Quantum simulation with driven-dissipative superconducting circuits

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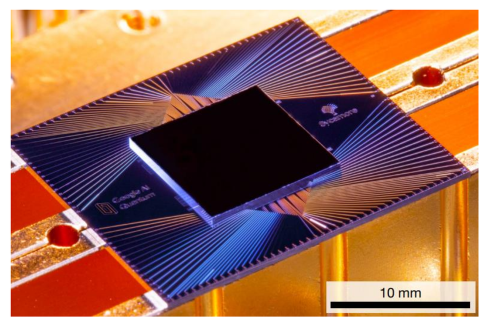
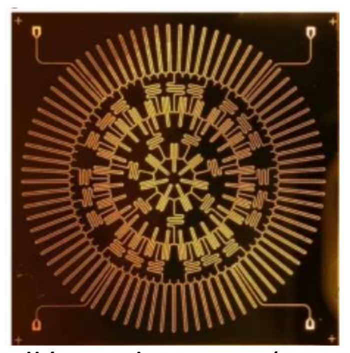
Superconducting Circuits for Quantum Simulation

53 qubit 2D-array



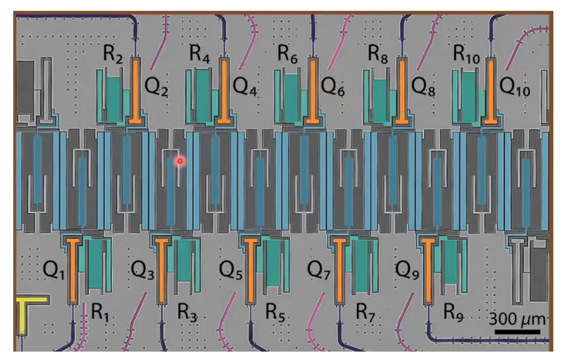
Google Sycamore (2019)

lattice on hyperbolic surface



Kollár et.al, Nature (2019)

Extended Bose-Hubbard lattice



X. Zhang, E Kim et al., arXiv:2206.12803
E Kim, X. Zhang et al., *Nature* (2019).

- Digital quantum simulation with NISQ devices
- Analog quantum simulation for lattice physics, waveguide QED, etc.

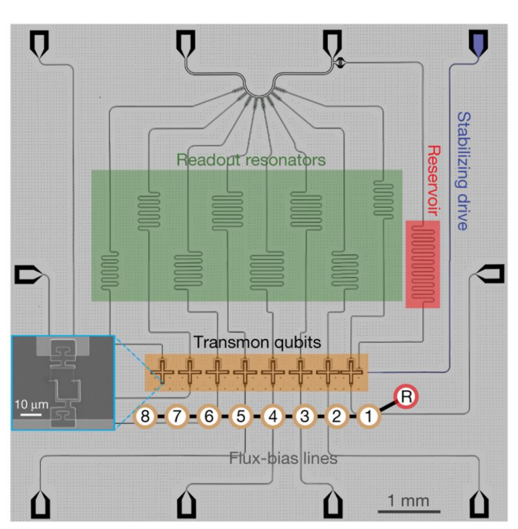
Synthetic quantum material in Circuits

➢ Advantages of SC circuits for quantum simulation:

- Long lifetime in superconducting cavities (milliseconds to seconds)
- Strong coherent interaction realized in circuit QED
- Flexibility in engineered dispersion, coupling, connectivity etc.

Great platform for studying many-body physics of synthetic quantum materials made of microwave photons

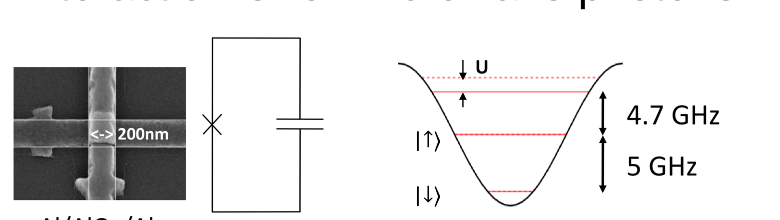
Drive-dissipative stabilization Mott-Insulator state



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

➢ On-site interaction of transmon qubits:

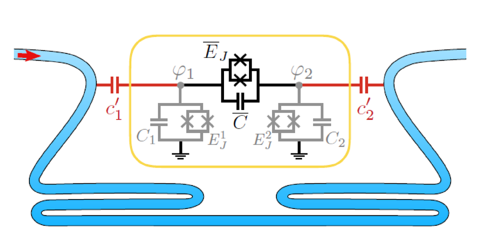
- Transmon qubit as an anharmonic oscillator provide effective on-site interaction U for microwave photons



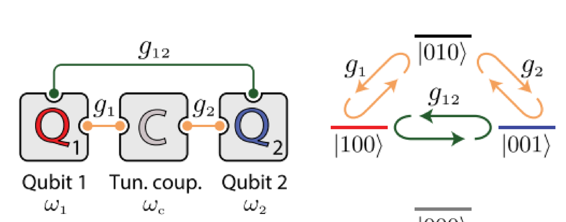
Al/AlOx/Al

➢ Different ways to engineer coupling:

- Direct Nearest-neighbor coupling of transmon qubits
- Coupling via shared waveguide
- Tunable coupling via virtual photon exchange path
- Dynamically tunable parametric coupling

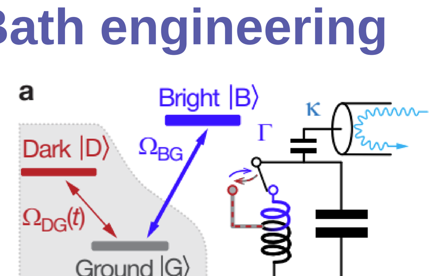


P.-O. Guimond et.al, npj quantum information (2019)

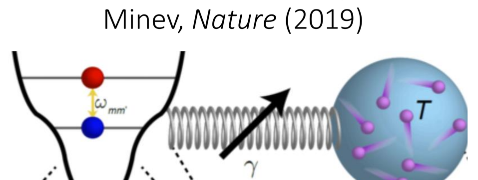


Yan, Fei, et al. PRA 10.5 (2018): 054062.

➢ Bath engineering



Minev, *Nature* (2019)



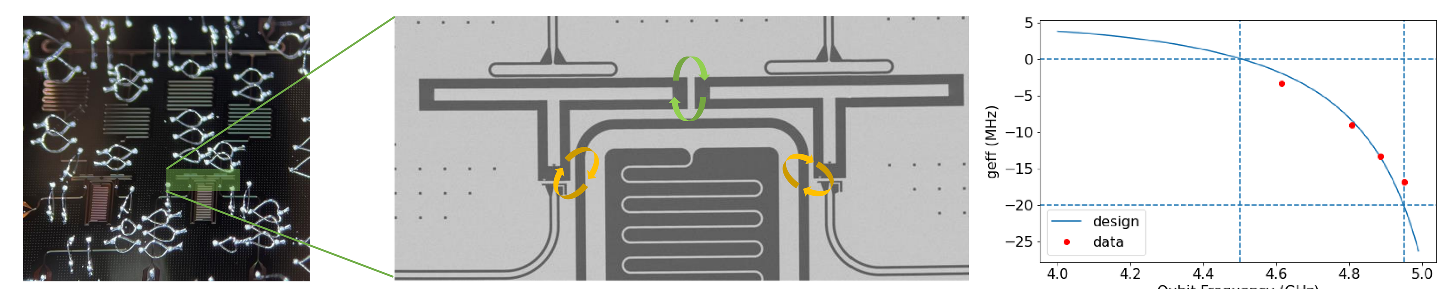
Möttönen group (2020)

- Precise, tunable control of coupling to dissipative environments.
- Driven-dissipative stablized quantum state/phase
- Intrinsic dissipation makes it natural to study open quantum systems

Tunable bath-system coupling

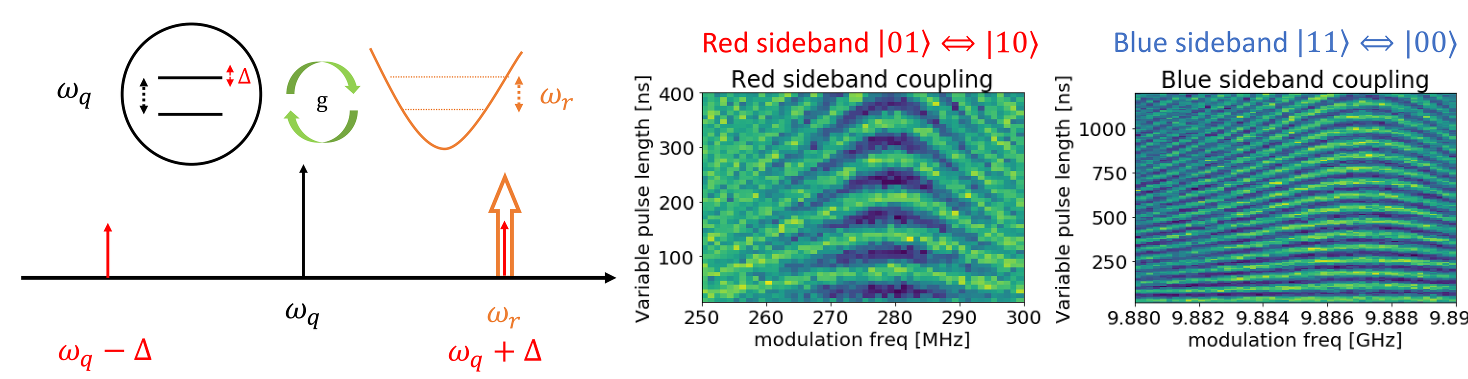
➢ Start from tunable coupler:

- Two components of qubit-qubit coupling
  - Direct qubit-qubit coupling
  - Virtual coupling via the detuned coupler site



➢ Probe parametric resonator-qubit interaction:

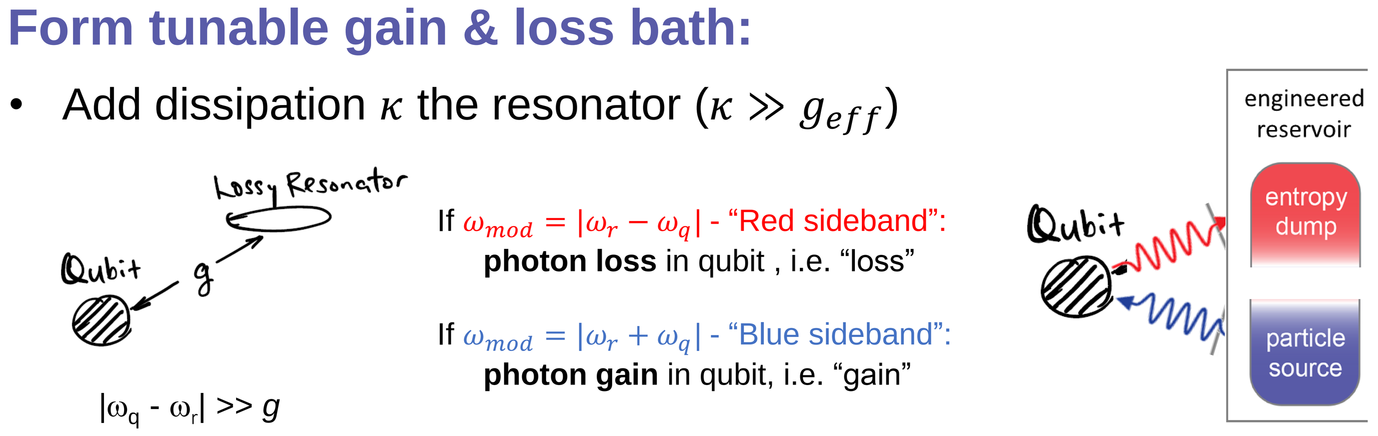
- Modulate the qubit flux at the sideband frequency
  - $\omega_{mod} = |\omega_r - \omega_q|$ "Red sideband"
  - $\omega_{mod} = |\omega_r + \omega_q|$ "Blue sideband"



- Dynamically tunable coupling rate by tune the modulation amplitude

➢ Form tunable gain & loss bath:

- Add dissipation κ the resonator ($\kappa \gg g_{eff}$)



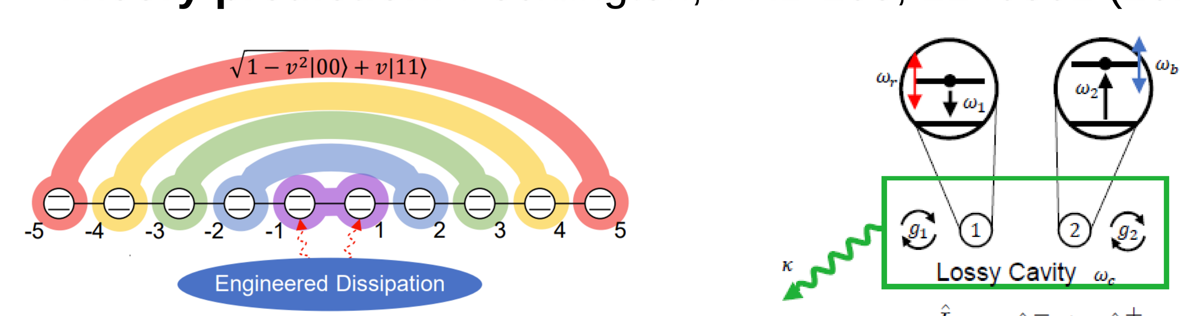
$|\omega_q - \omega_r| >> g$

If $\omega_{mod} = |\omega_r - \omega_q|$ - "Red sideband": **photon loss** in qubit , i.e. "loss"

If $\omega_{mod} = |\omega_r + \omega_q|$ - "Blue sideband": **photon gain** in qubit, i.e. "gain"

Generating 'Rainbow' State

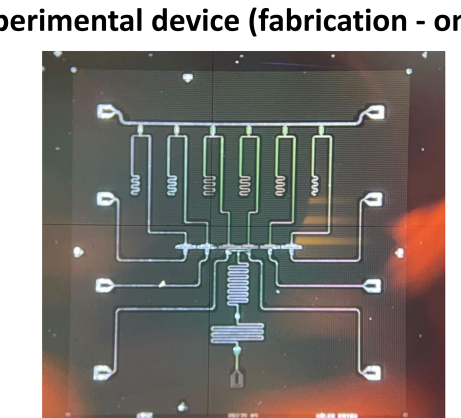
- **Motivation:** Dissipative stablized long-range entanglement with only NN tunneling and one local bath
- **Theory prediction:** Pocklington, PRB 105, L140301 (2022)



Pocklington, PRB 105, L140301 (2022)

- **Mechanism:** 2 qubit couple to the same lossy cavity via parametric red/blue sideband coupling -> effectively correate correlated loss and gain channel

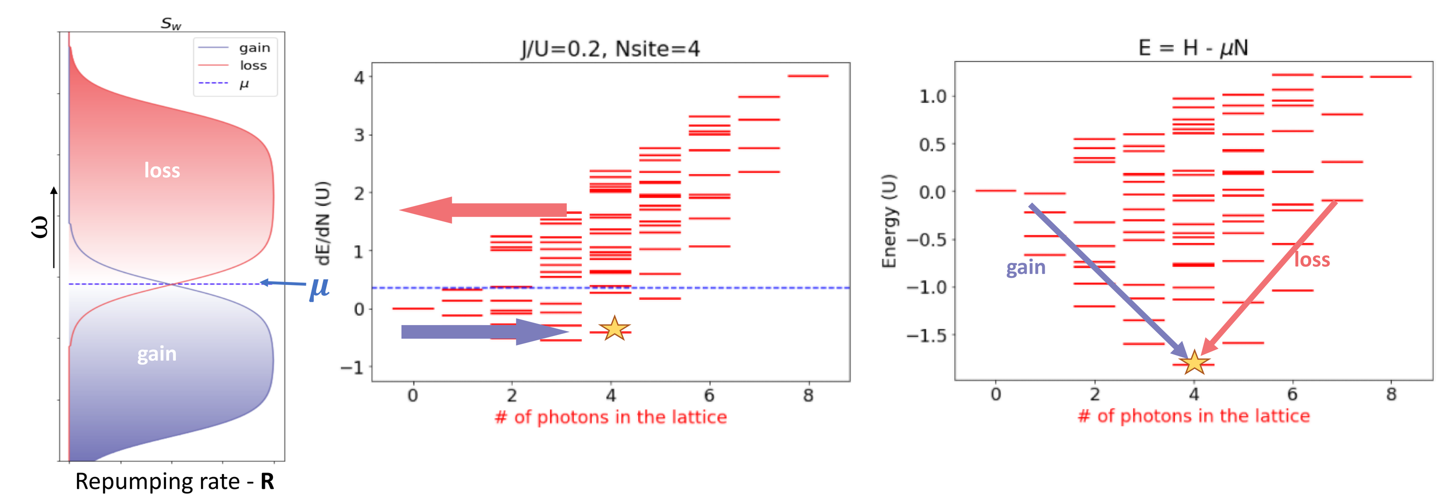
Experimental device (fabrication - on going)



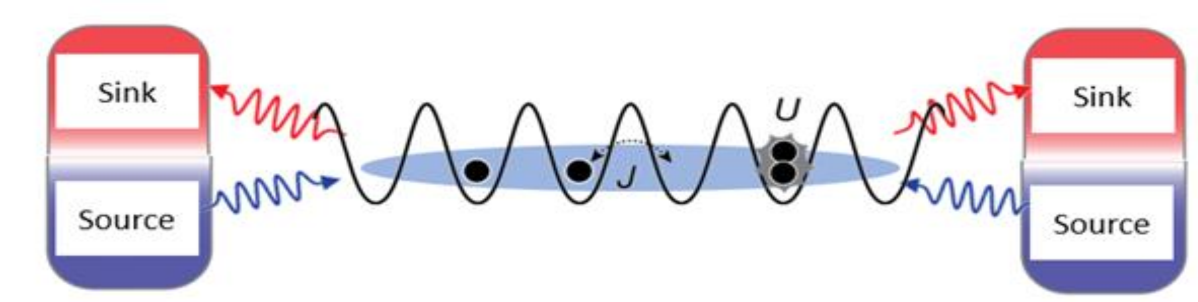
Bath-coupled Bose-Hubbard lattice

➢ Driven dissipative stablized many-body ground state

- **People has done: Drive-dissipative stabilization Mott-Insulator state.** R. Ma et al., Nature 566, 51–57 (2019).
- **Our focus: Towards strong correlated phase, e.g. strongly interacting super-fluid state**
  - Theory proposals: Kapit PRX 4, 031039 (2014); Hafezi PRB 92, 174305 (2015); Lebreuilly Phys. Rev. A 96, 033828 (2017)
  - Engineer effective chemical potential for light with broadband bath



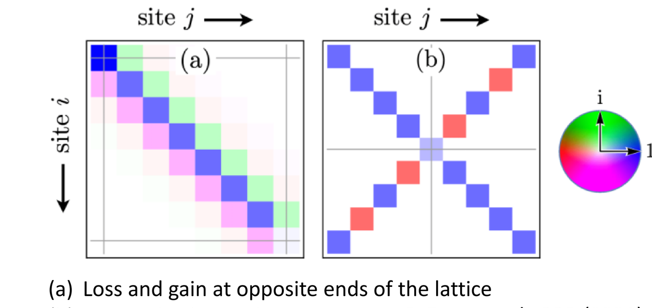
- **Our plan:** **Parametrically enabled coupling + variable linewidth + frequency modulation for dynamically tunable spectra**



➢ Dynamics/correlation in lattices coupled to local baths

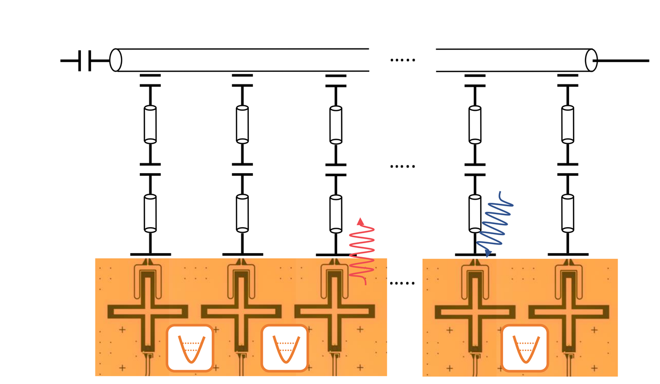
- **Theory proposal:** S. Dutta, PRR (2021)
- **Experimental setting:**
  - Tunable coupled qubit array
  - Locally coupled gain and loss bath
  - Fast readout cavity

Steady state correlation in 1D hard-core bose lattice



(a) Loss and gain at opposite ends of the lattice
(b) Loss and gain ate the center S. Dutta et.al , PRR (2021)

- **The readout resonator also serve as a knob to explore the interplay between**
  - Coherent interaction
  - Driven-dissipation
  - Measurement back action/feedback



Our proposed experimental system

Other directions

- Using superconducting circuits to probe (real) quantum materials
- Chiral quantum optics
- Robust quantum resources for QIP (quantum information processing)

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