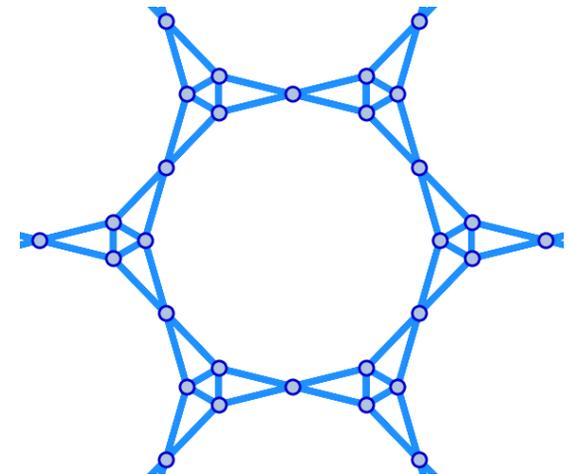
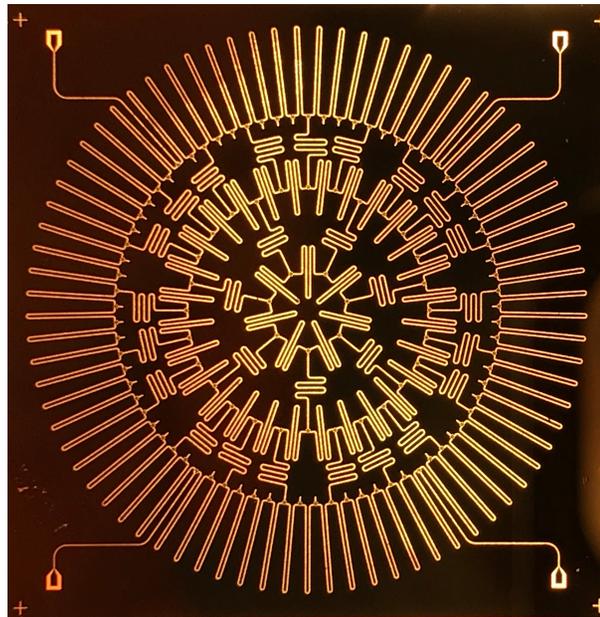
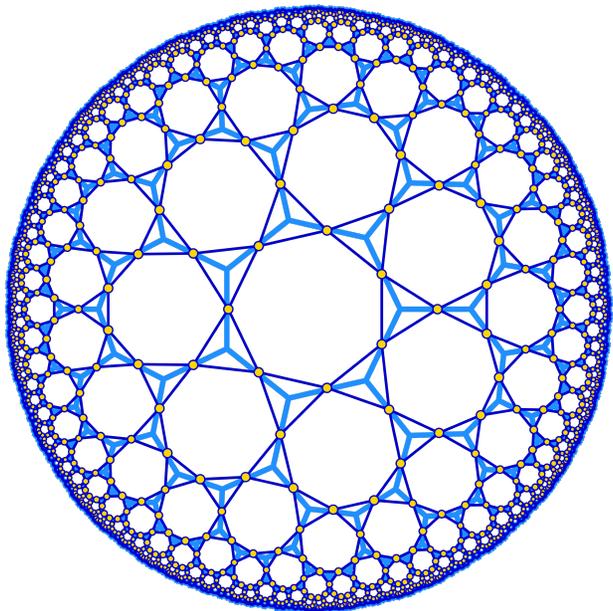


Engineering Qubit-Qubit Interactions in Circuit QED Lattices

Alicia Kollár

Department of Physics and JQI, University of Maryland

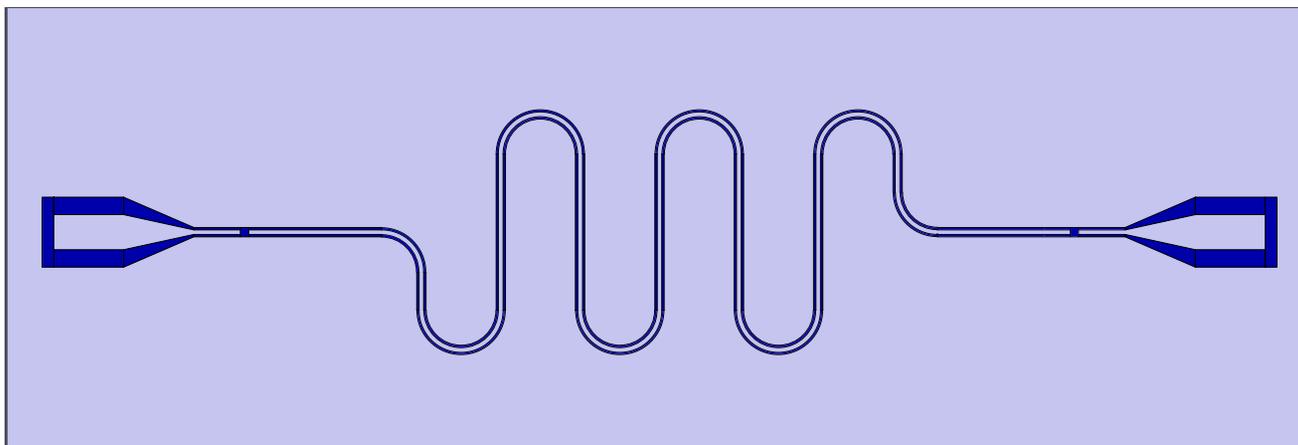
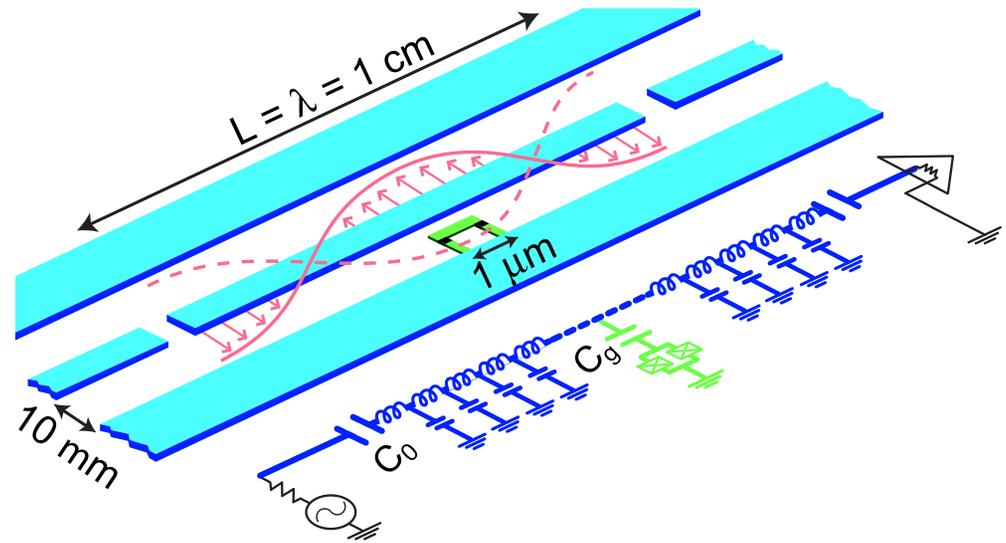


Microwave Coplanar Waveguide Resonators

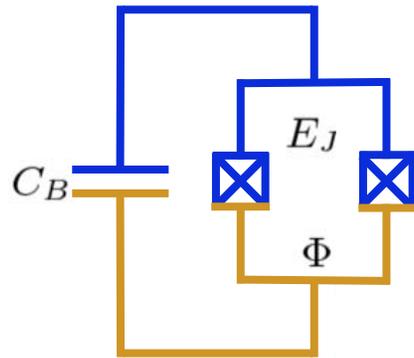
- 2D analog of coaxial cable
- Cavity defined by cutting center pin
- Voltage antinode at “mirror”

Harmonic oscillator

$$\hat{H} = \frac{1}{2C} \hat{n}^2 + \frac{1}{2L} \hat{\varphi}^2$$

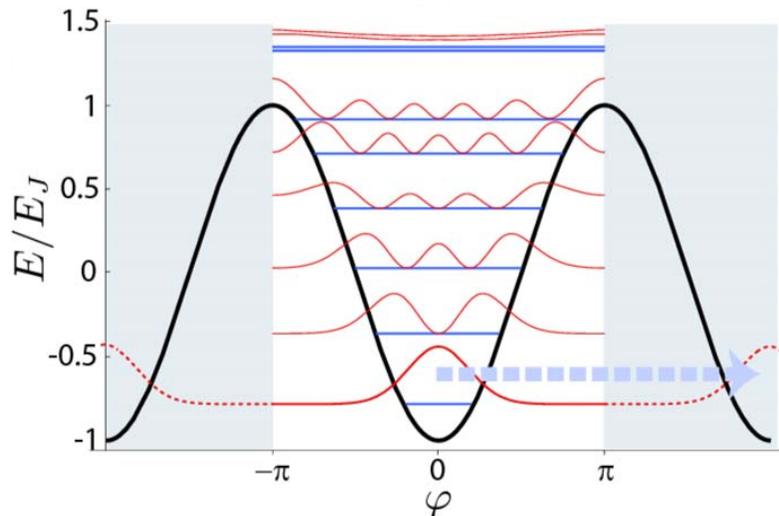


Transmon Qubit



Anharmonic oscillator

$$\hat{H} = 4E_C \hat{n}^2 - E_J \cos \hat{\varphi}$$

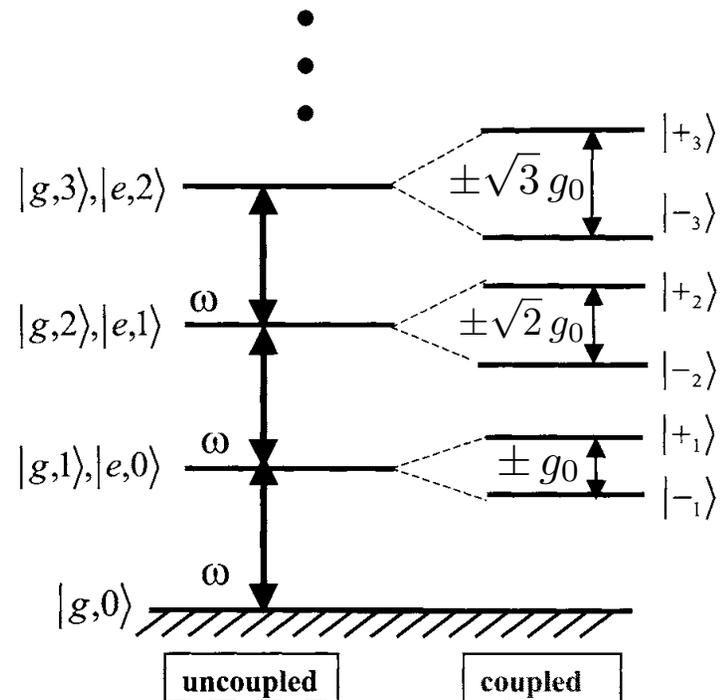


Qubit-Cavity

(Jaynes-Cummings Model)

$$H_{JC} = \omega_c a^\dagger a + \frac{1}{2} \omega_q \sigma_z + g_0 (a^\dagger \sigma^- + a \sigma^+)$$

$$|\pm_n\rangle = \frac{1}{\sqrt{2}} (|g, n\rangle \pm |e, n-1\rangle),$$



Photon-Mediated Interactions

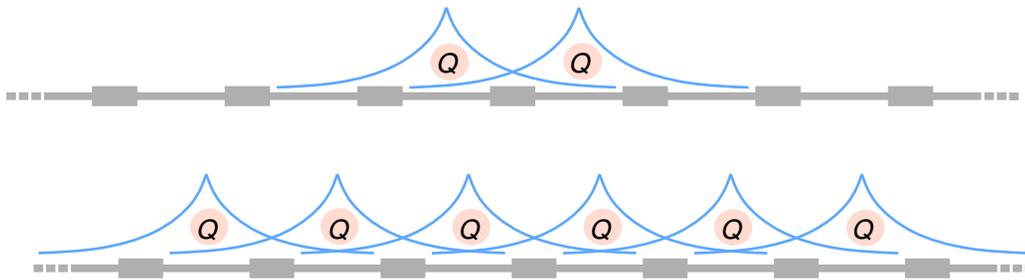
Photonic Crystal + qubits

- Effective swap interaction
- All modes in parallel

$$H = \hbar \sigma_1^+ \sigma_2^- \sum_m \frac{g_m^2}{\Delta(m)} \psi_m(x_1) \psi_m^*(x_2) + h.c.$$

1D-Photonic Crystal

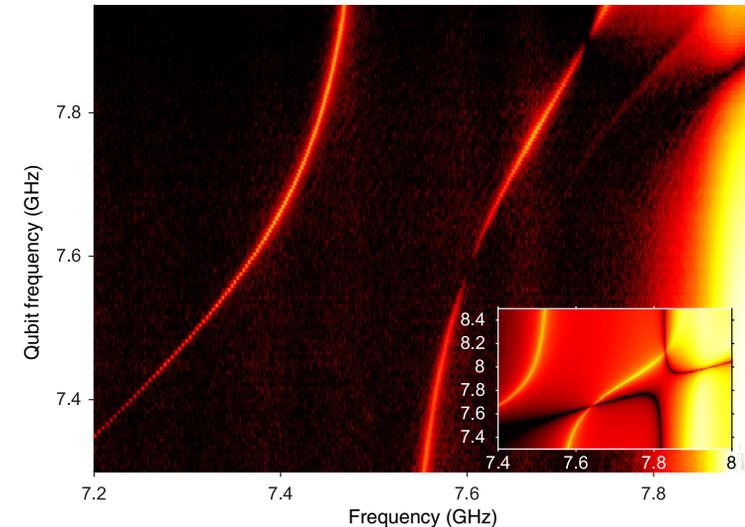
- Exponentially localized bound state



New Regimes:

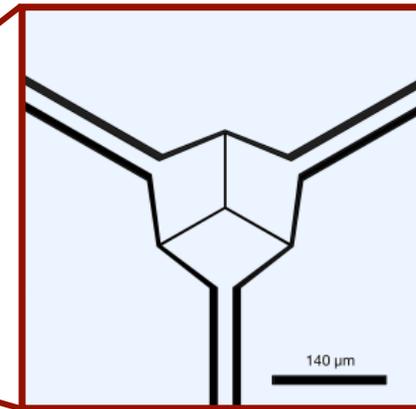
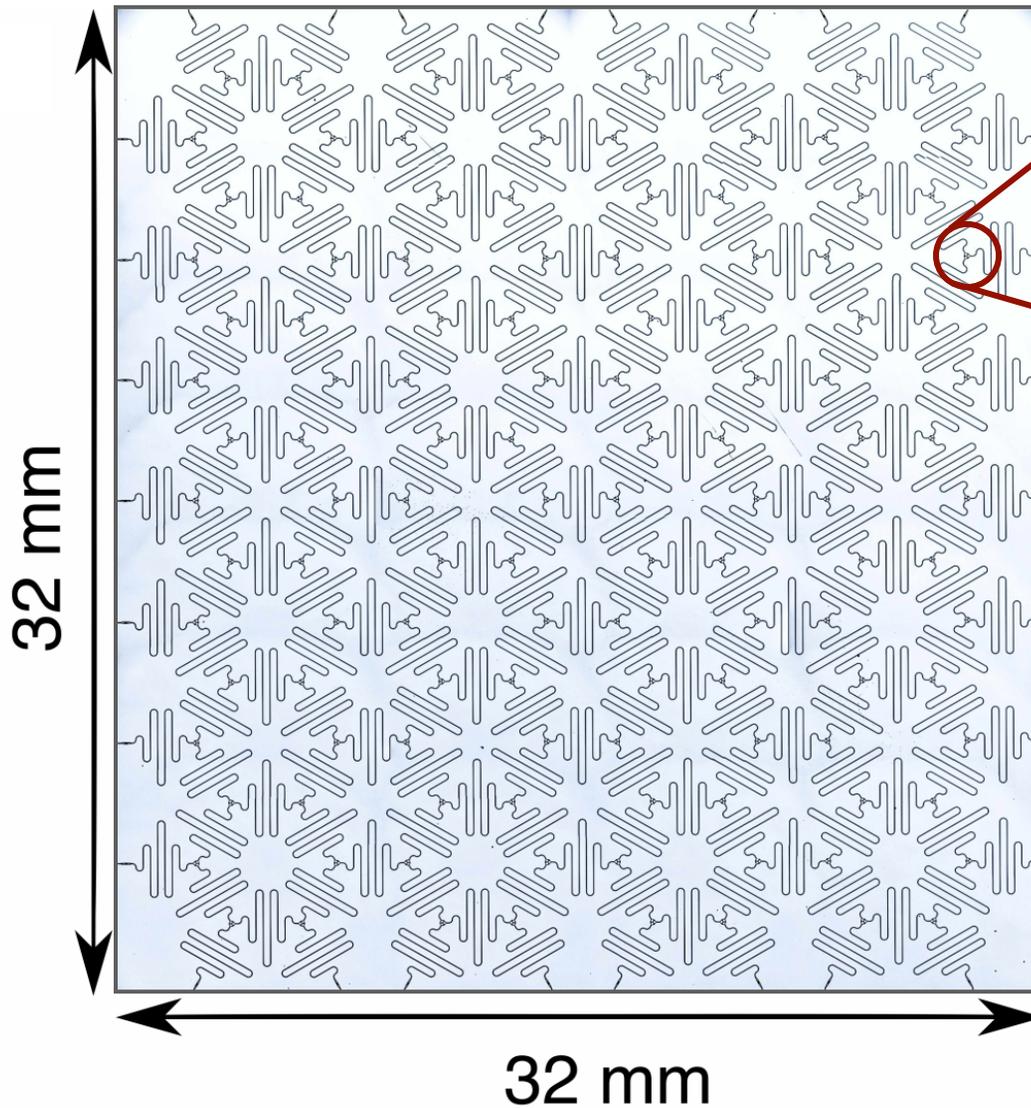
- New lattices
- Different coupling scheme

Photon-Mediated Avoided Crossing



- Douglas *et al.* Nat. Photon. (2015)
Calajó *et al.* PRA (2016)
Liu *et al.* Nature Physics (2016)
Sundaresan *et al.* PRX (2019)
Ferreira *et al.* arXiv 2001.0324 (2020)

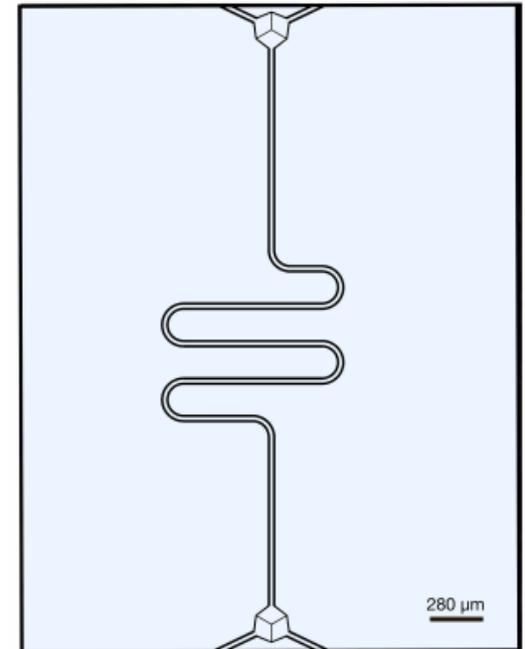
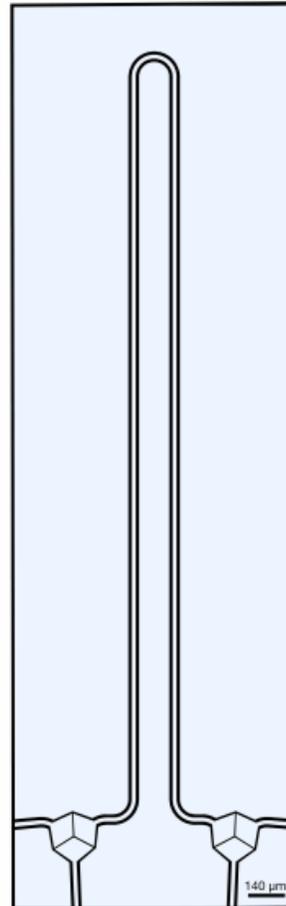
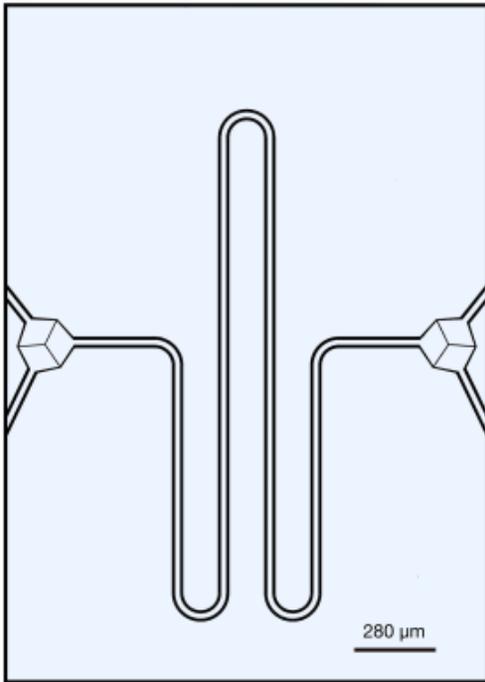
CPW Lattices



- Capacitive coupling of resonators
- Tight-binding solid
- $t < 0$

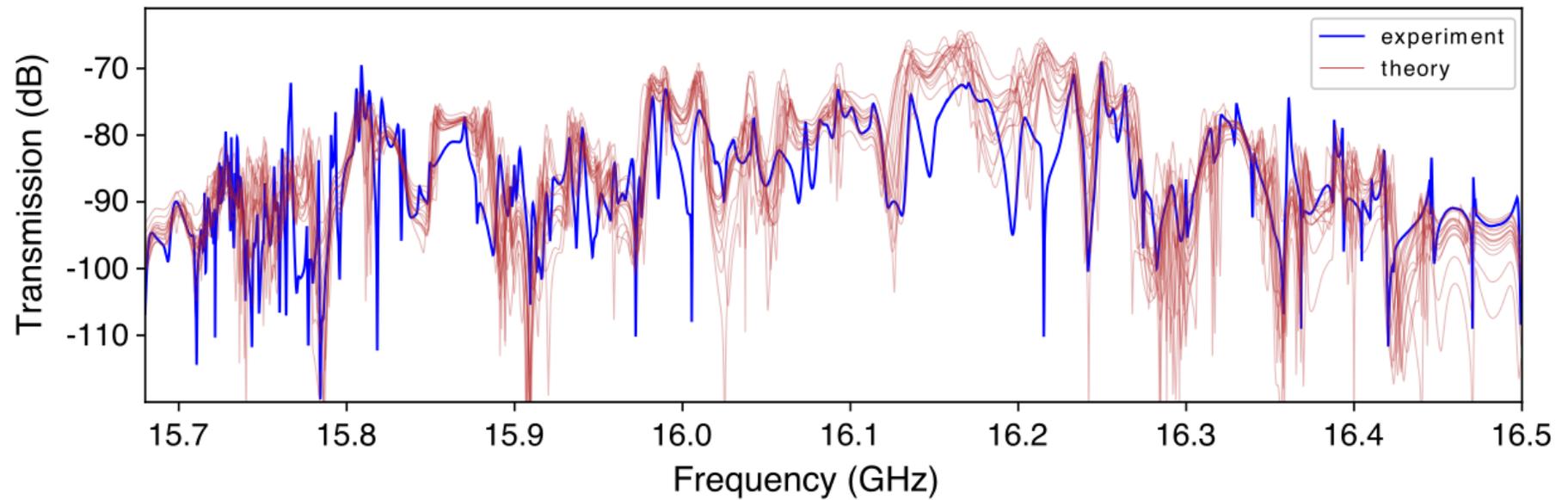
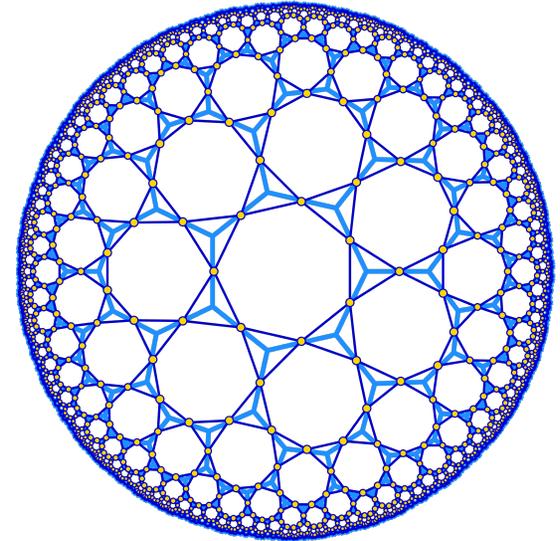
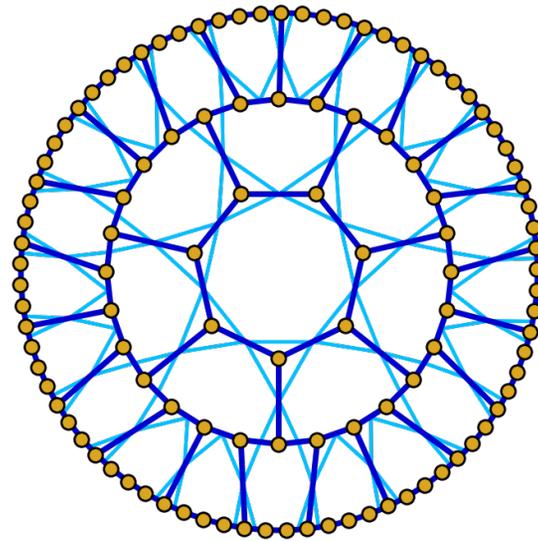
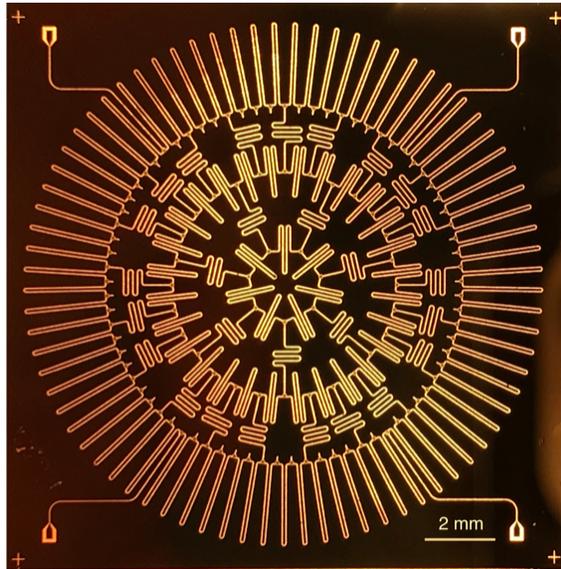
$$\mathbf{H}_{\text{TB}} = \omega_0 \sum_i \mathbf{a}_i^\dagger \mathbf{a}_i - t \sum_{\langle i,j \rangle} (\mathbf{a}_i^\dagger \mathbf{a}_j + \mathbf{a}_j^\dagger \mathbf{a}_i)$$

Deformable Resonators



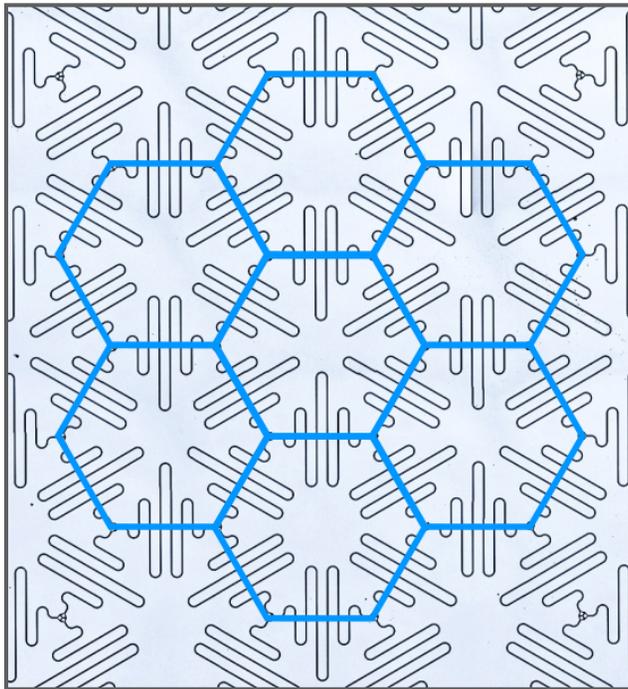
- Frequency depends only on length
- Coupling depends on ends
- “Bendable”

Hyperbolic Lattice



Layout and Effective Lattices

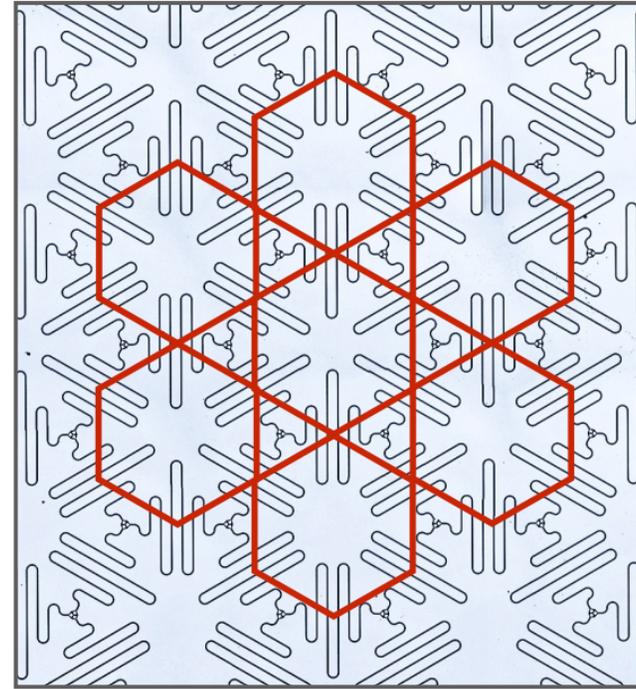
Resonator Lattice



- An *edge* on each resonator

Layout X

Effective Photonic Lattice

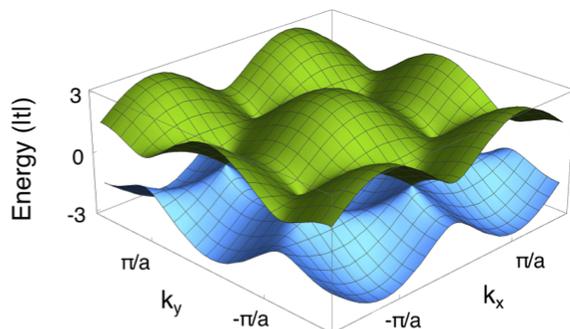
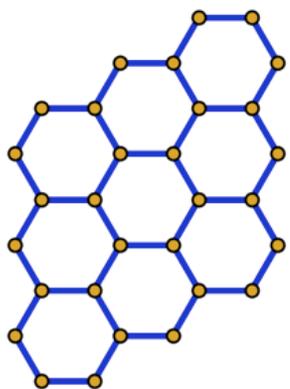


- A *vertex* on each resonator

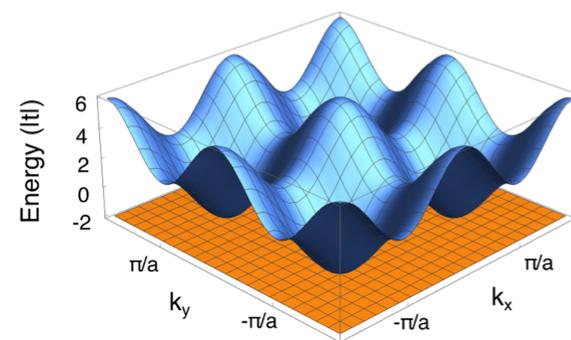
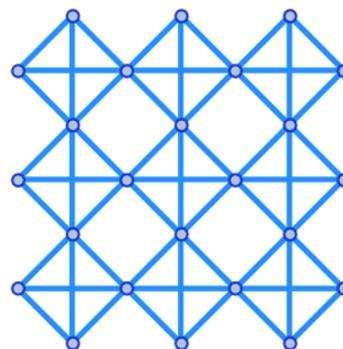
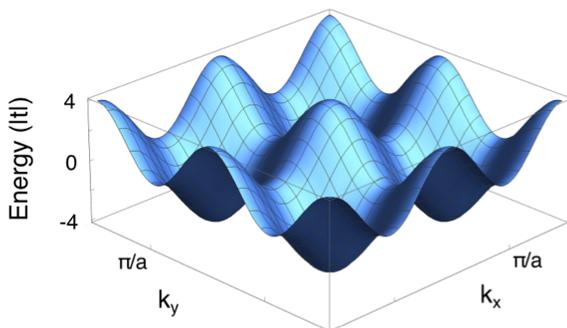
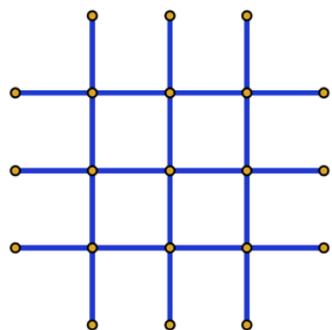
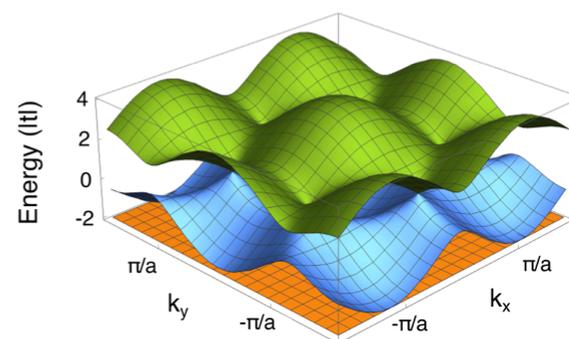
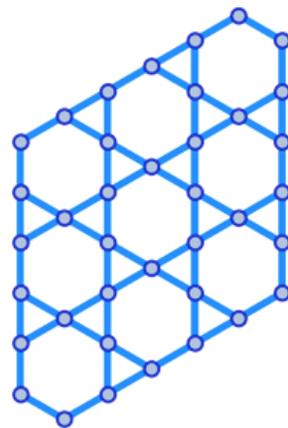
Line Graph $L(X)$

Line-Graph Flat Bands

Layout X



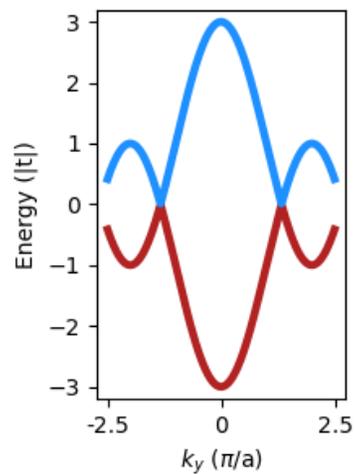
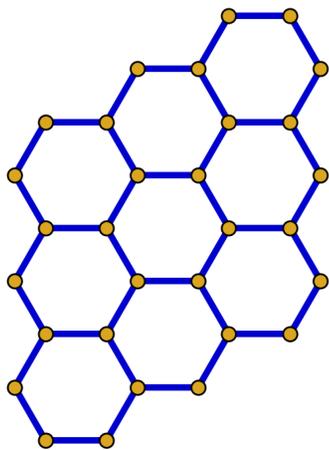
Line Graph $L(X)$



$$E_{\bar{H}_s} = \begin{cases} d - 2 + E_{H_X} & \leftarrow \text{Shifted Bands} \\ -2 & \leftarrow \text{Flat Band(s)} \end{cases}$$

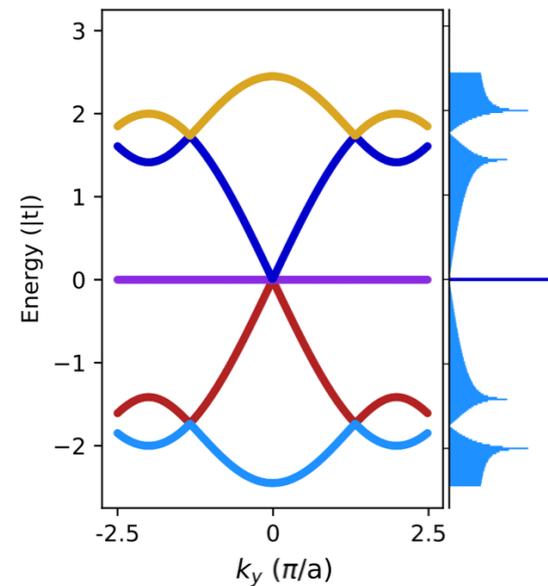
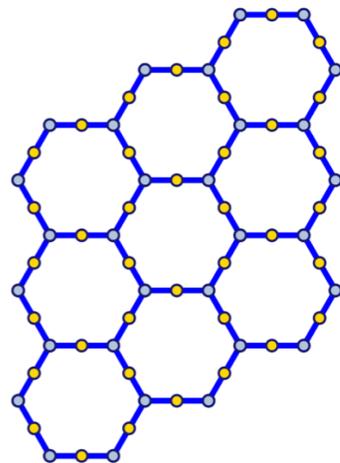
Subdivision Graphs and Optimally Gapped Flat Bands

X



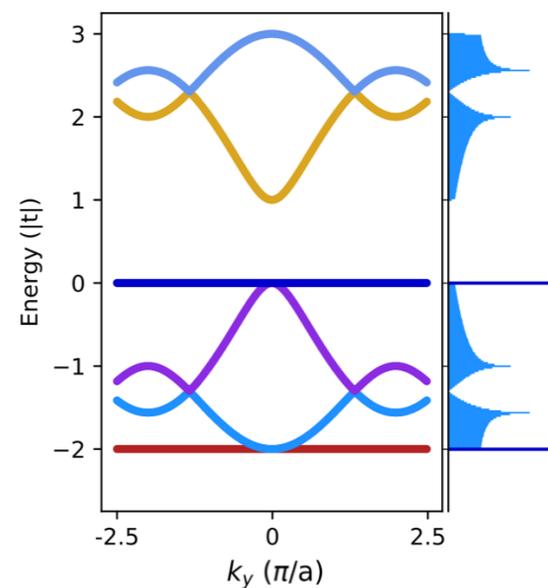
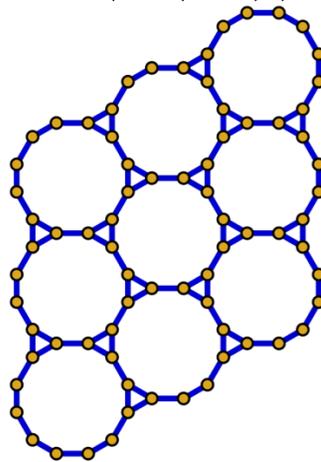
$$E_{\mathcal{S}(X)} = \begin{cases} \pm\sqrt{E_X + 3} \\ 0 \end{cases}$$

$\mathcal{S}(X)$



$$E_{L(\mathcal{S}(X))} = \begin{cases} \frac{1 \pm \sqrt{1 + 4(E_X + 3)}}{2} \\ 0 \\ -2 \end{cases}$$

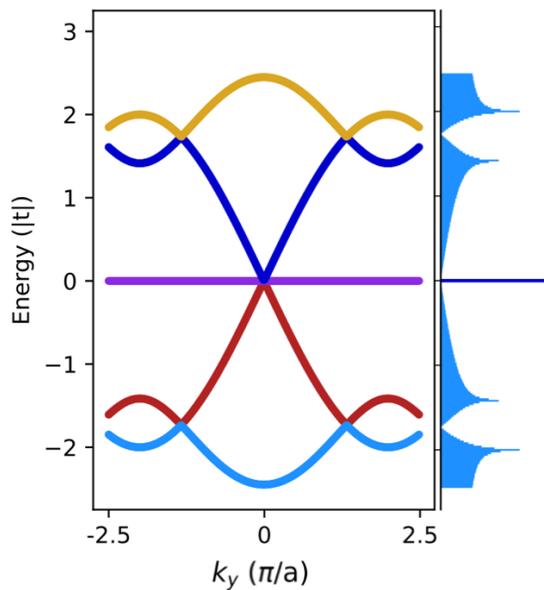
$L(\mathcal{S}(X))$



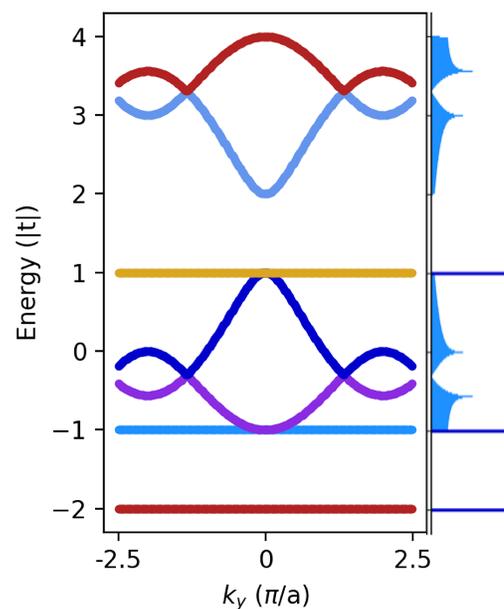
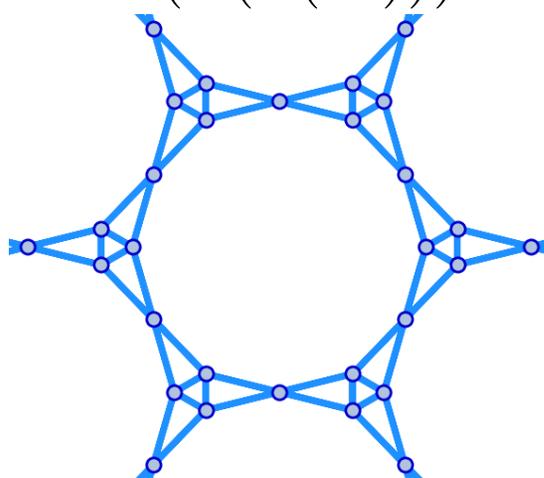
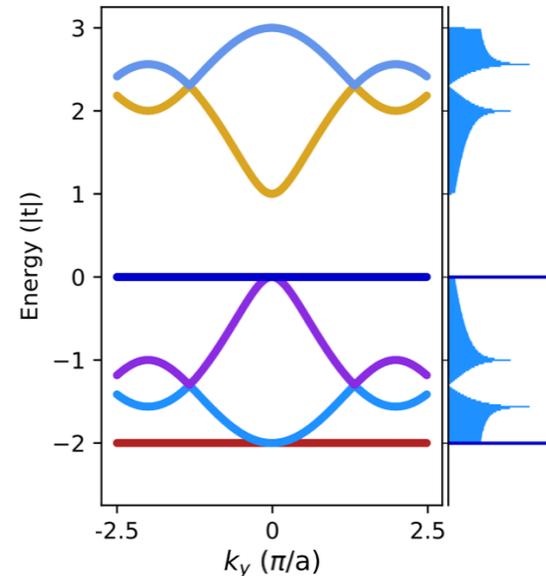
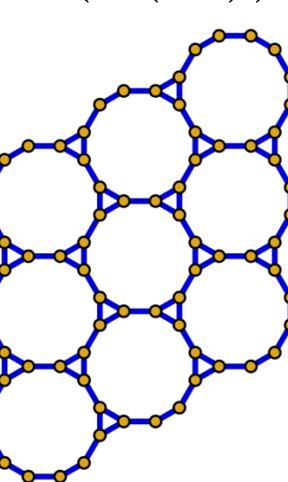
Subdivision Graphs and Optimally Gapped Flat Bands

$\mathcal{S}(X)$

$L(\mathcal{S}(X))$

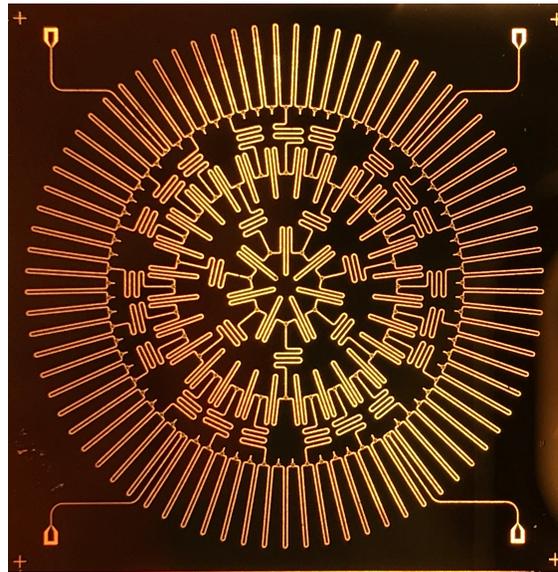


$L(L(\mathcal{S}(X)))$

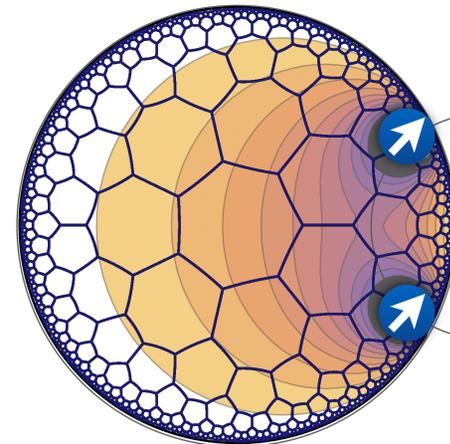


New Lattices for Photon-Mediated Interactions

AJK *et al.* Nature **571** (2019)



Bienieas, AJK *et al.* In Prep (2021)

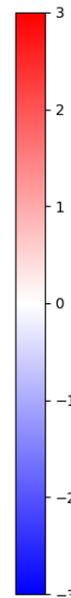
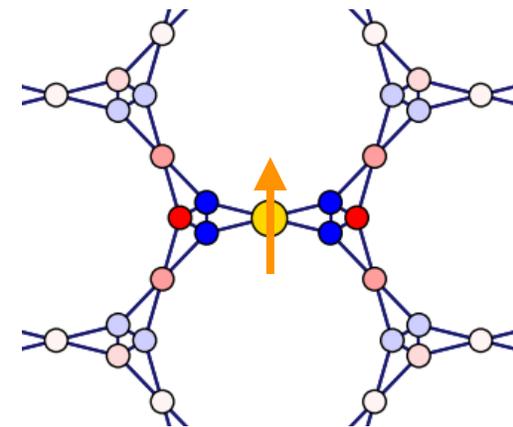
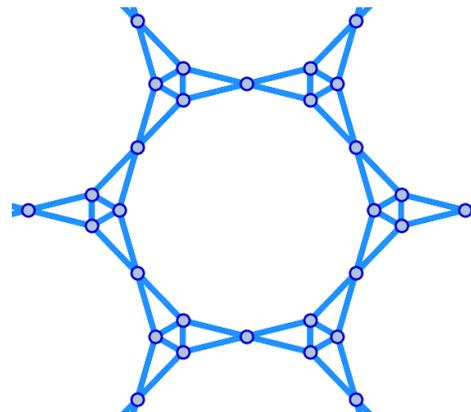
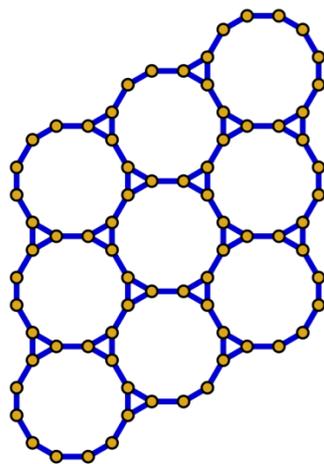


Hyperbolic Lattice

- Follows hyperbolic metric

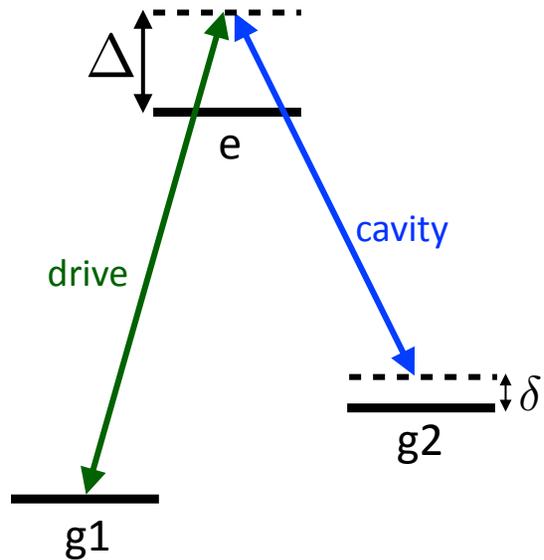
Flat-Band Lattice

- Frustrated Magnet



AJK *et al.* Comm. Math. Phys. **376**, 1909 (2020)

Raman-Coupled Spin Models

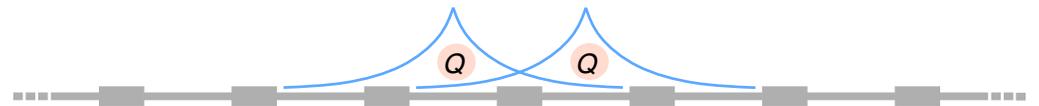


- Microwave-activated coupling
- Two relevant detunings
- Effective swap interaction

$$H_{Raman} = \hbar \frac{g^2 \Omega^2}{\Delta^2 \delta} \sigma_1^+ \sigma_2^- + h.c.$$

1D-Photonic Crystal + Single Drive

- Exponentially localized interaction



1D-Photonic Crystal + Multiple Drives

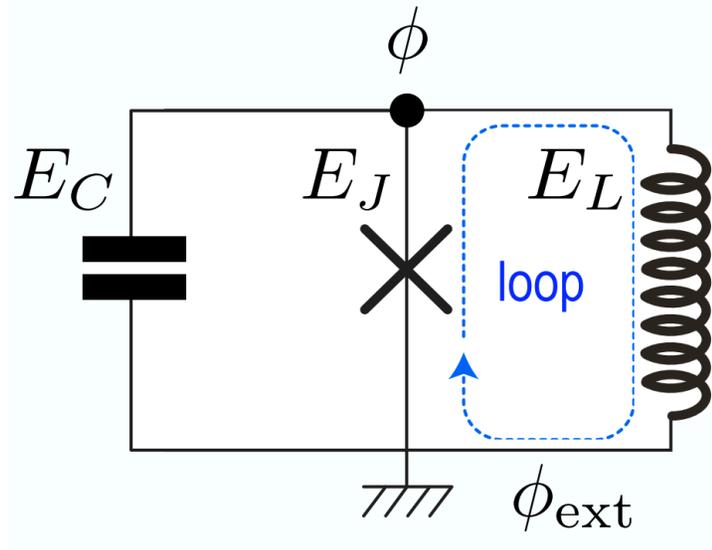
- Superposition of exponentials
- Approximate power-law interaction

Need 3-level qubit

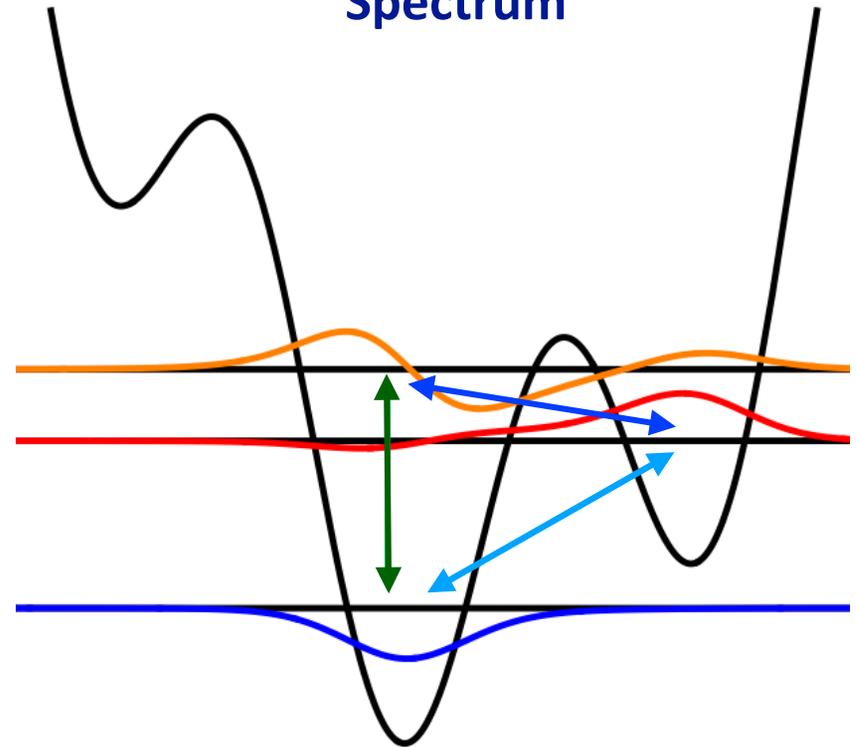
Fluxonium

Fluxonium

Circuit



Spectrum



Hamiltonian

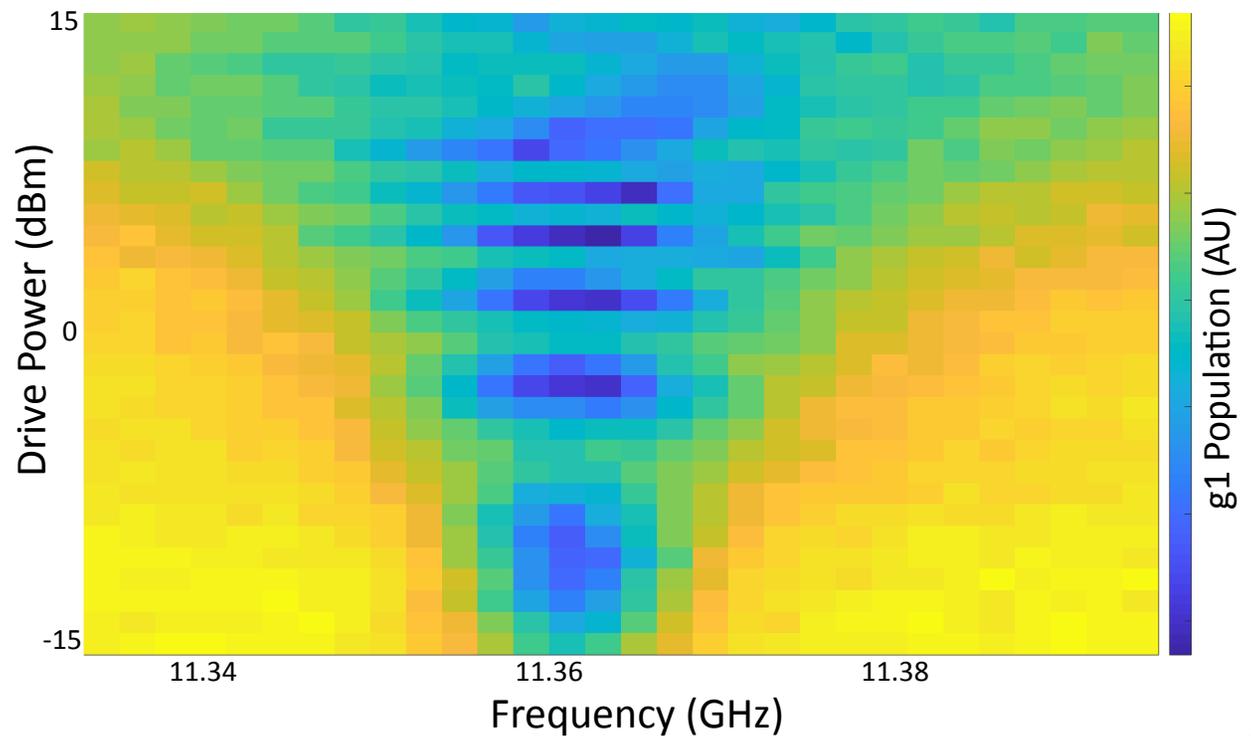
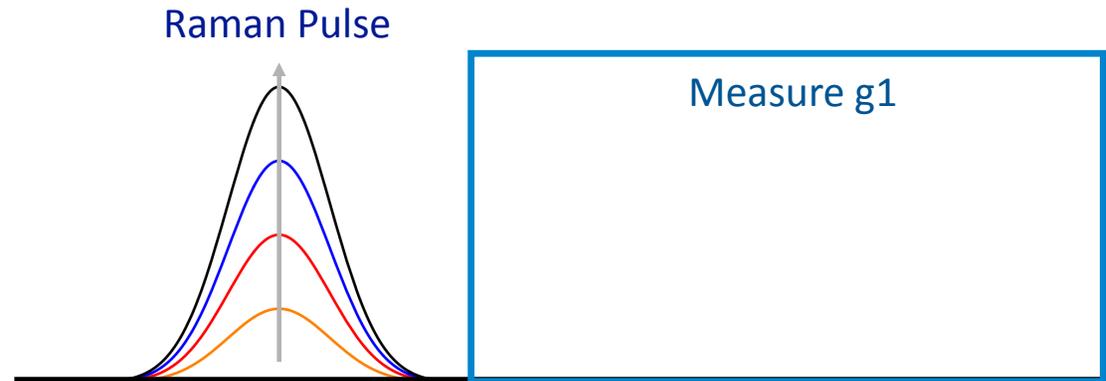
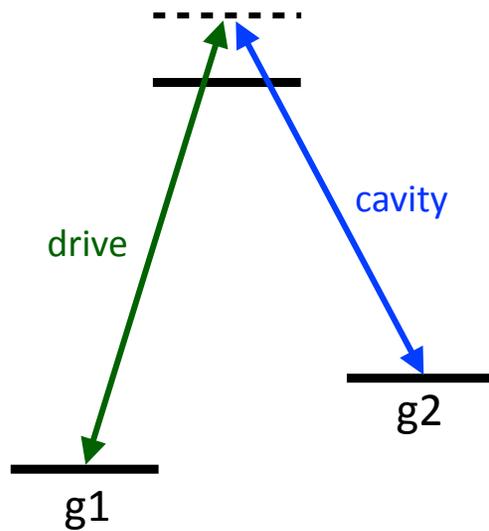
$$H = 4E_C n^2 + \frac{1}{2} E_L \phi^2 - E_J \cos(\phi - \phi_{ext})$$

- plasmon transitions
- fluxon transitions

Raman Transitions in Fluxonium

Rabi oscillation

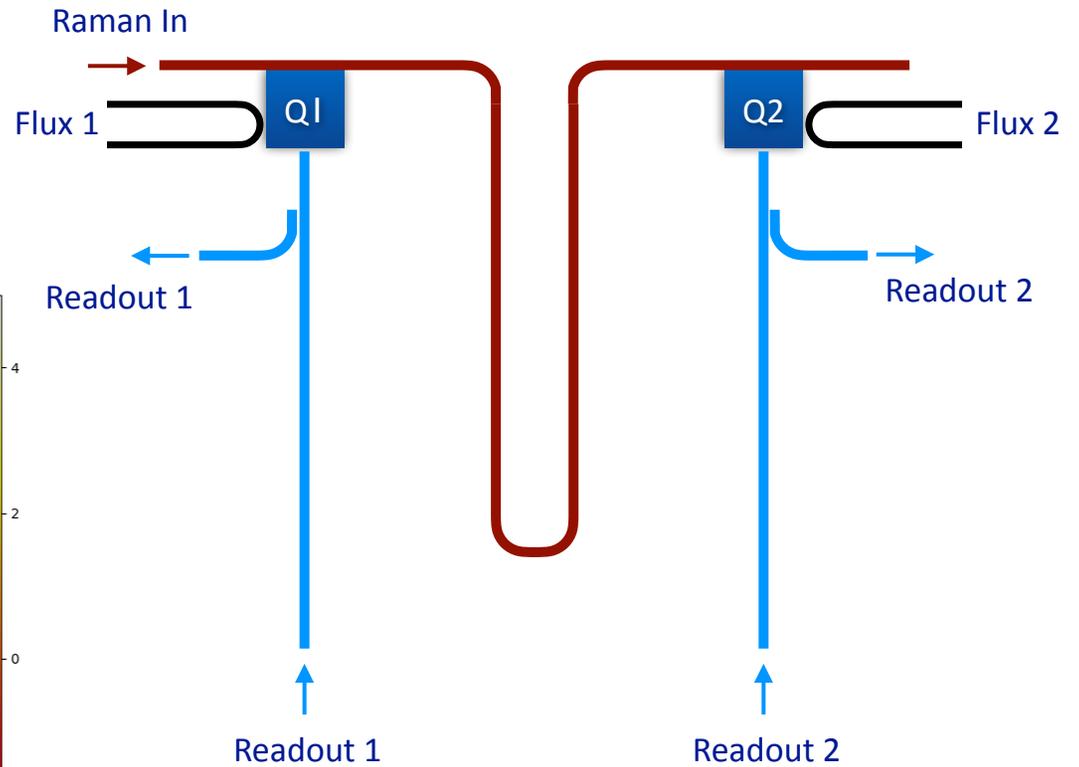
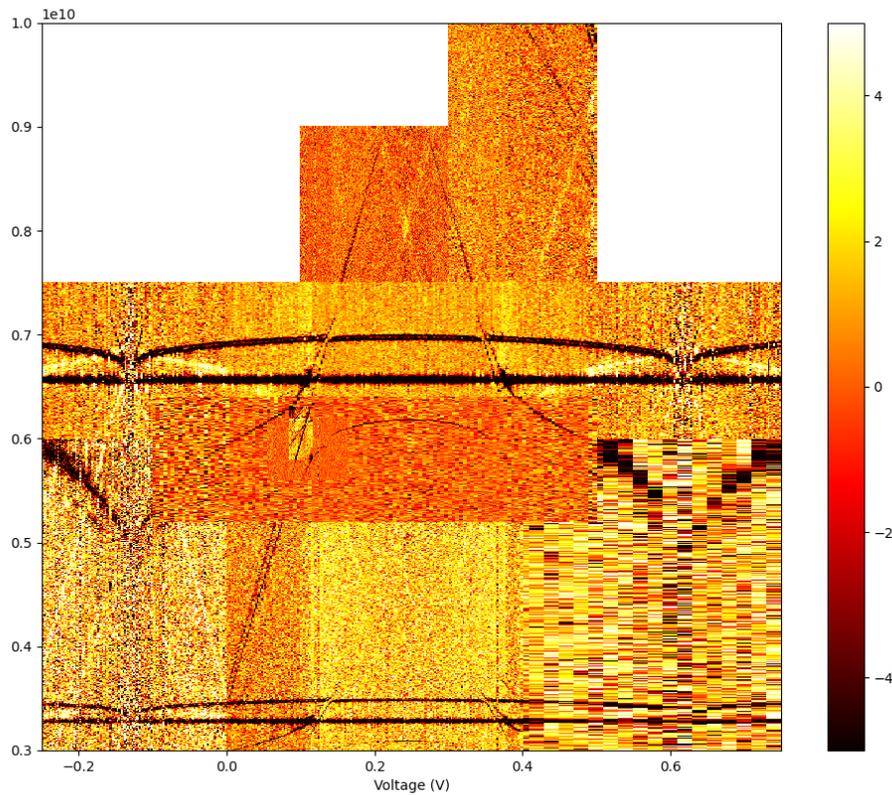
- Gaussian pulse off-resonant of plasmon
- Vacuum Rabi rate of fluxon



Second-Generation Raman Device

Redesigned Device

- 3-cavities
- Separate resonators allow
 - Optimized readout
 - Parallel readout and coupling

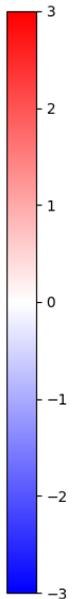
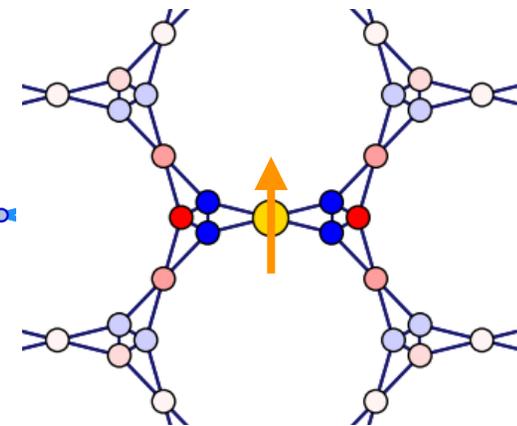
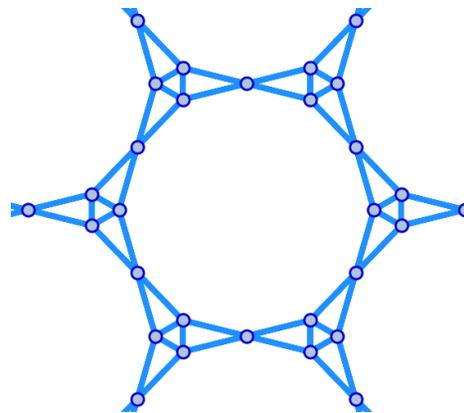
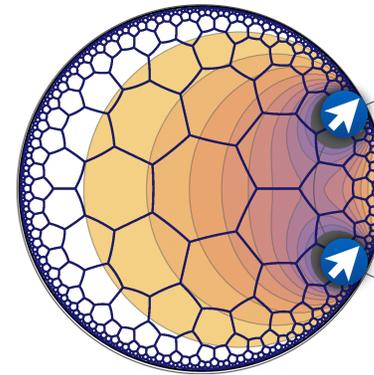
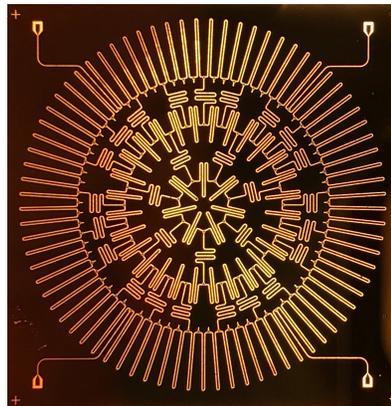


Conclusion and Outlook

- Circuit QED lattices
 - Photon-mediated interactions
 - Lithographic control
- Hyperbolic lattices
- Flat-band lattices

● Outlook

- Spin models in curved spaces
- Frustrated interactions in flat bands



Kollár *et al.* Nature **571** (2019)

Kollár *et al.* Comm. Math. Phys. **376**, 1909 (2020)

Kollár *et al.* arXiv:2005.05379 (2020)

Boettcher *et al.* Phys. Rev. A **102**, 032208 (2020)

Engineering Qubit-Qubit Interactions in Circuit QED Lattices

Andrew Houck
EE, Princeton



Peter Sarnak
Math, Princeton



Alexey Gorshkov
NIST, JQI



Steve Flammia
AWS



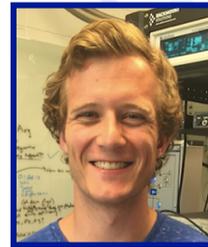
James Williams
UMD



Alicia Kollár

Department of Physics and JQI, University of Maryland

Mattias
Fitzpatrick



Jacob
Bryon



Sandesh
Kalantre



Maya
Amouzegar



Adrian
Chapman



Przemislav
Bienias



Igor
Boettcher



Martin
Ritter

PhD and Postdoc Positions Available

