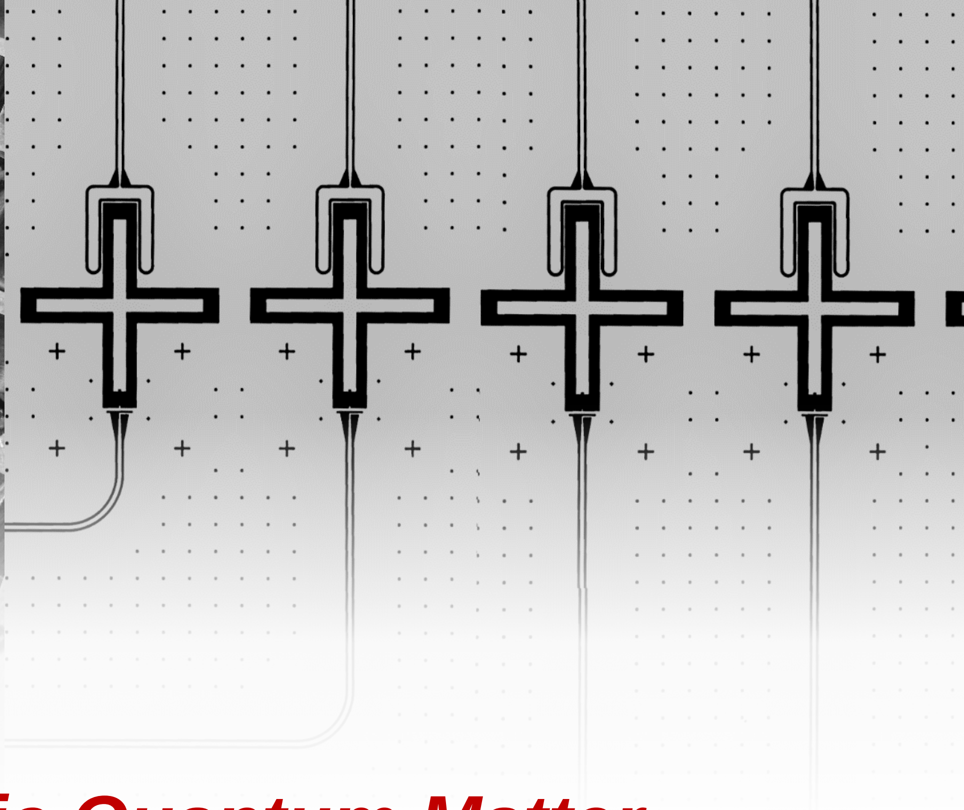



Exploring Synthetic Quantum Matter in Superconducting Circuits

Alex Ruichao Ma

Department of Physics and Astronomy, Purdue University

PQSEI Tuesday, 10/29/2019

Understanding strongly-correlated quantum materials

Synthetic quantum materials

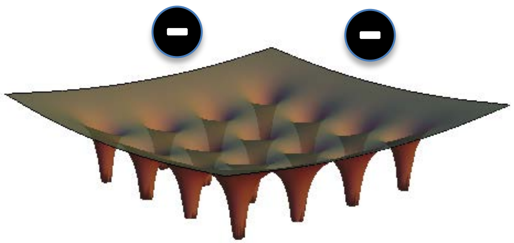
Engineered quantum systems … *as quantum simulators*

(more than just simulate!)

Platforms: cold atoms, trapped ions, photonics, defect centers, quantum dots, etc.

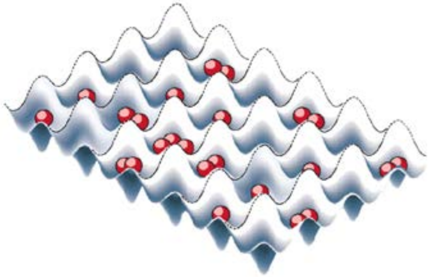
Solid State

Interacting electrons in ionic lattice



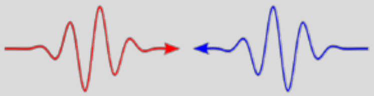
Ultracold Atoms

Interacting atoms in optical lattice



Photonics

Interacting photons in superconducting microwave lattices



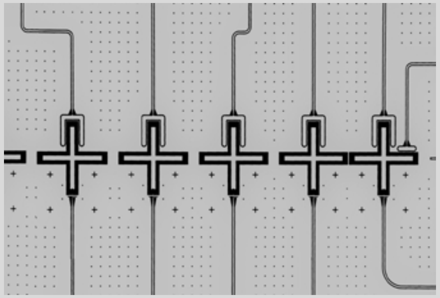
See e.g. Nat Phys: Insight - Quantum Simulation (2012); 'The rise of quantum materials' (2016)

Outline

Why photons, why superconducting circuits?

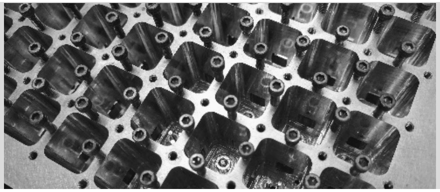
Building the circuit quantum matter platform

- Building a Bose-Hubbard lattice
- Control and characterization



- A reservoir for photons
- Populate many-body states (Mott insulator)

Creating a topological lattice



Summary & Outlook

Photonic synthetic quantum materials

Why microwave photons in circuits?

Engineer/control the quantum Hamiltonians:

- **Long lifetime**

  Up to seconds in superconducting cavities
- **Strong interaction**
  MHz – GHz (t ~ ns) with the circuit QED toolbox
- **Flexibility of "printed circuits"**
  engineer geometry, topology, interactions…

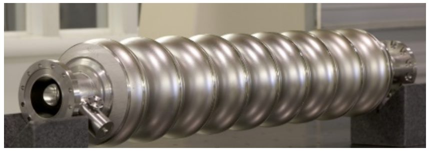
Measuring the states:

- **Spectroscopy**
- **Microscopy +**

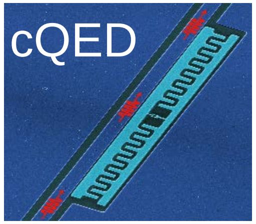
State preparation:

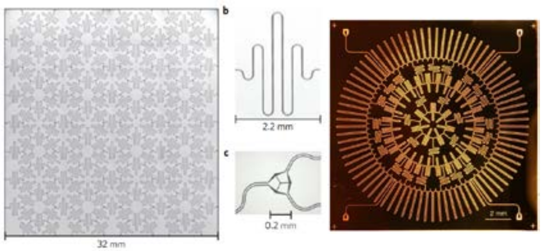
- **Intrinsically lossy:**
  no photon number conservation

→ How to populate a many-body phase?

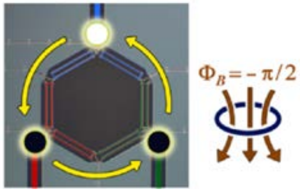


SRF cavity, FermiLab





Houck (Princeton)



Martinis (Google/UCSB)

Quantum simulation with photons:
Houck, Türeci & Koch, *Nature* (2012); Carusotto & Ciuti, *RMP* (2013);
Hartmann, *J. Opt.* (2016); Noh & Angelakis, *RPP* (2016); etc.

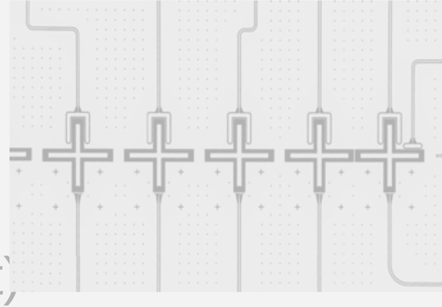
Outline

Why photons, why superconducting circuits?

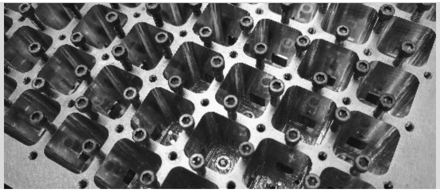
Building the circuit quantum matter platform

- Building a Bose-Hubbard lattice
- Control and characterization

- A reservoir for photons
- Populate many-body states (Mott)

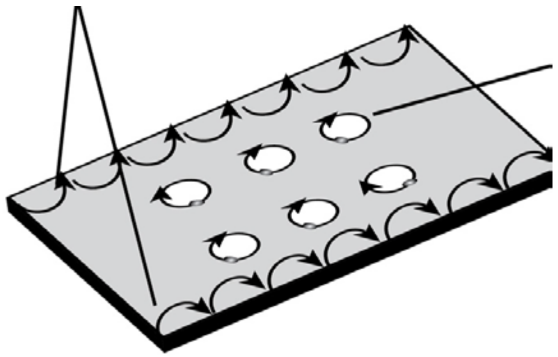


Creating a topological lattice



Summary & Outlook

Creating effective B field for photons

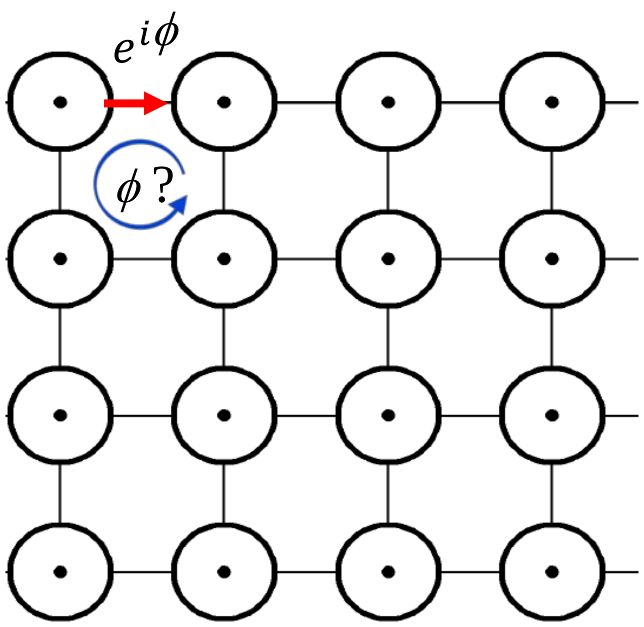


Effective magnetic field on lattice:

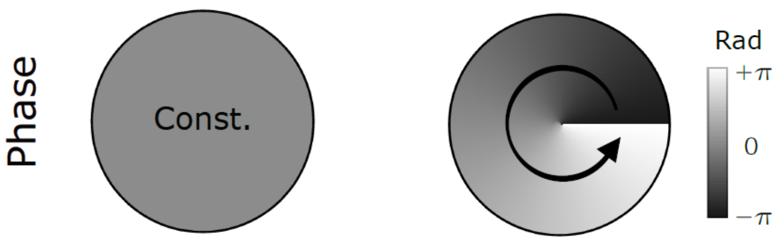
Non-reciprocal Peierls phase going around a plaquette

Usually: Phase from tunneling

Here: from on-site mode structure



"S" "P" (x+iy)



Cho, Angelakis, Bose, PRL **101**, 246809

B. Anderson *et al.*, PRX **6**, 041043 (2016)

Ultracold atoms: Spielman, Bloch, Ketterle etc.

Creating effective B field for photons

Effective magnetic field on lattice:

Non-reciprocal Peierls phase going around a plaquette

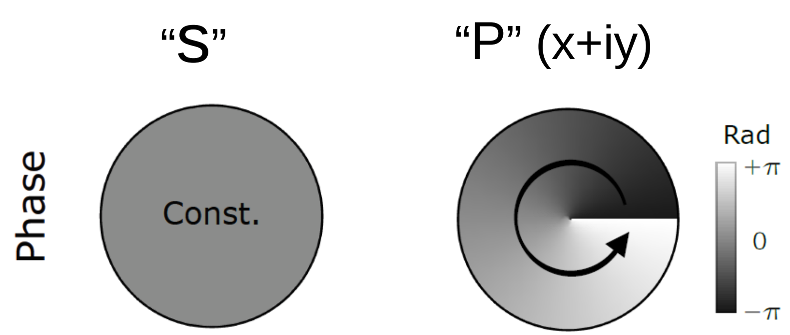
Hofstadter model

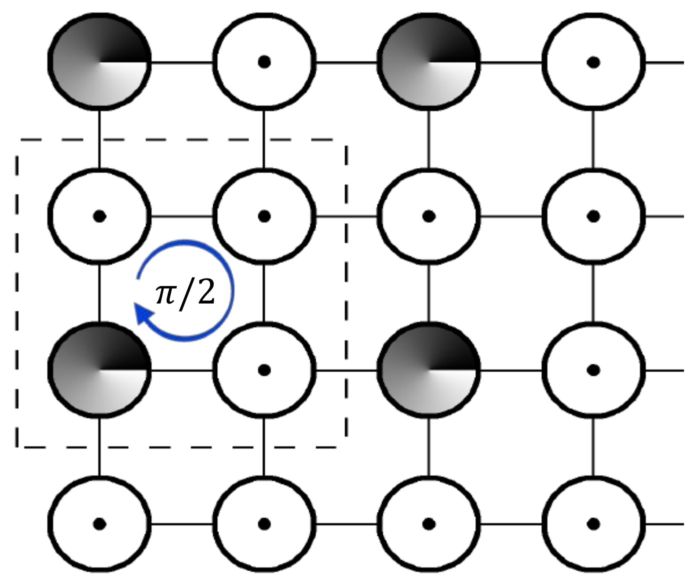
(α=1/4, uniform flux)

Chern insulator

Usually: Phase from tunneling

Here: from on-site mode structure



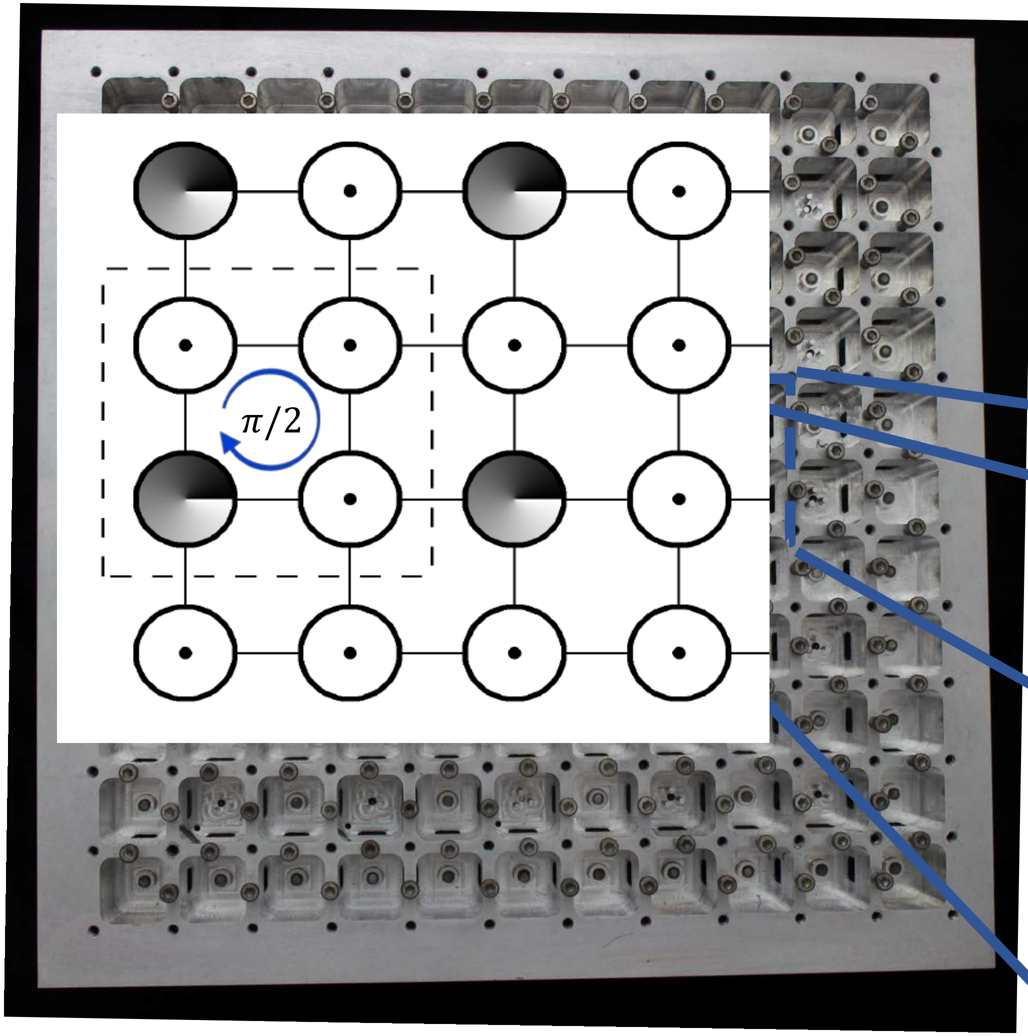


Cho, Angelakis, Bose, PRL **101**, 246809

B. Anderson *et al.*, PRX **6**, 041043 (2016)

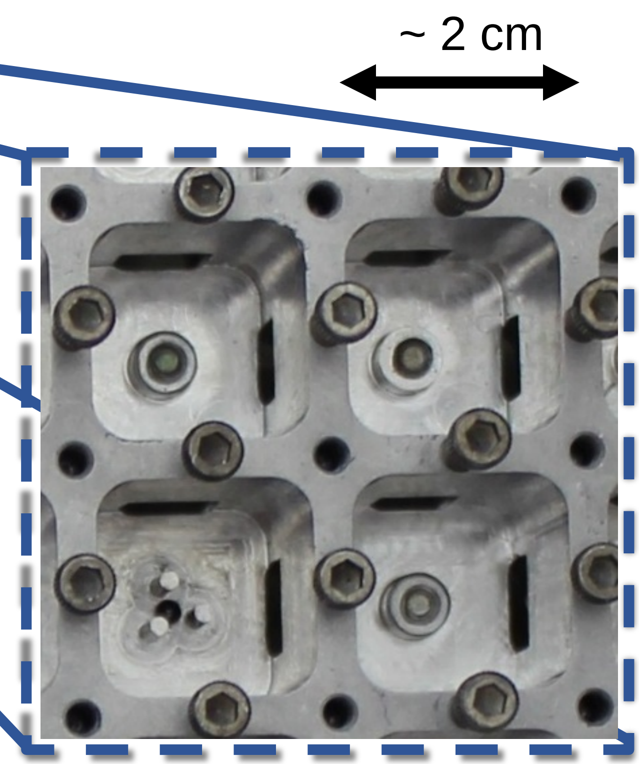
Ultracold atoms: Spielman, Bloch, Ketterle etc.

Building a microwave Chern insulator



Hofstadter lattice, α = 1/4

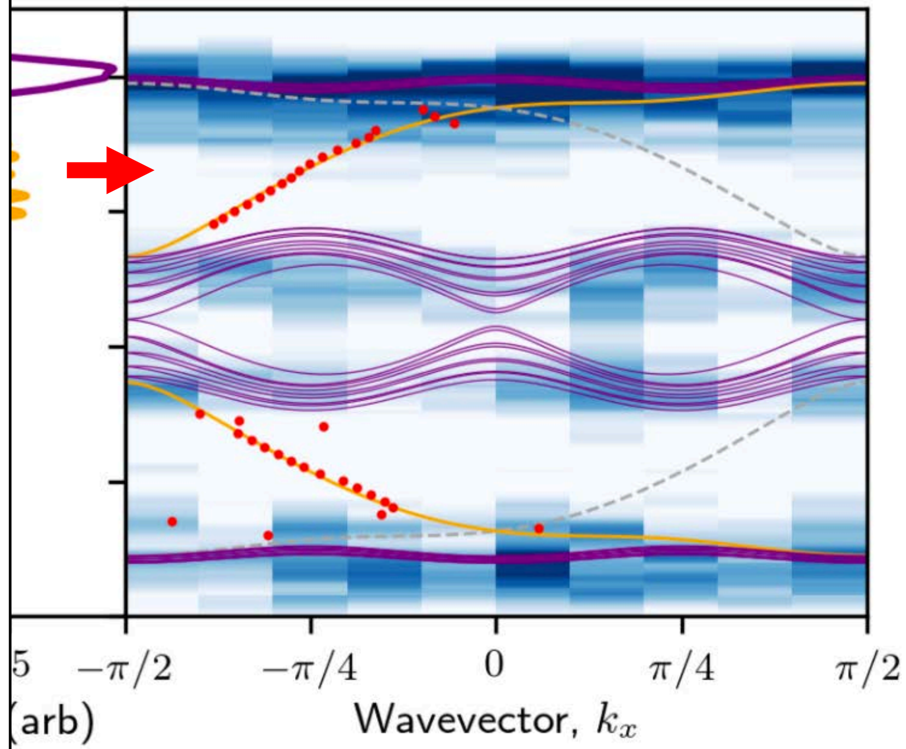
- Full tunable onsite + tunneling
- Site- & Time- resolved readout



C Owens,…, R Ma, J Simon, DI Schuster, *PRA* 97, 013818 (2018);
BM Anderson, R Ma, …, *PRX* 6, 041043 (2016); *Prev. related*: Wang, Joannopoulos, & Soljačić (MIT)

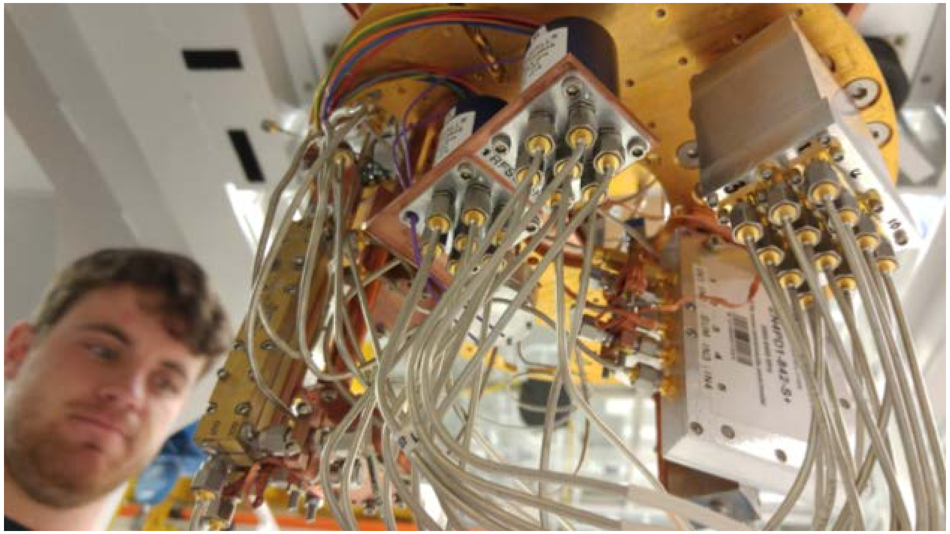
Observing protected edge states

Hofstadter lattice, α = 1/4



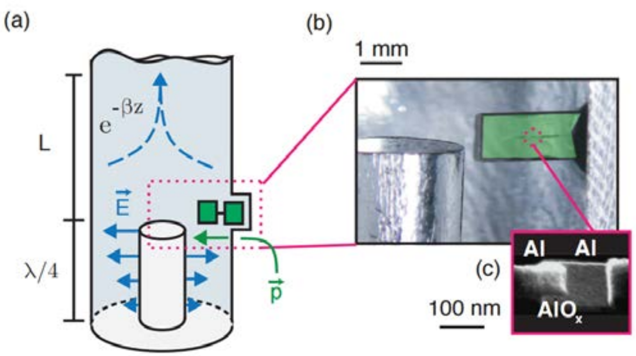
C Owens,…, R Ma, J Simon, DI Schuster, *PRA* 97, 013818 (2018)
BM Anderson, R Ma, …, *PRX* 6, 041043 (2016)

Towards strong interactions



Site resolved readout of 2D lattice

Q> 200k at 20mK



Reagor *et al.*, PRB (2016)

Interacting quantum regime –

- High coherence superconducting lattice
- Superconducting qubit mediated interaction

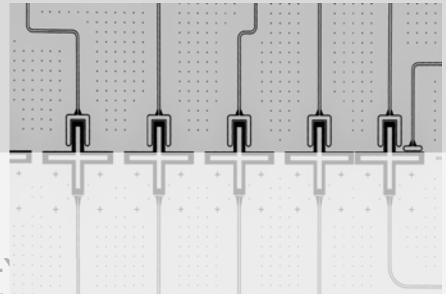
  - interacting edge channel (dynamics, correlated states)
  - full interacting lattice: bosonic FQH physics

Outline

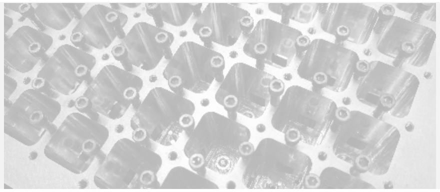
Why photons, why superconducting circuits?

Building the circuit quantum matter platform

- Building a Bose-Hubbard lattice
- Control and characterization
- A reservoir for photons
- Populate many-body states (Mott)



Creating a topological lattice

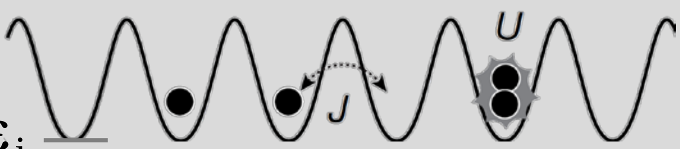


Summary & Outlook

Bose Hubbard model

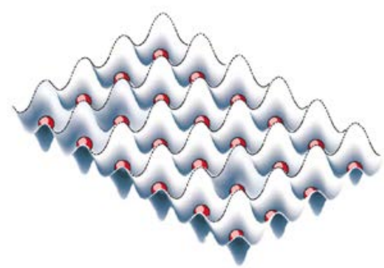
on-site interaction

Local offset ε_i



Tunneling

Superfluid $(J >> U)$



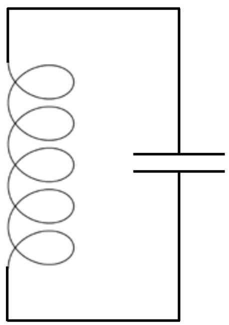
Mott insulator $(J << U)$

Gersch & Knollman (1963); Fisher, Grinstein & Fisher (1989); Jaksch & Zoller (2005).

A lattice site for photon

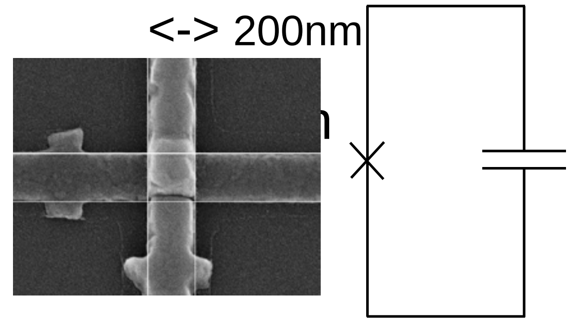
Linear L-C Resonator

Constant L



Non-Linear L-C Resonator

<-> 200nm



Al/AlOx/Al

“transmon qubit”

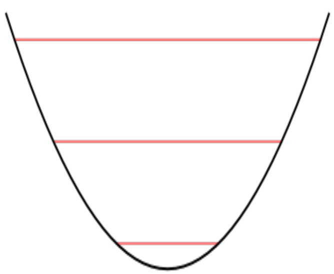
Interaction:

U **= -300MHz**

2 photons

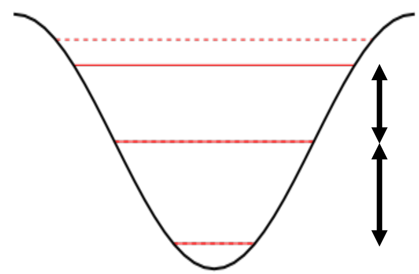
1 photon

0 photon



5 GHz

5 GHz

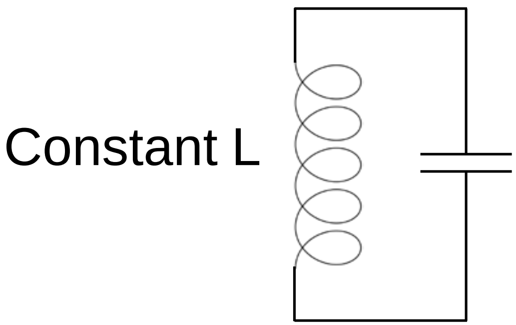


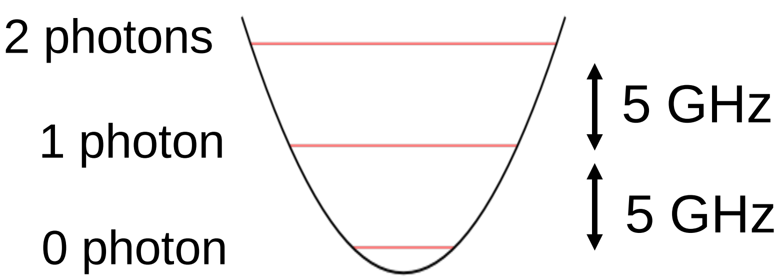
4.7 GHz

5 GHz

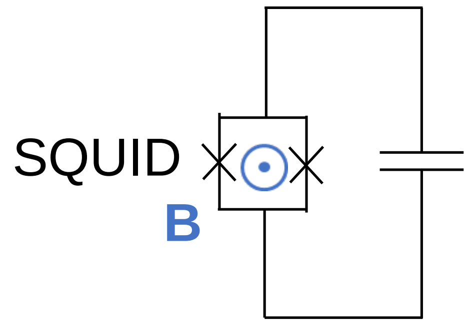
Building a lattice site

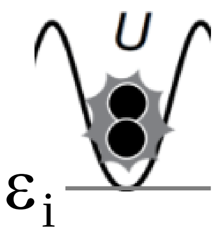
Linear L-C Resonator

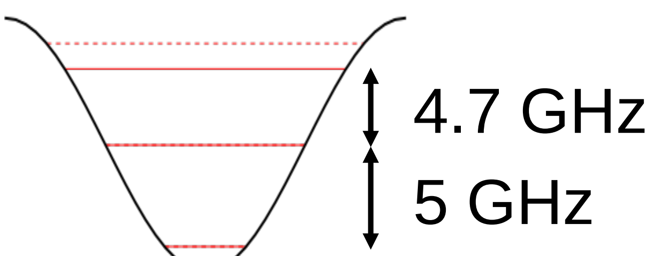




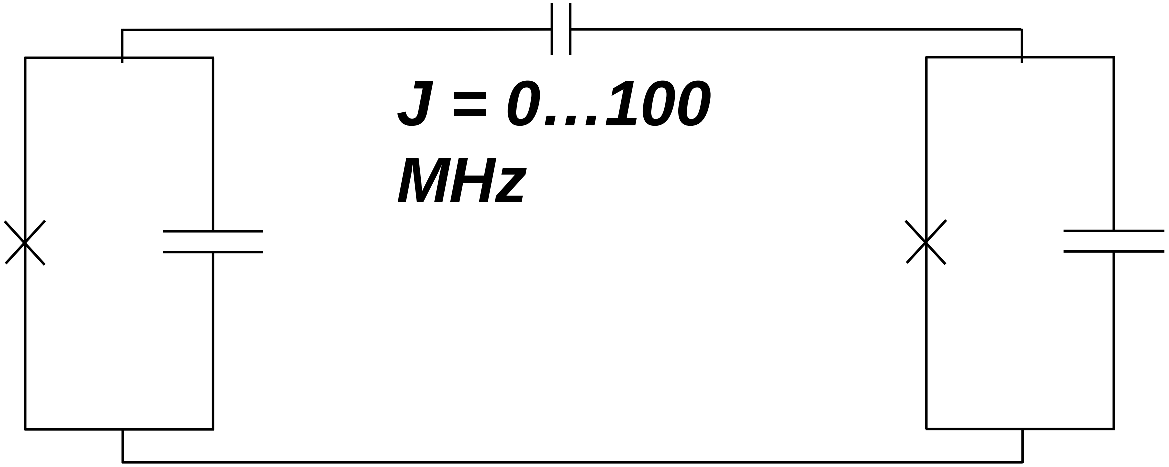
Non-Linear L-C Resonator

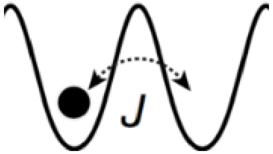




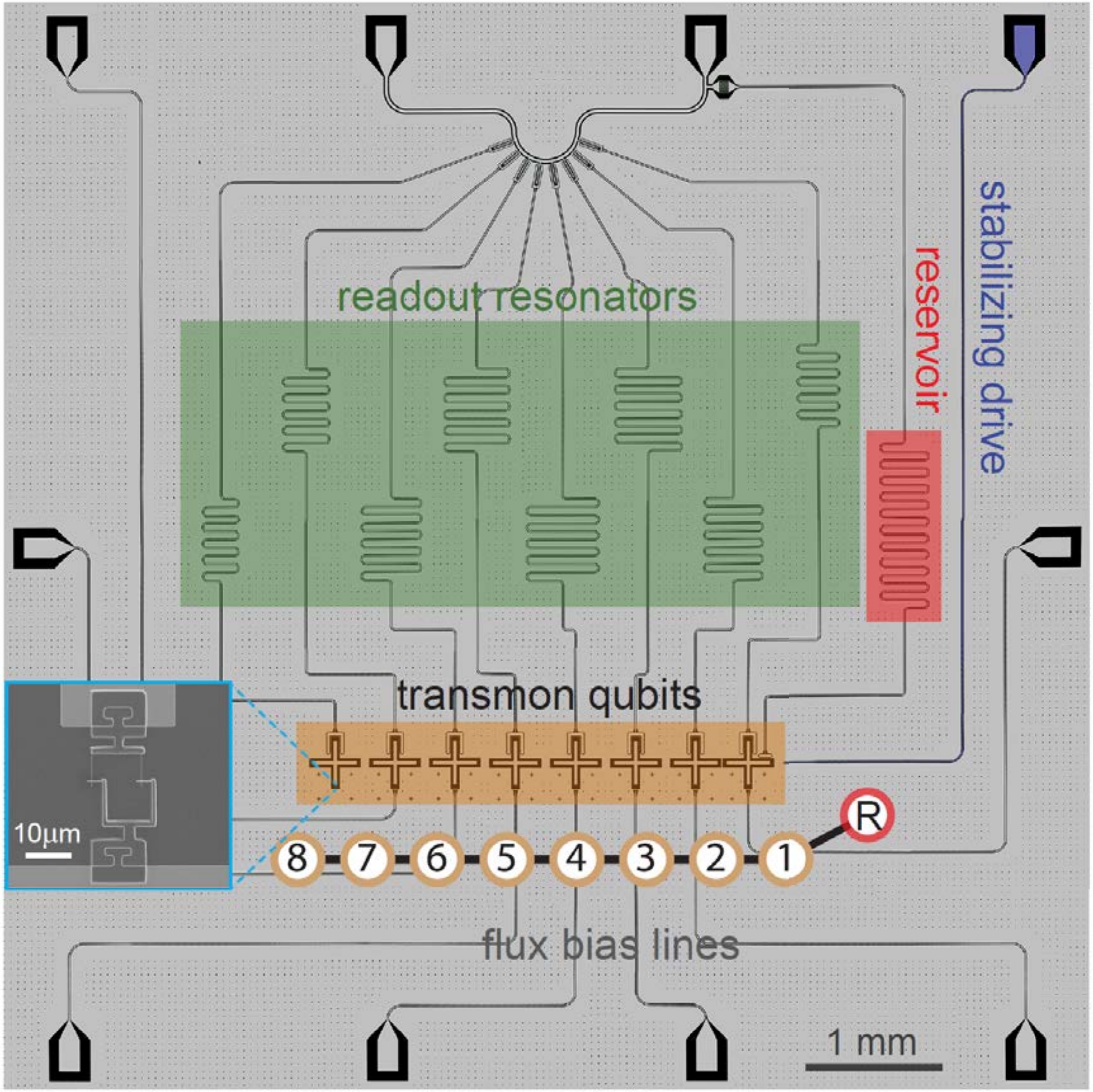


Tunnel coupling





Our circuit Bose Hubbard lattice



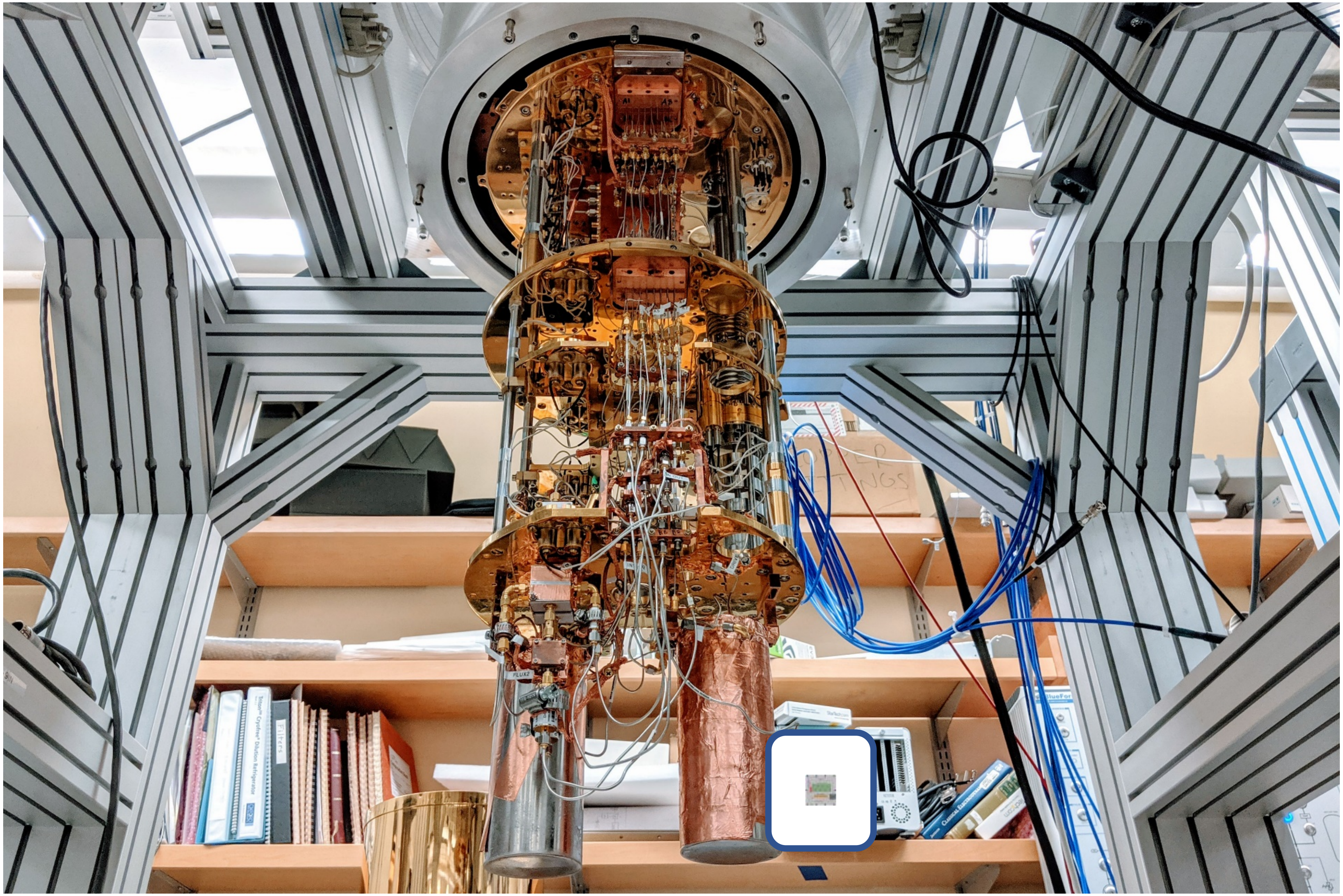
@ 20mK in dilution fridge
Patterned Nb on Sapphire, Al JJs

- BH lattice, |U|>> J
- Dynamically tunable on-site energies
- Site resolved readout
- Engineered reservoir

R. Ma et al., *Nature* 566, 51–57 (2019).

Xmon lattice: UCSB/Google - P. Roushan et al., Science (2017); BH in 3D cQED: Hacohen-Gourgy et al., PRL (2015)

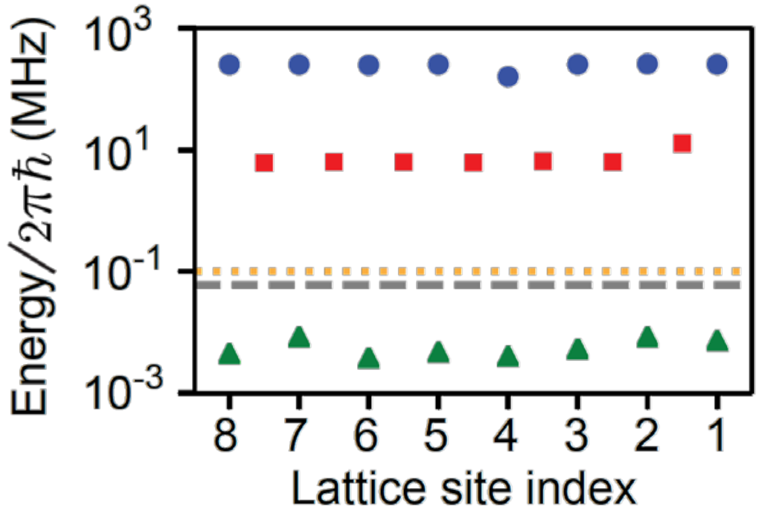
Dilution refrigerator at 20mK



Characterizing the BH lattice

Repetition rate: tens of kHz ☺

Measured energies



|U| = 250 MHz

J = 6.5 MHz

Single particle loss ~ 4 kHz

Onsite dephasing ~ 40 kHz

Onsite disorder < 100 kHz

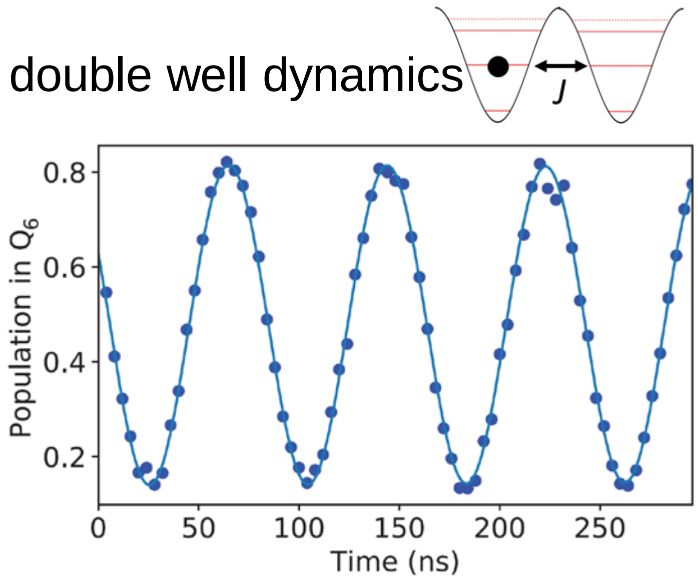
- highly coherent
- strongly interacting
- low disorder

R. Ma et al., A dissipatively stabilized Mott insulator of photons, *Nature* 566, 51–57 (2019).

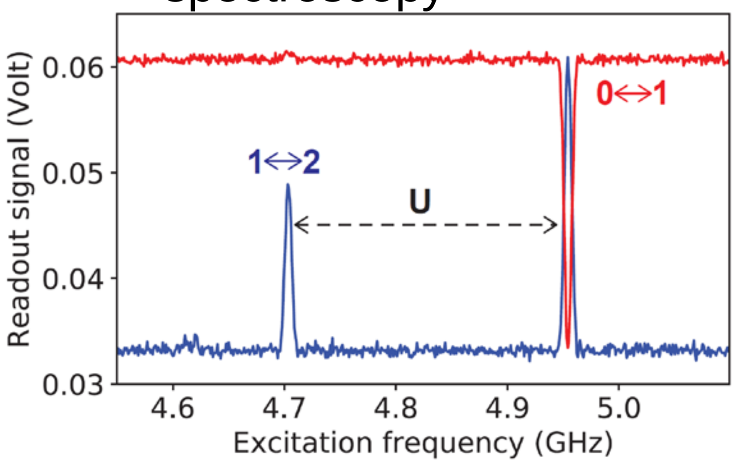
Site-resolved microscopy & spectroscopy

Characterization

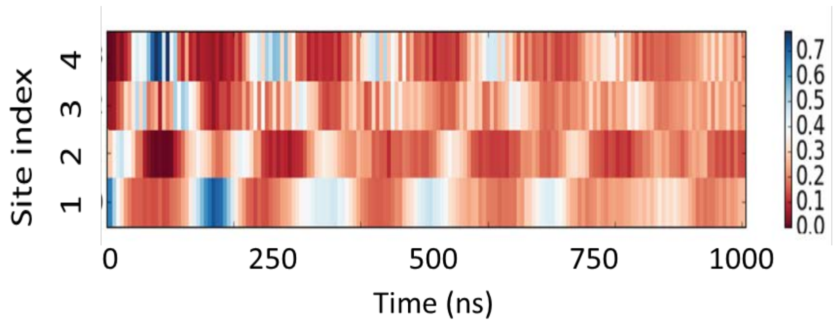
double well dynamics



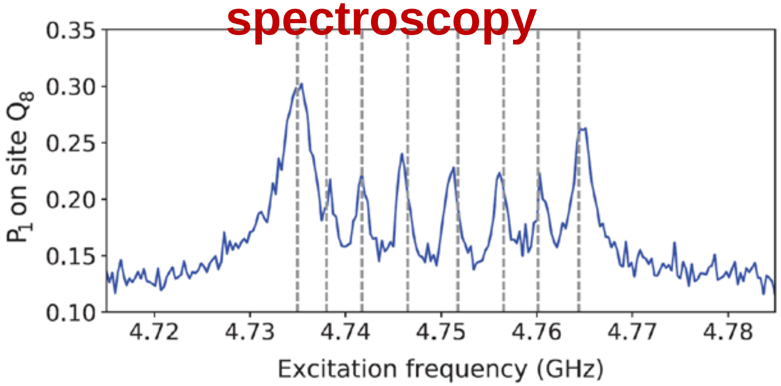
single site spectroscopy



Single particle quantum walk



Lattice spectroscopy



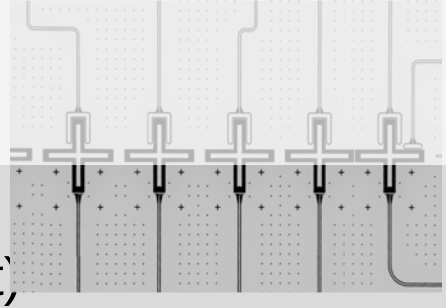
R Ma, …, Hamiltonian Tomography of Photonic Lattices. *PRA* (2

Outline

Why photons, why superconducting circuits?

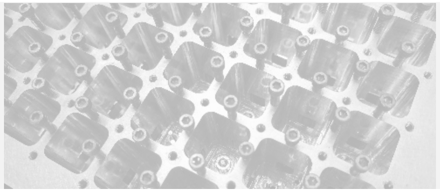
Building the circuit quantum matter platform

- Building a Bose-Hubbard lattice
- Control and characterization



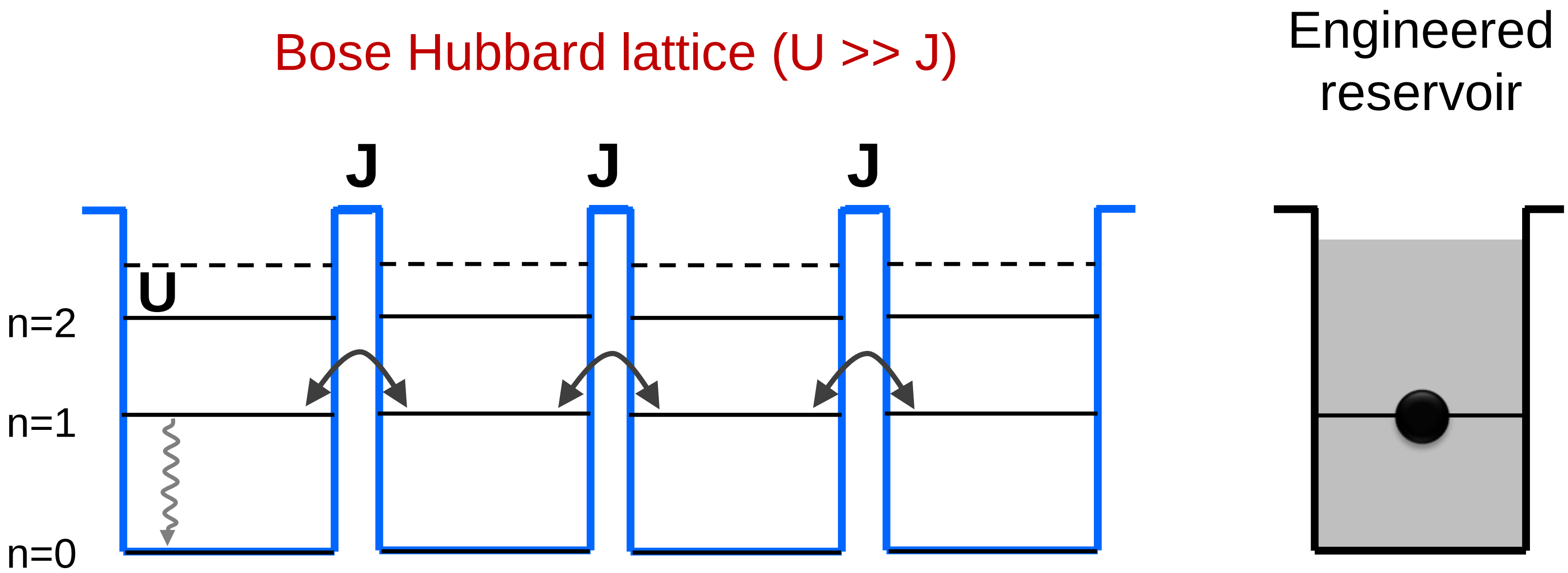
- A reservoir for photons
- Populate many-body states (Mott)

Creating a topological lattice



Summary & Outlook

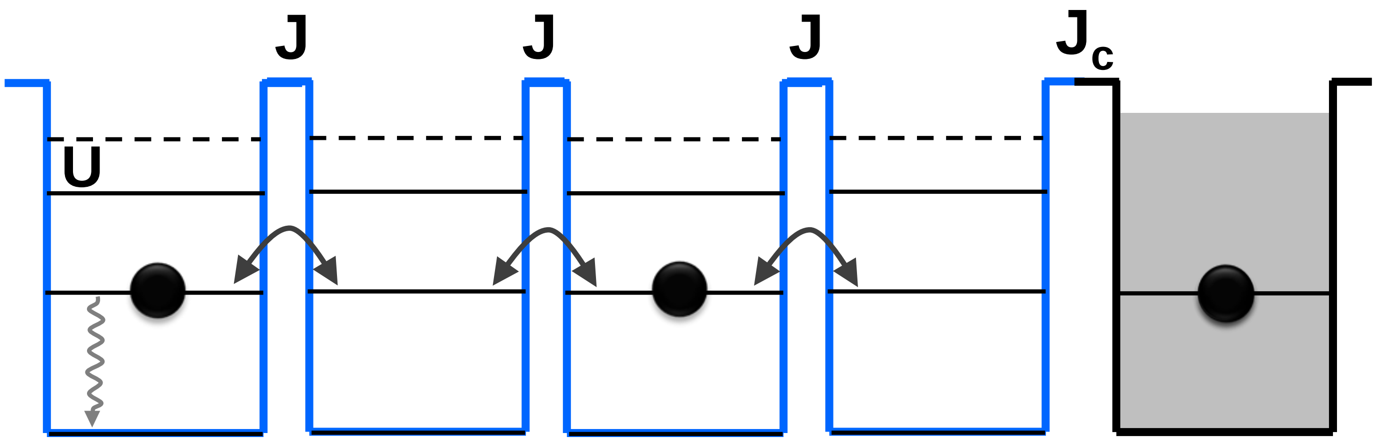
Populating a photonic many-body state



R Ma et al., An Autonomous Stabilizer for Incompressible Photon Fluids and Solids. PRA 95, 043811 (2017)

Populating a photonic many-body state

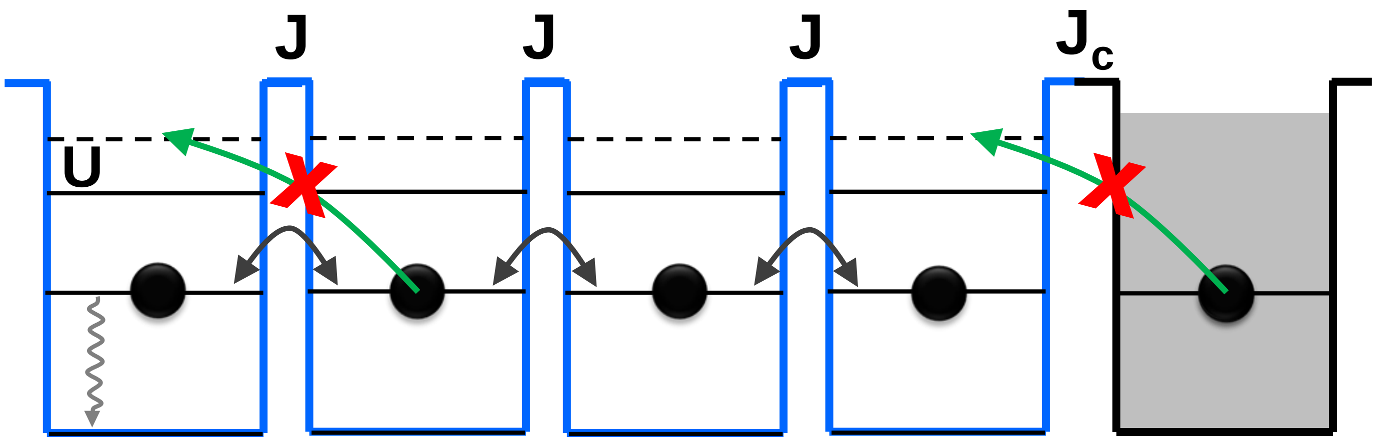
Bose Hubbard lattice (U >> J)



R Ma et al., An Autonomous Stabilizer for Incompressible Photon Fluids and Solids. PRA 95, 043811 (2017)

Populating a photonic many-body state

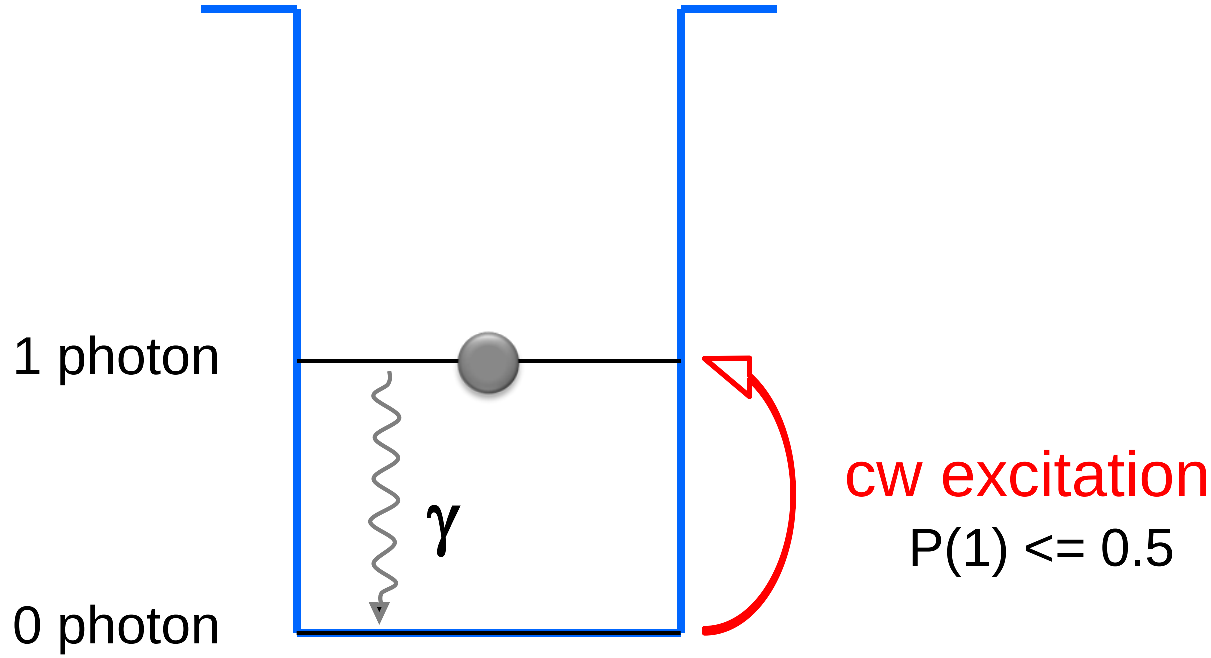
Bose Hubbard lattice (U >> J)



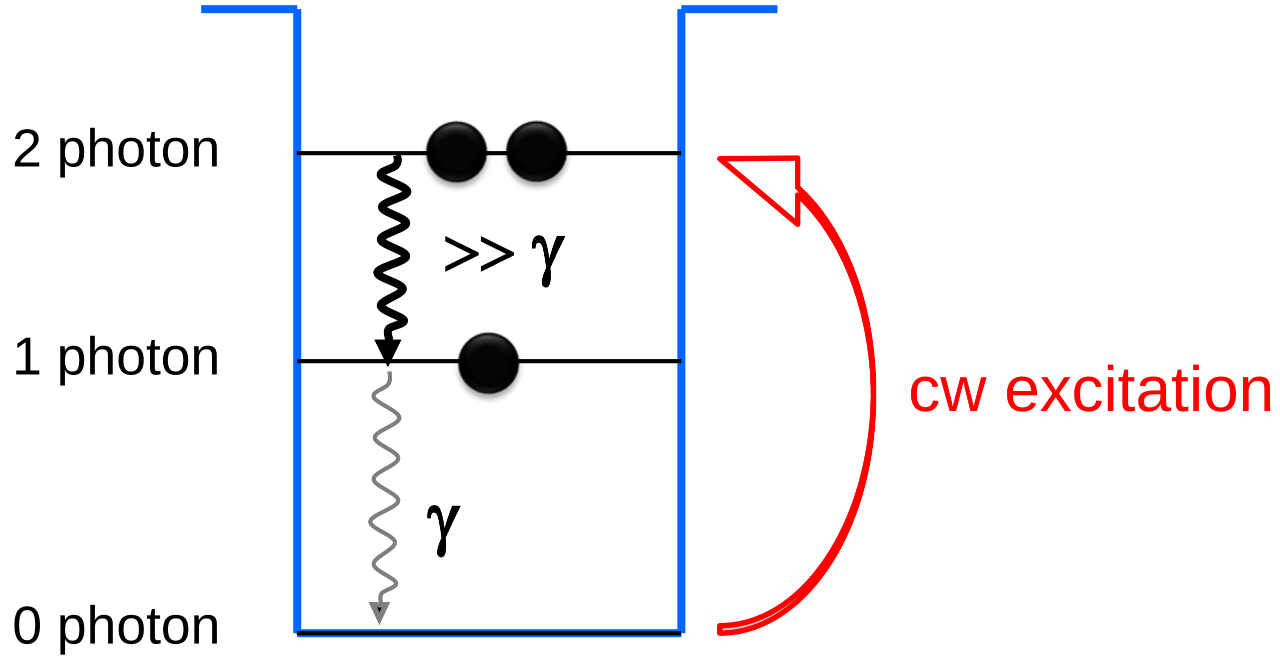
Stabilize a n=1 Mott insulator, against intrinsic photon loss

R Ma et al., An Autonomous Stabilizer for Incompressible Photon Fluids and Solids. PRA 95, 043811 (2017)

A lattice site with exactly one photon?



Stabilize a lattice site with exactly one photon

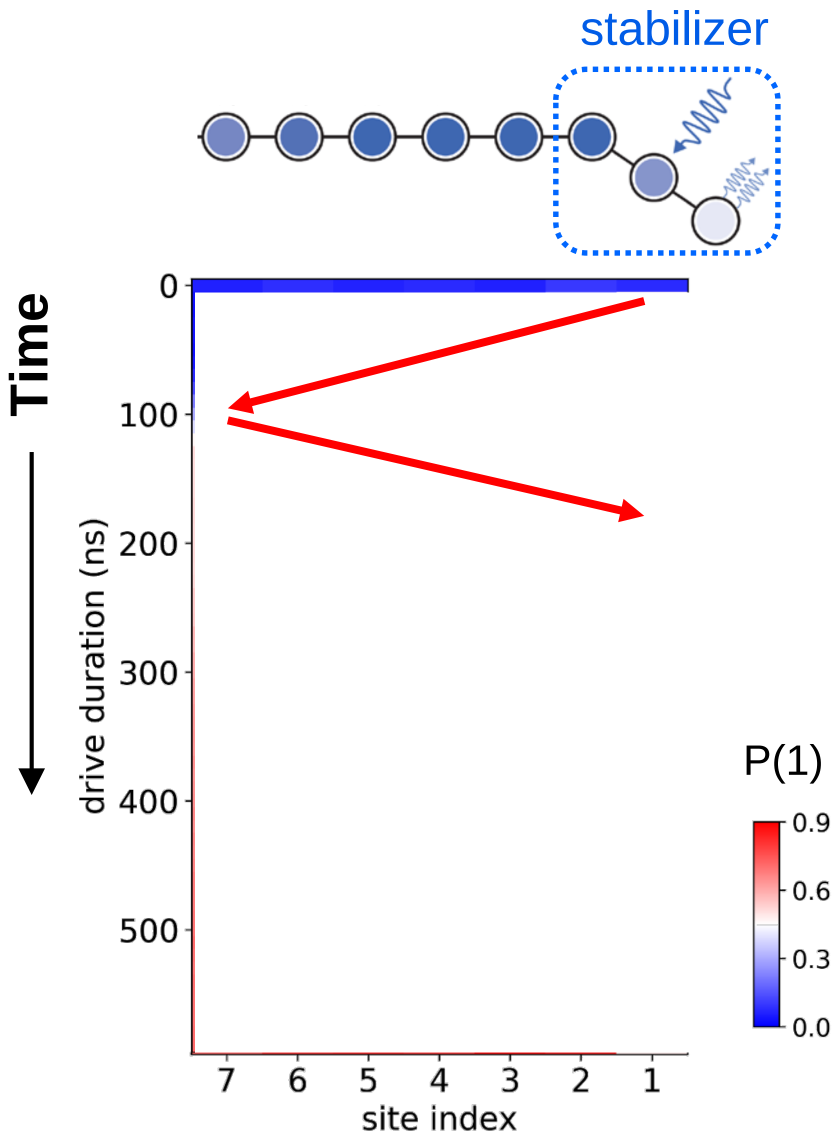


Analogous to: **optical pumping** in atomic systems

Stabilizing a photonic Mott insulator

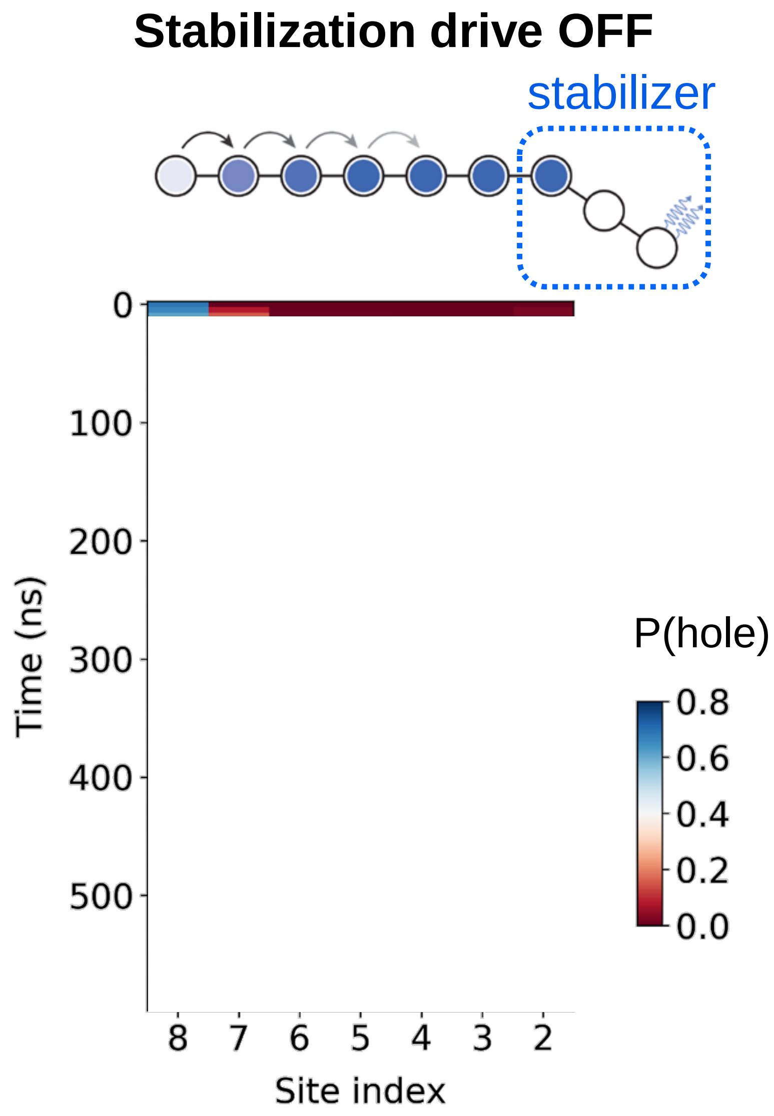
Average Mott fidelity: P(n=1) = 0.90,

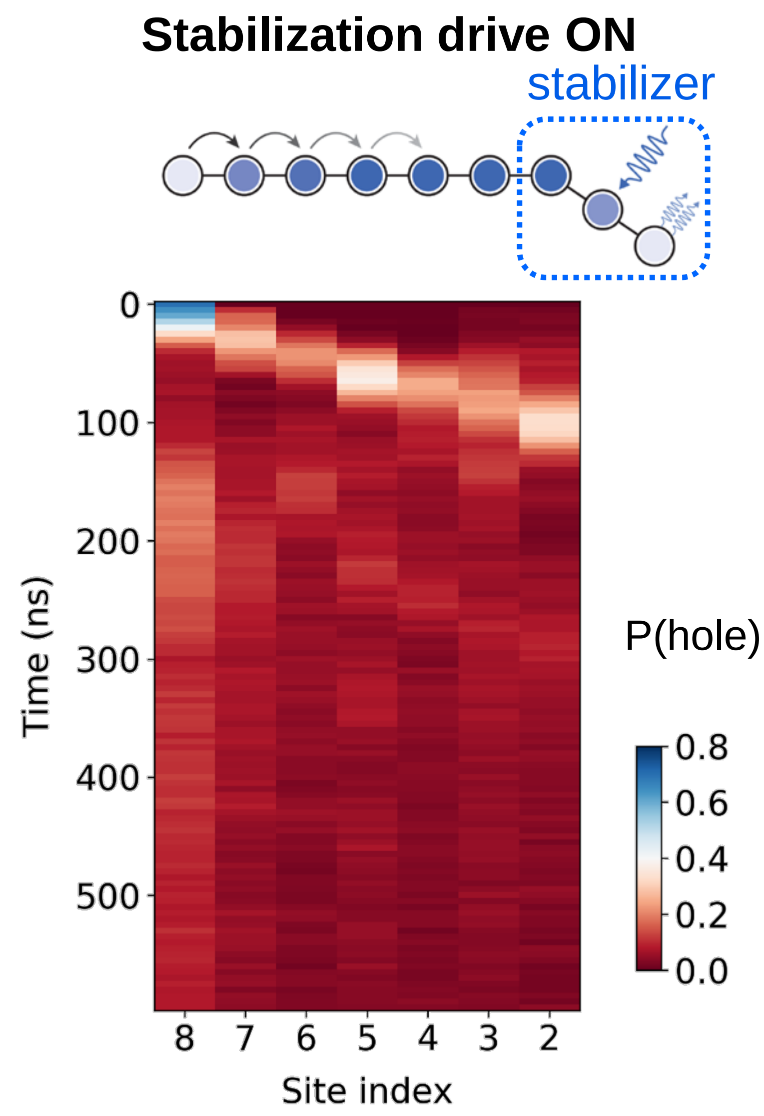
Defects: dominated by holes due to reservoir thermal population



R. Ma et al., *Nature* 566, 51–57 (2019)

Dynamics of a hole defect in the Mott insulator





R. Ma et al., *Nature* 566, 51–57 (2019)

Dissipative preparation

- Protect against losses
- Additional continuous cooling
- **Works directly in final phase**

v.s. “cool then adiabatically evolve”

Questions:

- Can we stabilize compressible phases? Quantum correlations?
- Optimal spectral/spatial distribution of reservoirs?
- Driven-dissipative vs equilibrium?
- Dynamics of the “thermalization” process; transport, etc.

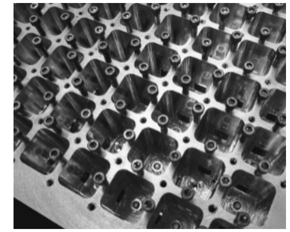
Effective chemical potential for light
- Hafezi, *PRB* 92, 174305 (2015);
- Lebreuilly, *PRA* 96, 033828 (2017) etc.

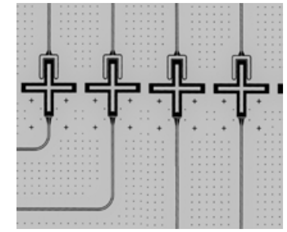
Lebreuilly, Wouters & Carusotto, Comptes Rendus Physique 17, 836 (2016).
R Ma et al., PRA 95, 043811 (2017);

Closely related to – bath engineering / autonomous error corrections, etc

Synthetic quantum matter in superconducting circuits

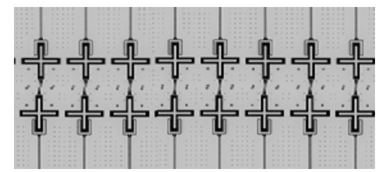
Summary





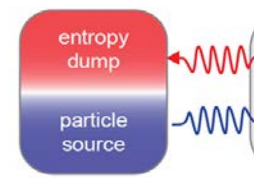
- ➢ Engineering quantum matter in circuits
- ➢ Control and characterization
- ➢ Manipulating many-body states using *engineered environment*

Future directions

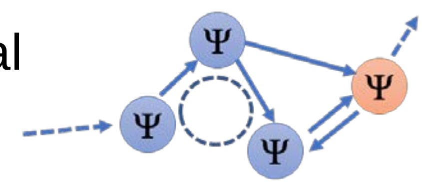


2xN ladder

- ➢ Exploring novel many-body phases
  - Dissipation as a resource for preparation
  - e.g. Strongly-interacting topological phases
- ➢ Quantum thermodynamics



  - coherent dynamics… + engineered environment
    Fate of quantum correlations in open systems?
- ➢ Networks of coupled quantum circuit/emitters
  - waveguide QED; cascaded systems w/ non-reciprocal couplings



- ➢ Circuits used to probe/couple to other physical platforms

Thank you!

@ UChicago

David Schuster
Jonathan Simon

Clai Owens (PhD)
Brendan Saxberg (PhD)
Gabrielle Roberts (PhD)
Sarayu Narayan (Undergrad)
Aman Lachapelle (Undergrad)

Team @ Purdue

Miguel Alarcón
Botao Du
Guga Khundzakishvili

Mackenzie Geckler
Lingxue He
Maaz Ahmed

ma-quantumlab.com

Post-doc position available!