

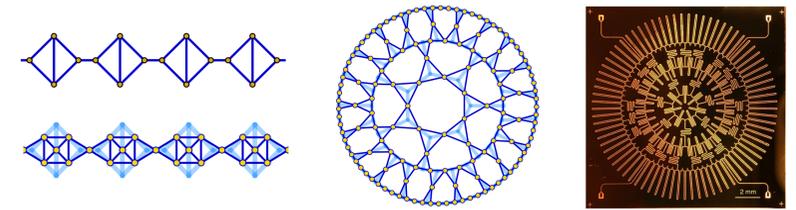
# Quantum Simulation in Circuit QED Lattices

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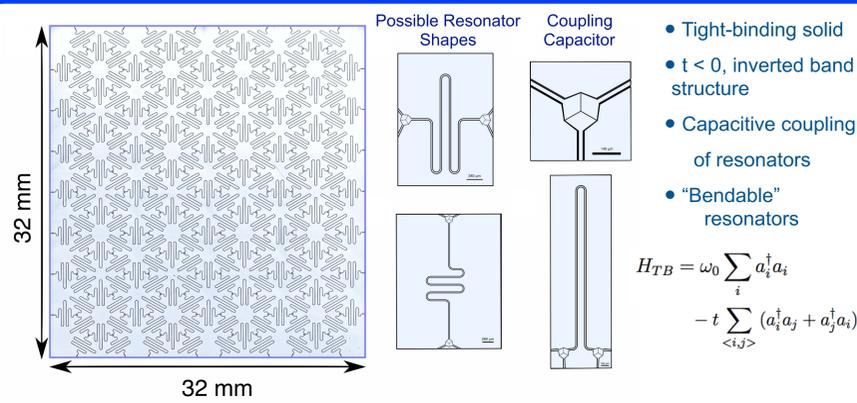
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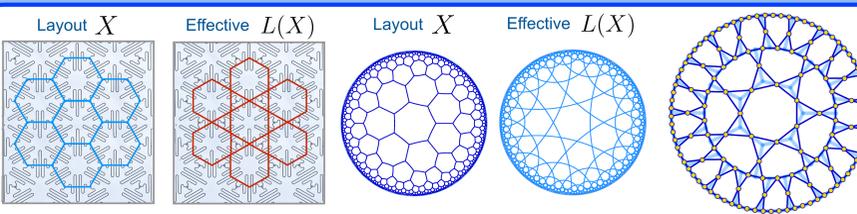
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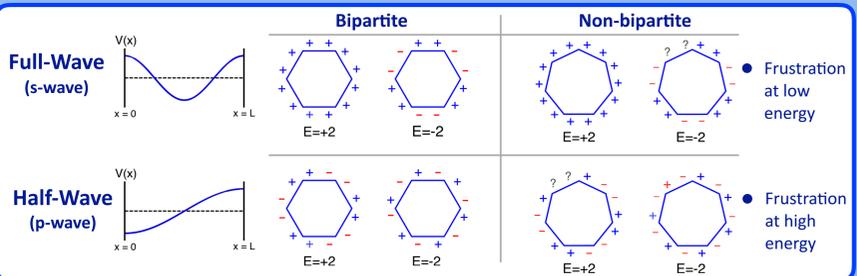
## Circuit QED Lattices



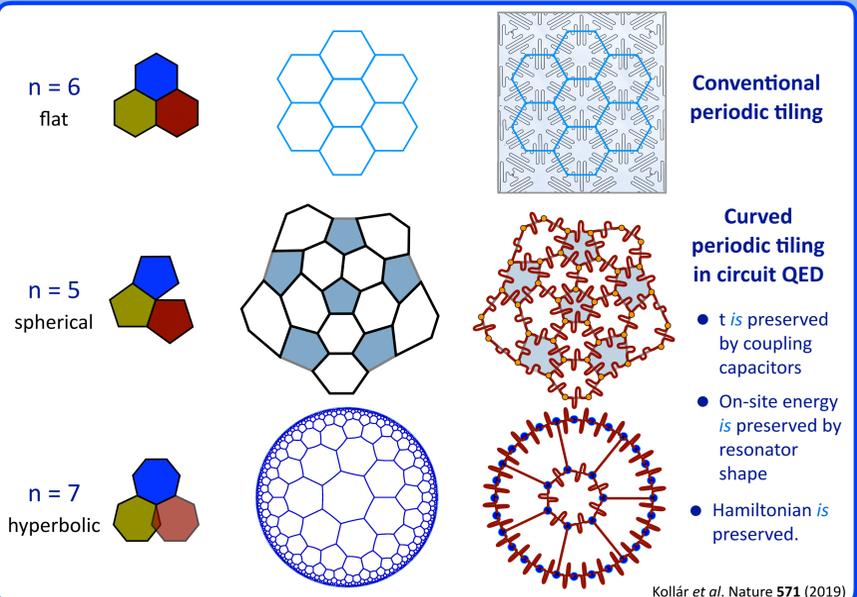
## Layout and Effective (Line-Graph) Lattices



## Mode Functions and Frustration



## Flat and Non-Flat Tilings



## Band Structures and Flat Bands

### Effective Full-Wave Hamiltonian

$$\bar{H}_s(X) = H_{L(X)}$$

- Can be derived from layout and graph theory

### Combining:

#### Incidence Operator

$$M: \ell^2(X) \rightarrow \ell^2(L(X))$$

$$m(\epsilon, \nu) = \begin{cases} 1, & \text{if } \epsilon \text{ and } \nu \text{ are incident,} \\ 0 & \text{otherwise.} \end{cases}$$

#### Degree Matrix

$$D_X = \text{diag}(\text{coordination numbers})$$

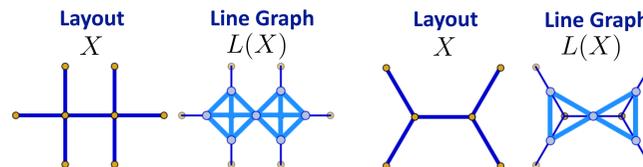
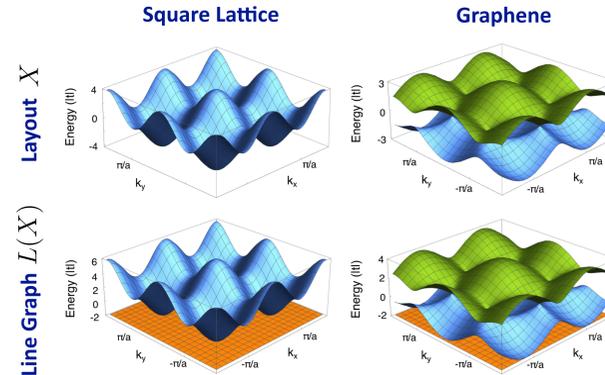
$$M^t M = D_X + H_X$$

$$M M^t = 2I + \bar{H}_s(X)$$

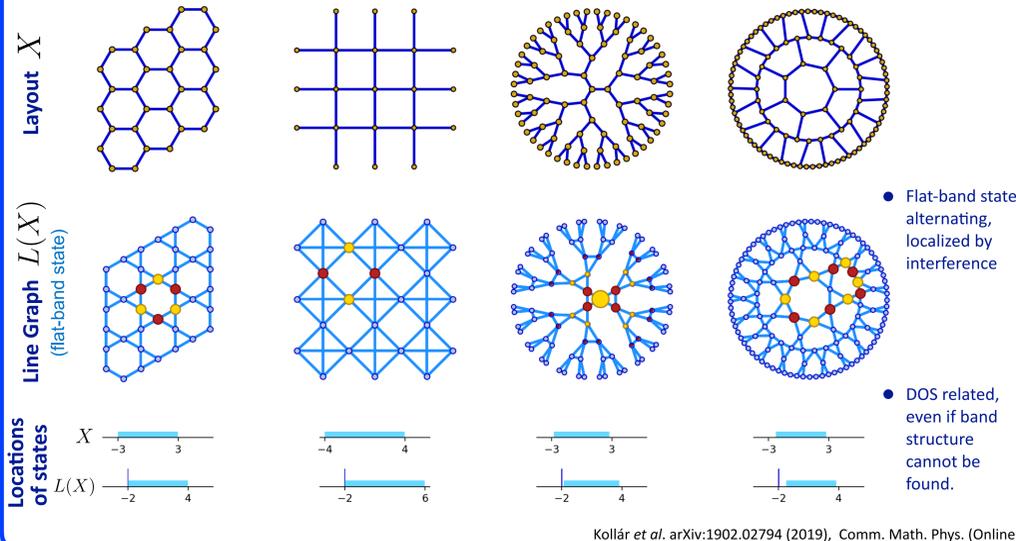
$$E_{\bar{H}_s} = \begin{cases} d - 2 + E_X \\ -2 \end{cases}$$

### If coordination number is constant:

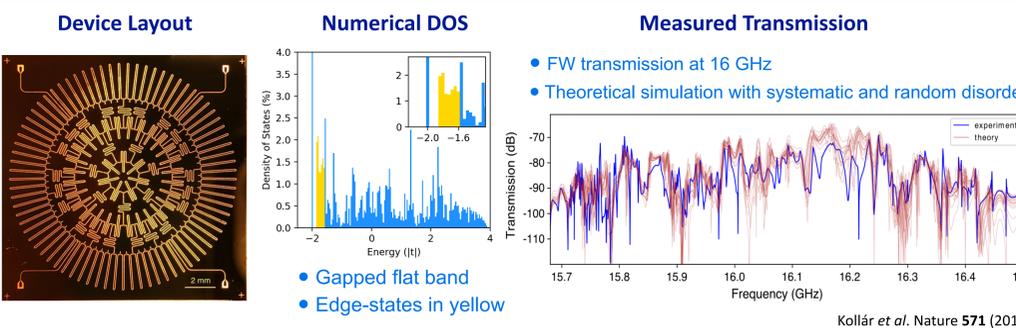
- Energies shift up
- Momentum structure unchanged
- Flat band(s) appear at -2



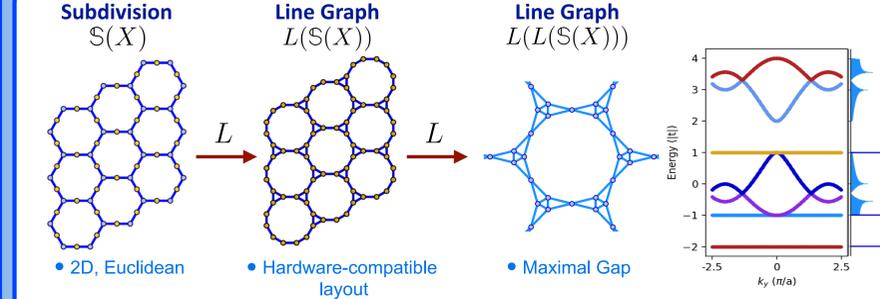
- Layout edges become line-graph points
- Vertex creates all-to-all coupling
- 4-way vertex  $\rightarrow$  square with diagonal hopping
- Layout edges become line-graph points
- Vertex creates all-to-all coupling
- 3-way vertex  $\rightarrow$  triangle



## Heptagon-Kagome Device

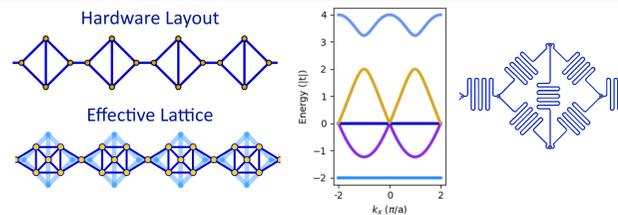


## Subdivision Graphs and Maximal Gaps



### Quasi-1D Chain

- Good surface to volume
- Side access to bulk
- Small unit cell
- Near-maximal gap
- Topological edge states



## Photonic Bound States

### 1D-Photonic Crystal + qubit

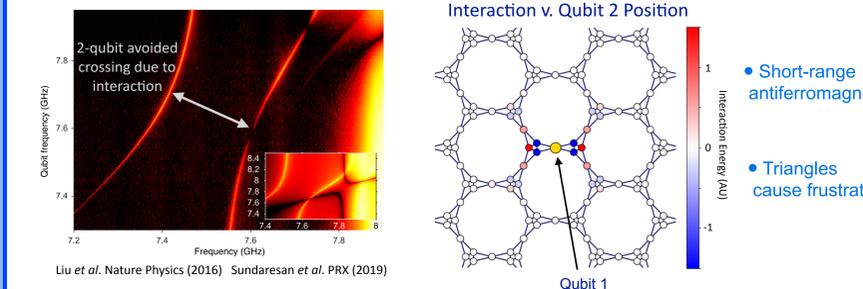
- Effective swap interaction
- All modes in parallel
- Exponentially localized interaction

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

### Other Forms of Interaction Need:

- More sophisticated coupling scheme
  - Raman-coupled Fluxonium
- More sophisticated photonic crystal
  - Flat band
  - Dirac Cone
  - 2D
  - Hyperbolic lattice

### Flat-band-mediated Interaction:

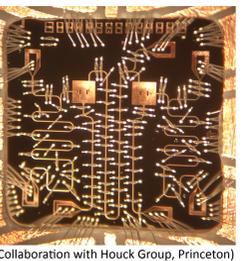


### Raman Coupling

- Microwave-activated coupling
  - Two relevant detunings
  - Effective swap interaction
  - Multiple microwave drives superimpose interactions
  - e.g. Approximate power-law interactions
- $$H_{Raman} = \hbar \frac{g^2 \Omega^2}{\Delta_1 \Delta_2} \sigma_1^+ \sigma_2^- + h.c.$$

Douglas et al. Nat. Photon. (2015) Calajó et al. PRA (2016)

### Two-Qubit Prototype



## Acknowledgements

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