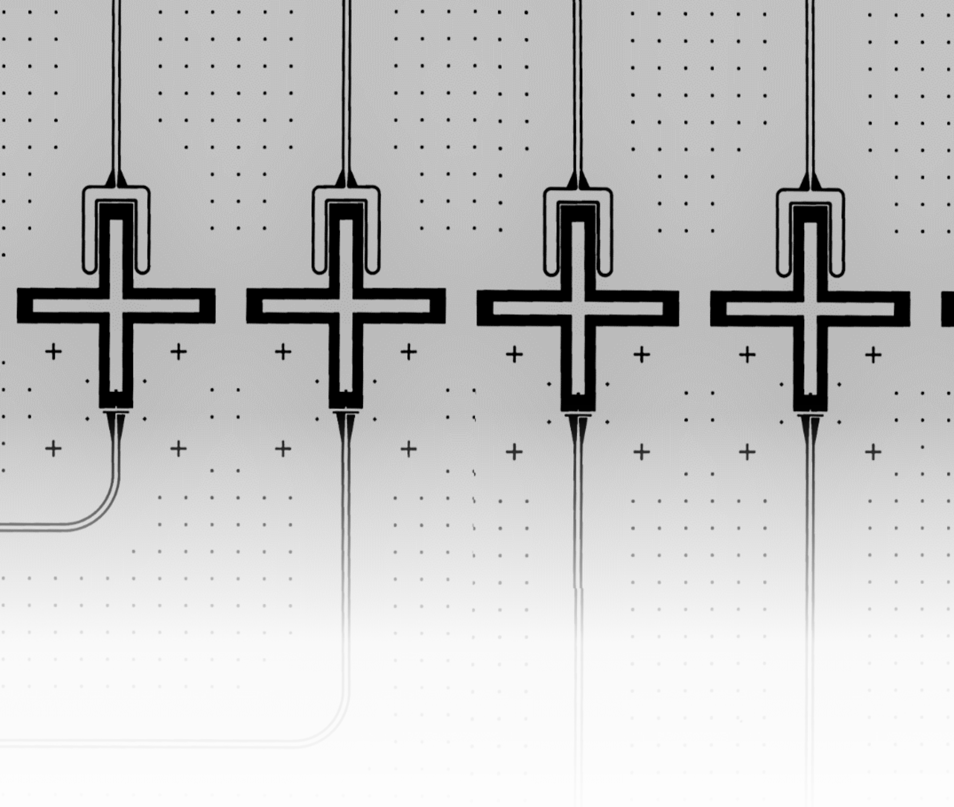


Quantum Simulation with Superconducting Circuits

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10/07/2023

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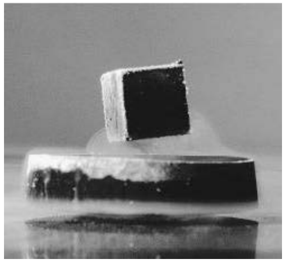
Three things to cover

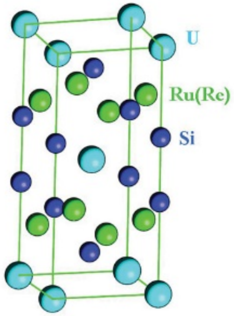
- Quantum computers vs quantum simulators
- Superconducting qubits and circuits
- Is noise always bad?

Quantum materials

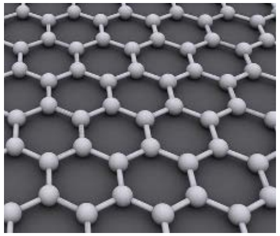
Unique properties due to quantum mechanics



High T_c superconductors



Quantum magnets



Graphene

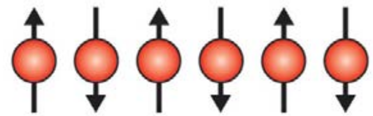
Technological relevance:

- Power/energy transfer
- Data storage and spintronics
- Quantum information processing
- …

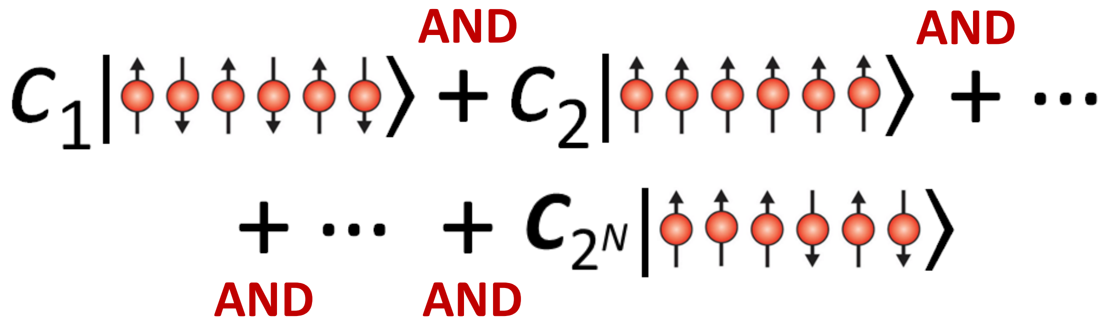
Essential physics captured in relatively simple models…
But extremely challenging to calculate…

Why are these models hard to simulate on a compu

Classical state:
O(N) parameters



Quantum state:
O(2^N) parameters

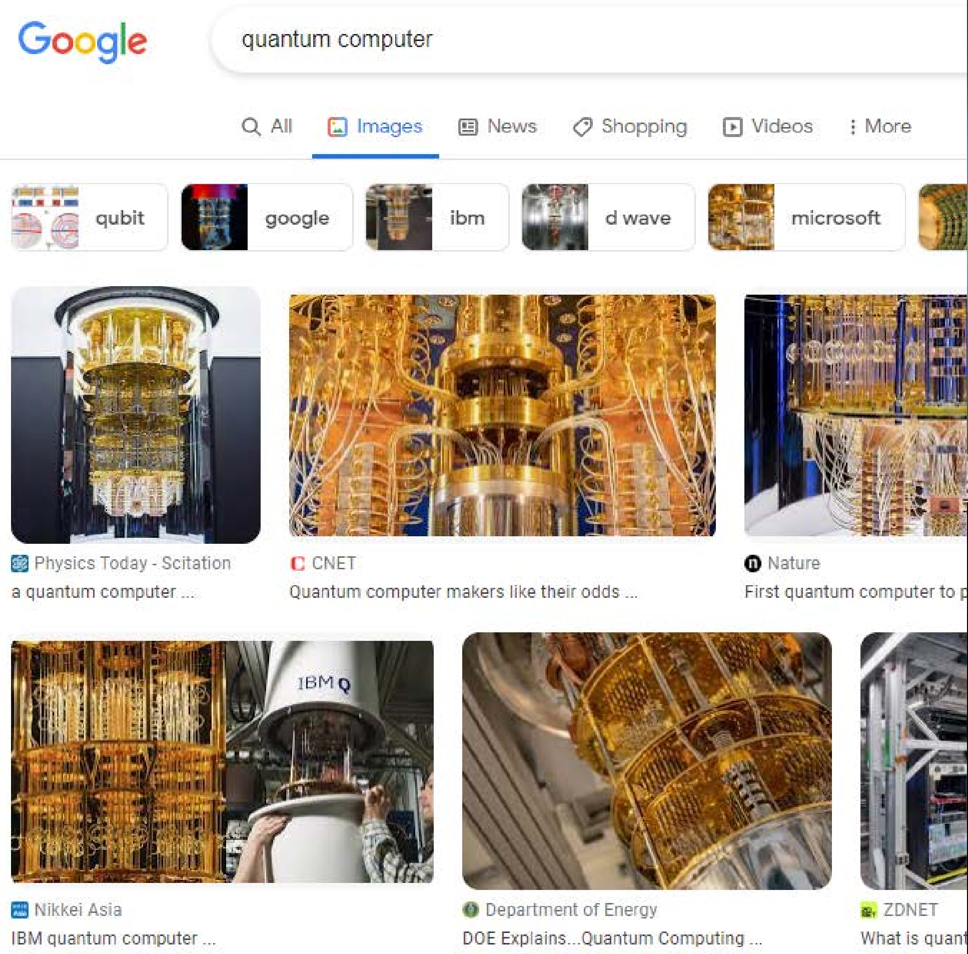


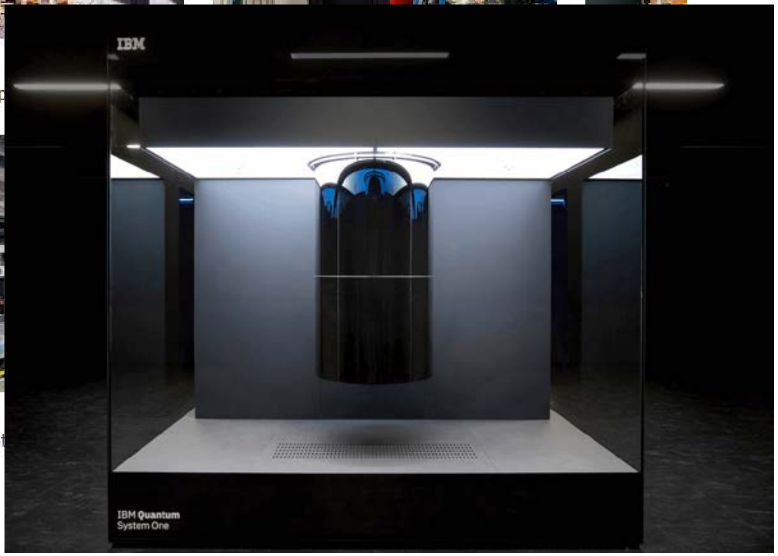
"Superposition": 2^N configurations simultaneously!

Exponential resources required for simulation on classical computer

Needs a quantum computer! Or…

Wait… Don’t we already have quantum computers?



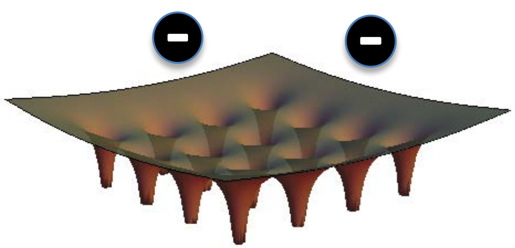


Quantum Simulators ("special purpose quantum computers"):

to study the dynamics of another quantum system

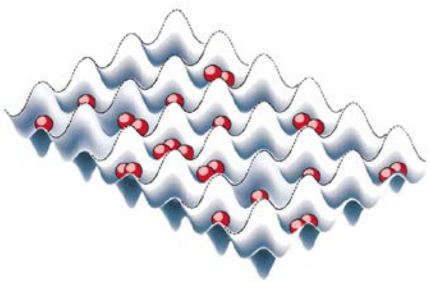
Solid State

Interacting electrons in ionic lattice



Ultracold Atoms

Interacting atoms in optical lattice



Photonics

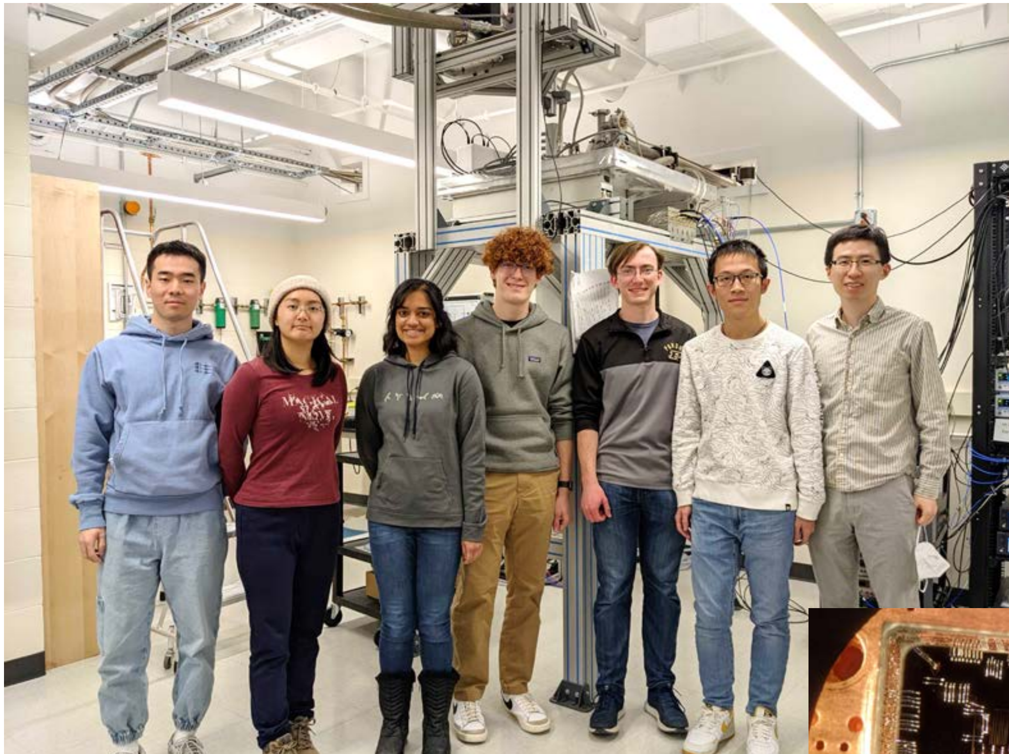
Interacting microwave photons in superconducting qubit arrays / lattices

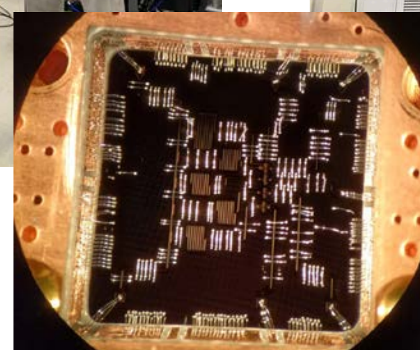
"synthetic quantum materials"

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

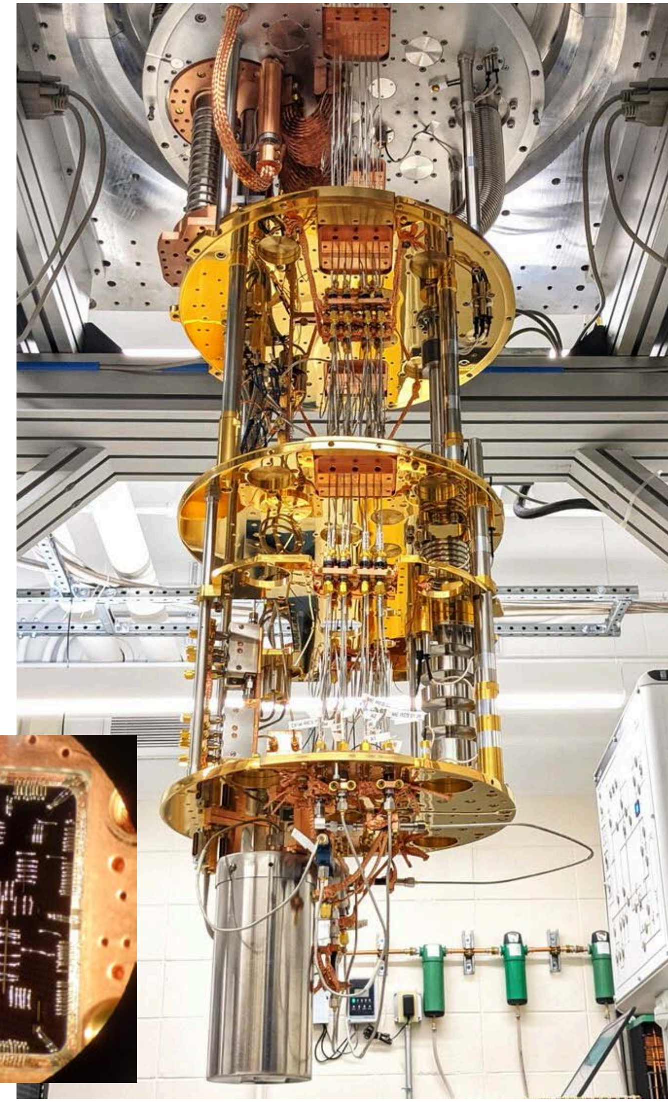
Ma Lab @ Purdue - Superconducting Circuits for Quantum Simulation

https://www.ma-quantumlab.com/





“4 bit QPU”



Dilution refrigerator cooled to 10 milli-Kelvin

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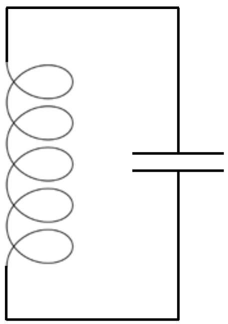
A lattice site for photon

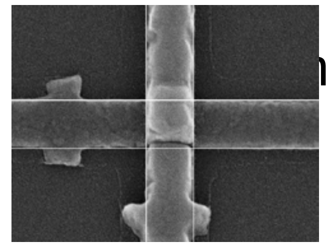
Linear L-C Resonator

Constant L

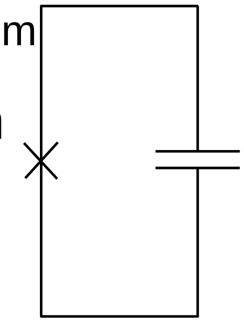


Non-Linear L-C Resonator

<-> 200nm



Al/AlOx/Al



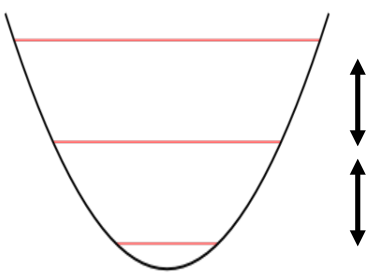
“transmon qubit”

Interaction:
***U*= -300MHz**

2 photons

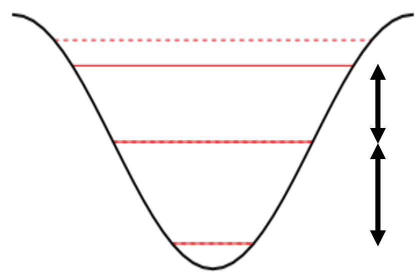
1 photon

0 photon



5 GHz

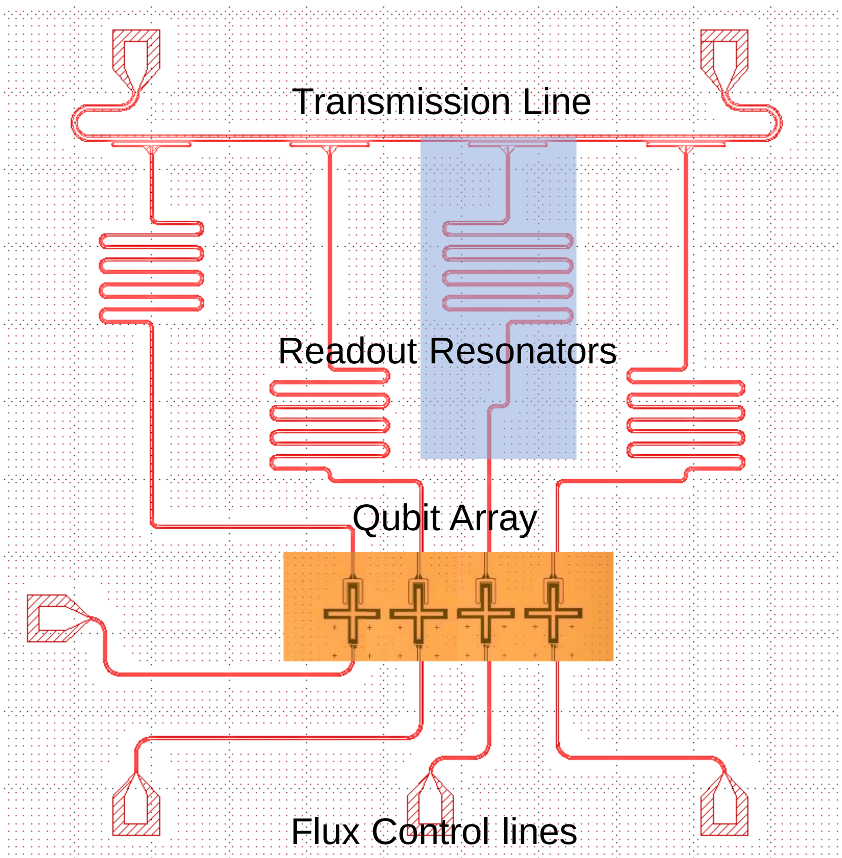
5 GHz

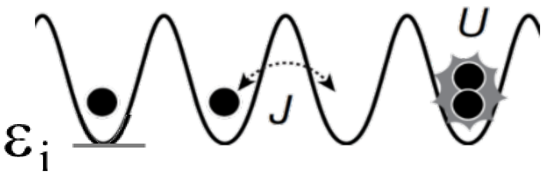


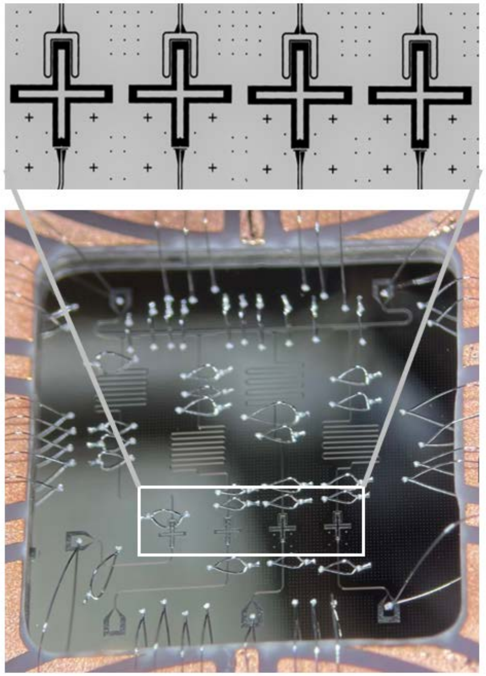
4.7 GHz

5 GHz

Quantum simulator: a lattice for photons using superconducting circuits





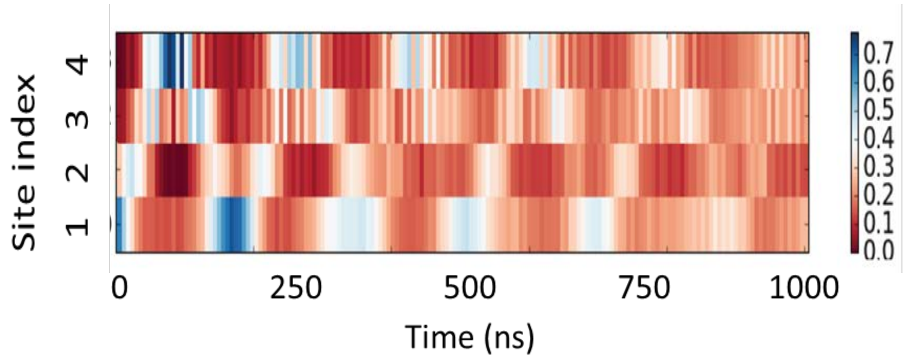


cooled to 10 milli-Kelvin

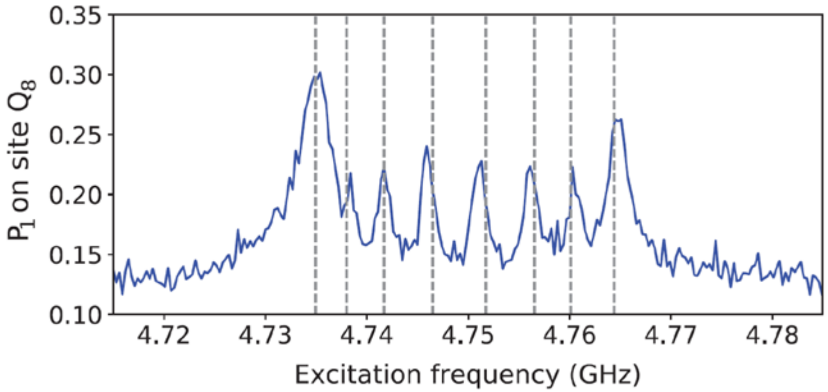
- Quantum electrical circuits – capacitors, inductors, Josephson junctions…
- Site resolved readout – “image” the motion of the photons in the lattice!

Observing the motion of the photons

Single particle “quantum walk”



Lattice spectroscopy (8 site)



Open quantum systems

***Usually*, noise and interactions with an environment (bath) tend to destroy the quantum state...** Detrimental for quantum simulators and quantum computers

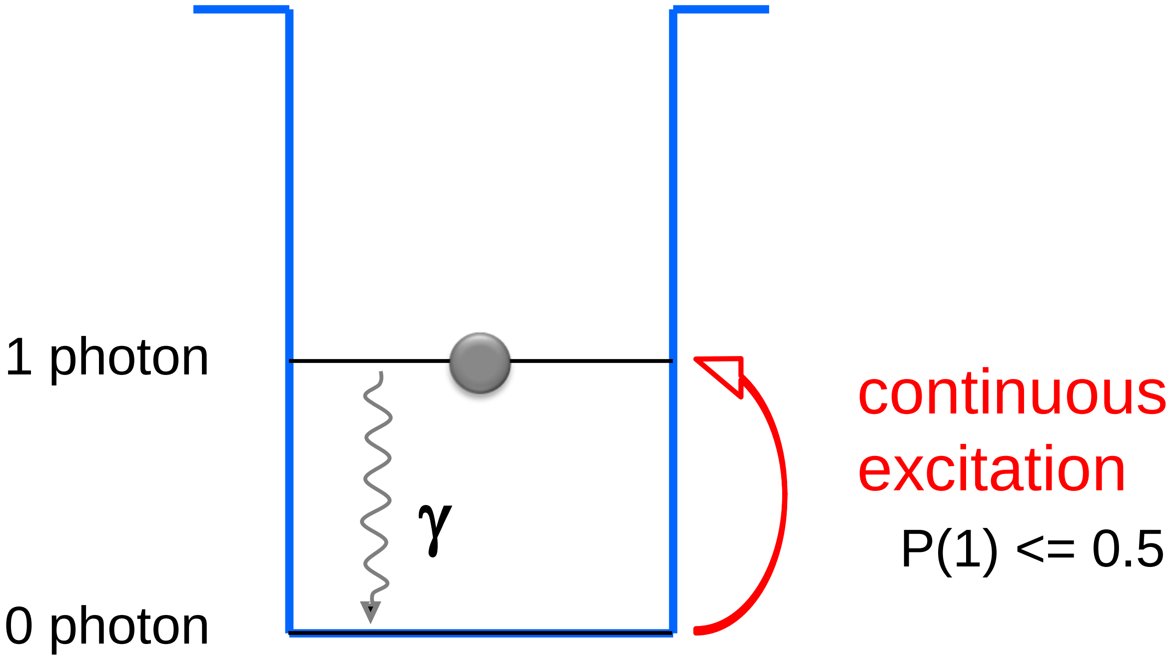
- For example: photon loss in our circuit – end up with empty lattice

But turns out, carefully designed "noise/dissipation", or carefully-engineered "bath" can actually be a powerful resource to control quantum systems

- Generate and protect (!) entanglement in quantum simulators
- Autonomous error correction in quantum computers

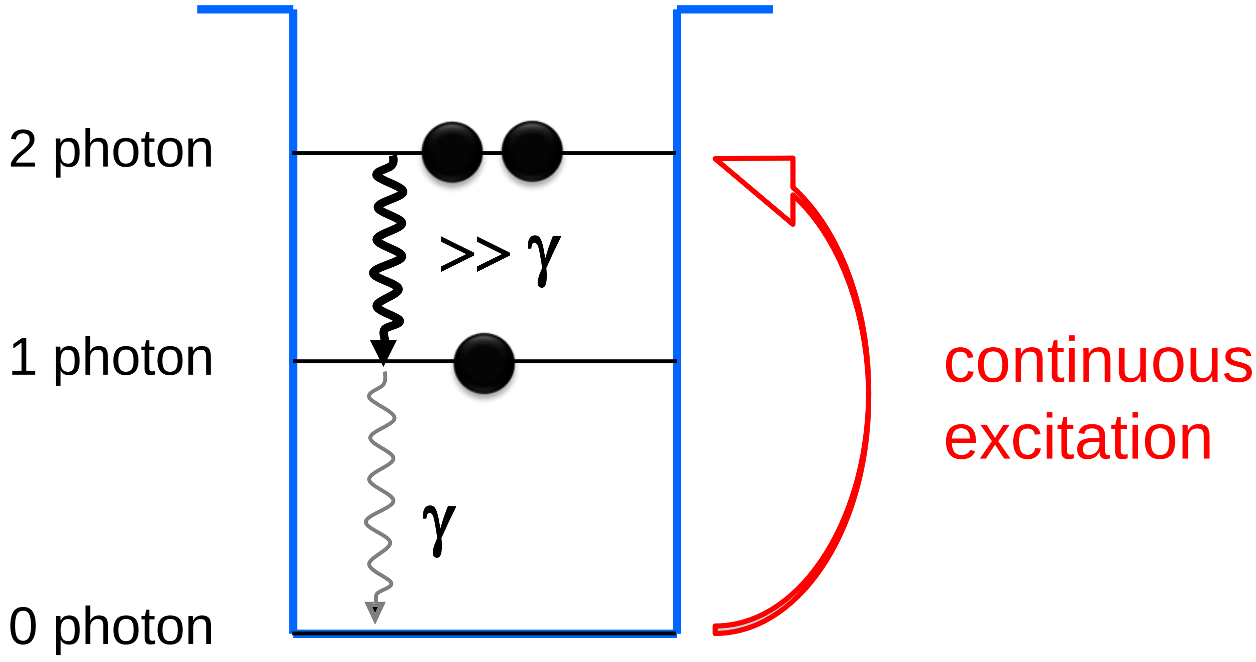
Counter-intuitive? This is natural in real materials!

Use dissipation to control quantum system: Exampl photon reservoir



Use dissipation to control quantum system: Example

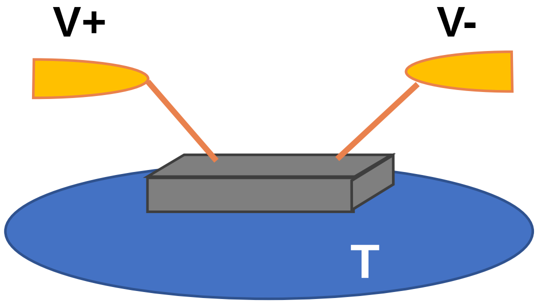
photon reservoir



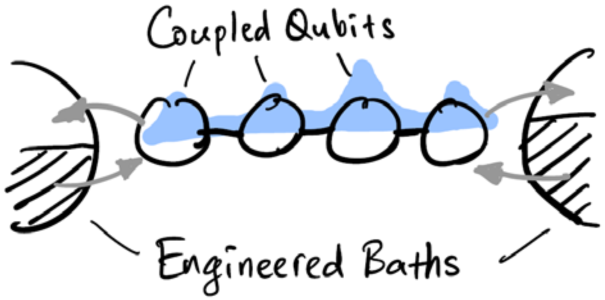
Related: **optical pumping** in atomic systems; lasers

Quantum systems coupled to baths…

Many-body state?



Real materials, interacting with thermal / particle baths

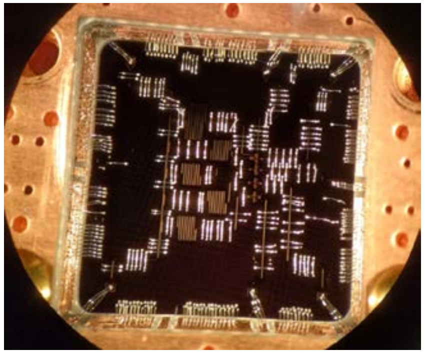


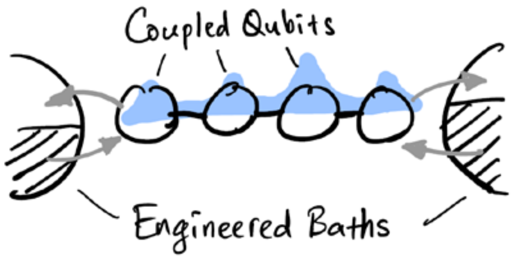
Synthetic quantum matter, with engineered baths

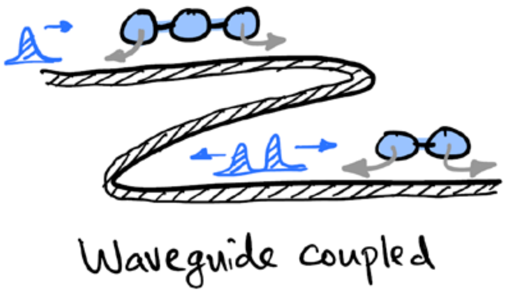
Summary

Superconducting circuits as quantum simulators

Full control of the quantum system, and its interaction with the engineered environment/bath







Carefully designed noise can be a quantum resource

Use engineered bath to:

- Prepare and control entanglement
- Explore fundamental questions about open system quantum dynamics
- New tools for probing synthetic quantum materials