} J_{i,j}\sigma_i^z\sigma_j^z$$

$$J_{i,j} \sim \frac{1}{|\mathbf{r}_i-\mathbf{r}_j|^\alpha} \quad 0 \le \alpha \le 3$$

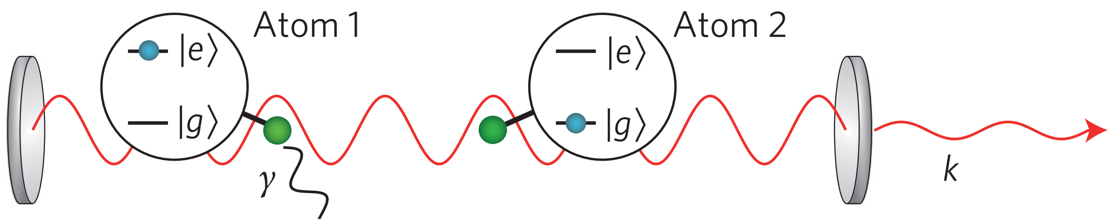
Photon-mediated spin models

before: qubits provide non-linearities for photons

now: photons eliminated to get spin model on qubits

optical

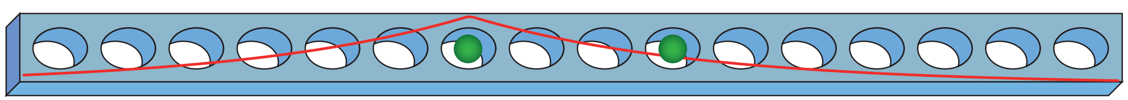
microwave superconducting



[e.g. Lev, Schleier-Smith, …]

same idea

more control near band edge:



1D theory: e.g. Douglas, Habibian, Hung, AVG, Kimble, Chang, Nature Photon. 9, 326 (2015)

2D theory: González-Tudela et al, Nat. Photon. 9, 320 (2015)

1D expt: Hood et al (Kimble), PNAS 113, 10507 (2016)

Review: Chang et al, Rev. Mod. Phys. 90, 031002 (2018)

Review: Houck, Tureci, Koch, Nature Phys. 8, 292 (2012)

1D expt: Sundaresan et al (AVG, Houck), PRX 9, 011021 (2019)

Topological phases with AMO spins

Outlook

- no topological phases yet except for 1D SPT with Rydbergs
- probably soon, especially Rydbergs
- what are effects of long-range interactions?

  e.g.:
  Gong, Maghrebi, Hu, Wall, Foss-Feig, AVG, PRB 93, 041102(R) (2016)
  Gong, Maghrebi, Hu, Foss-Feig, Richerme, Monroe, AVG, PRB 93, 205115 (2016)

- digital simulation on a quantum computer?

Thank you

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$$$: DoE ASCR Quantum Testbed Pathfinder, NSF PFCQC, NSF PFC@JQI, AFOSR, ARO MURI, ARL CDQI, DoE BES QIS

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