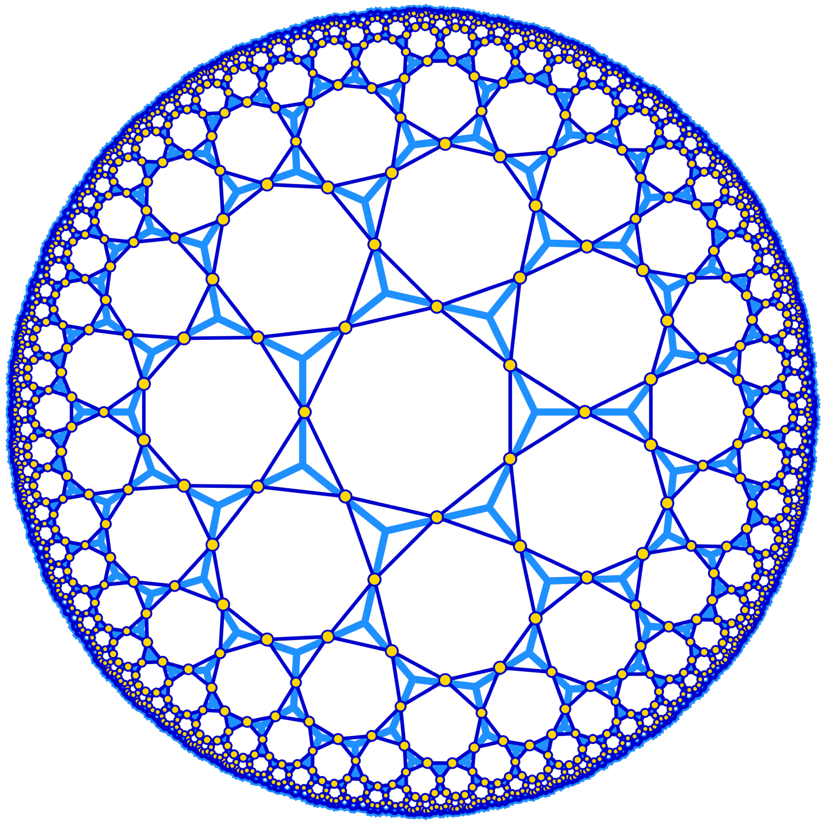
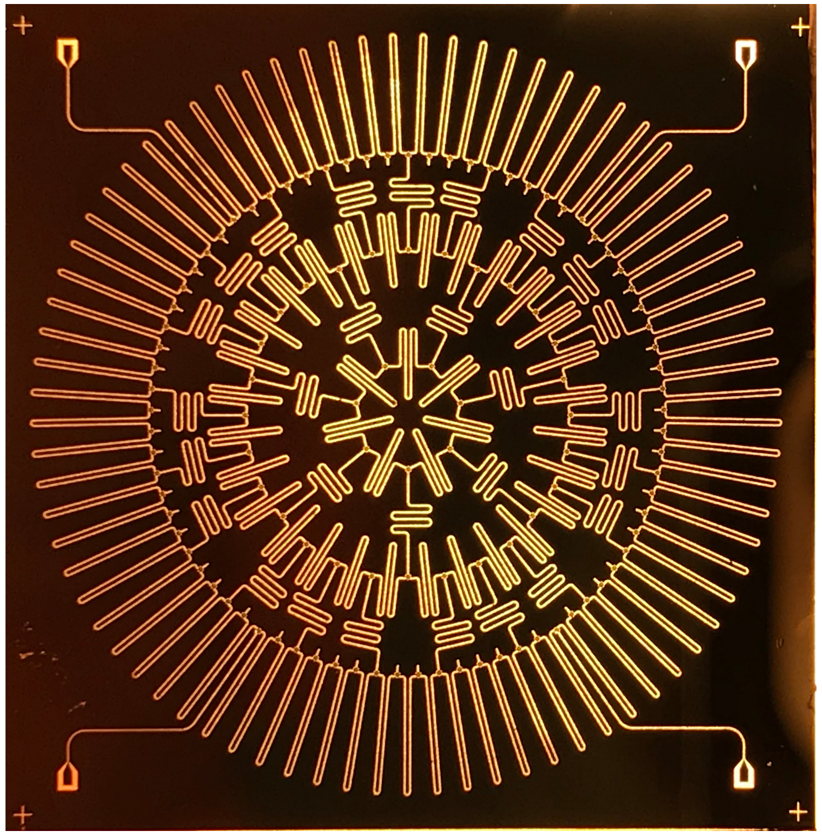
Lattice Simulators in Circuit QED

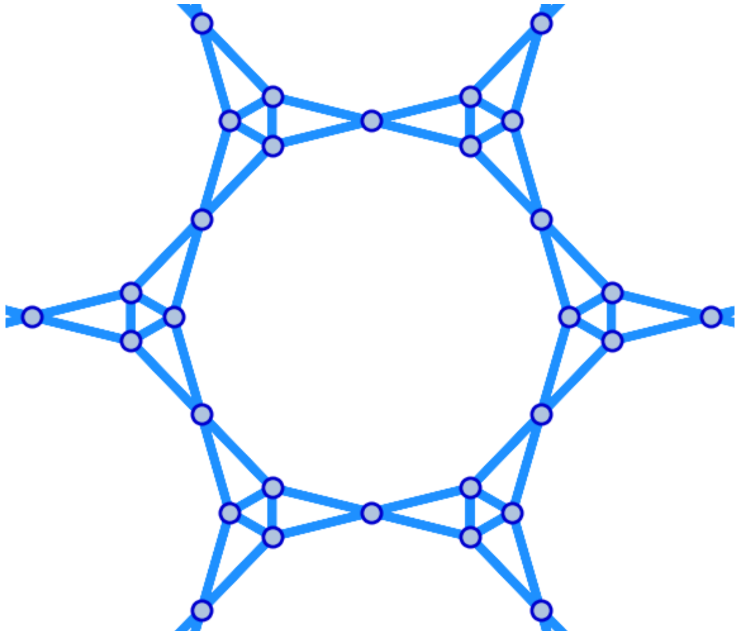
Alicia Kollár

Department of Physics, University of Maryland

Department of Electrical Engineering, Princeton University







KITP, April 9th, 2019

Outline

- Coplanar Waveguide (CPW) Lattices
  - Interacting photons
- Hyperbolic lattices
  - Projection to flat space
  - Deformable resonators
- Flat-band lattices
  - Line graphs
  - Maximal gaps
- Non-linear lattices
  - Limit cycles
  - Chaos

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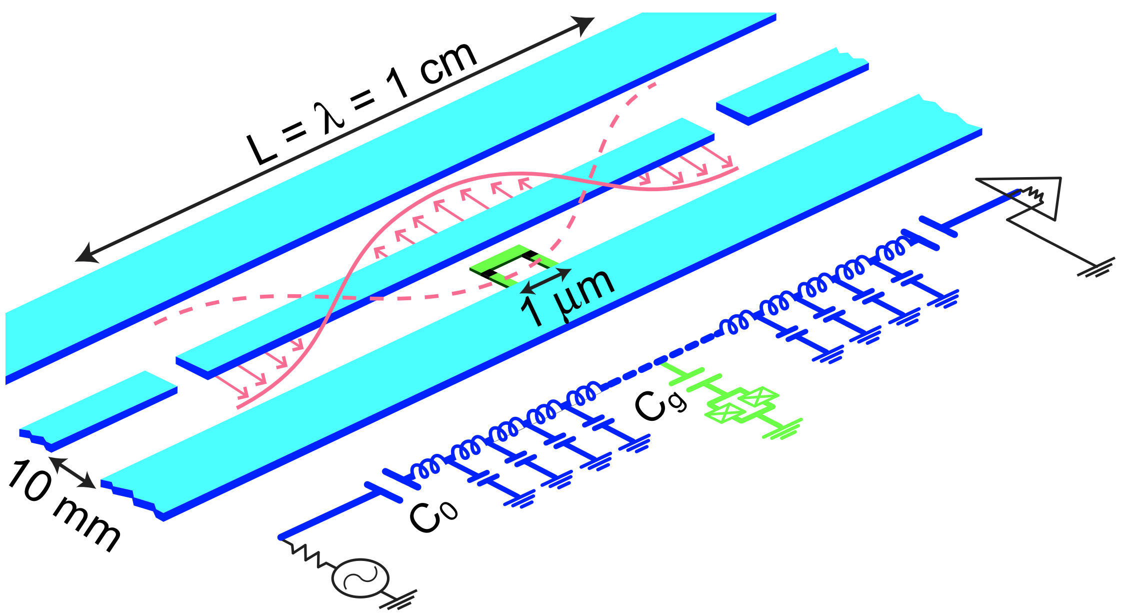
Microwave Lattice Sites

Coplanar Waveguide Resonator



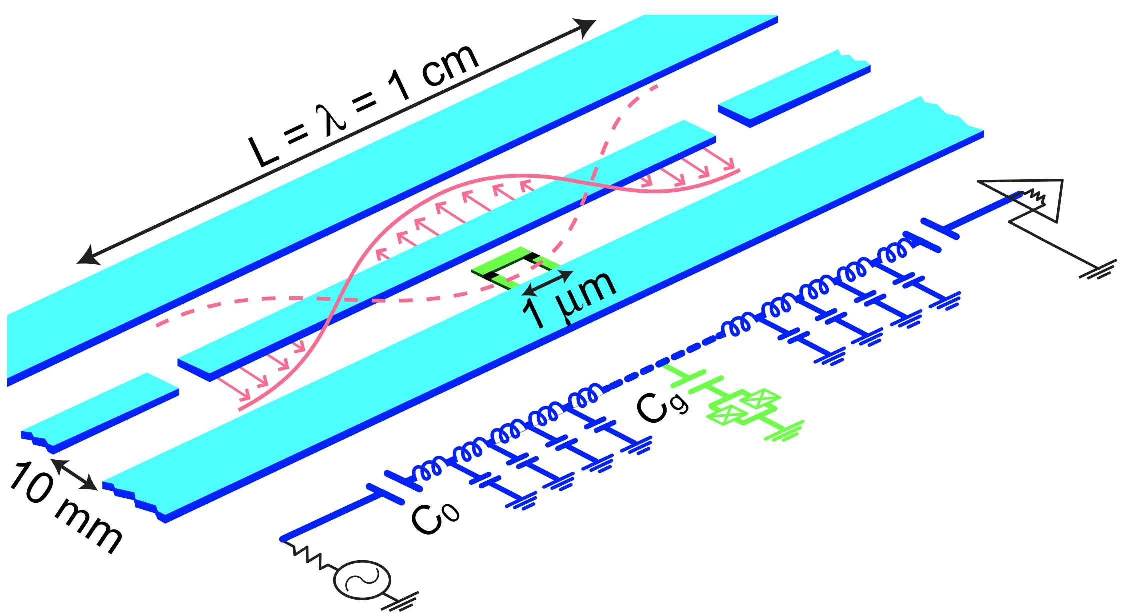
Microwave Lattice Sites

Qubit-Cavity

(Jaynes-Cummings Model)

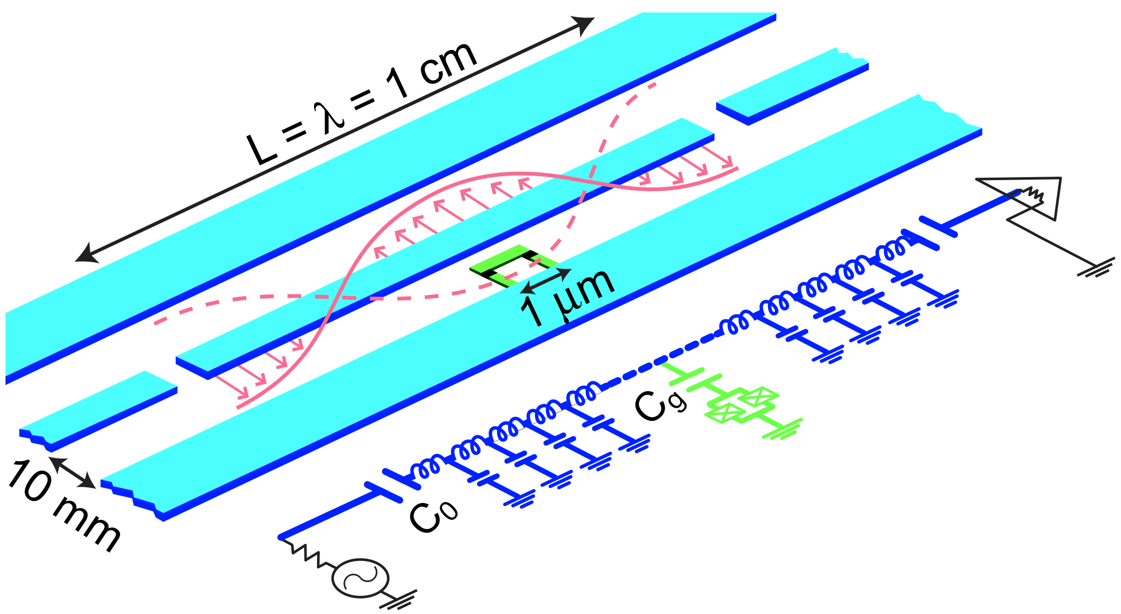
$$H_{JC} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + g_0(a^\dagger \sigma^- + a\,\sigma^+)$$

Coplanar Waveguide Resonator



Microwave Lattice Sites

Coplanar Waveguide Resonator

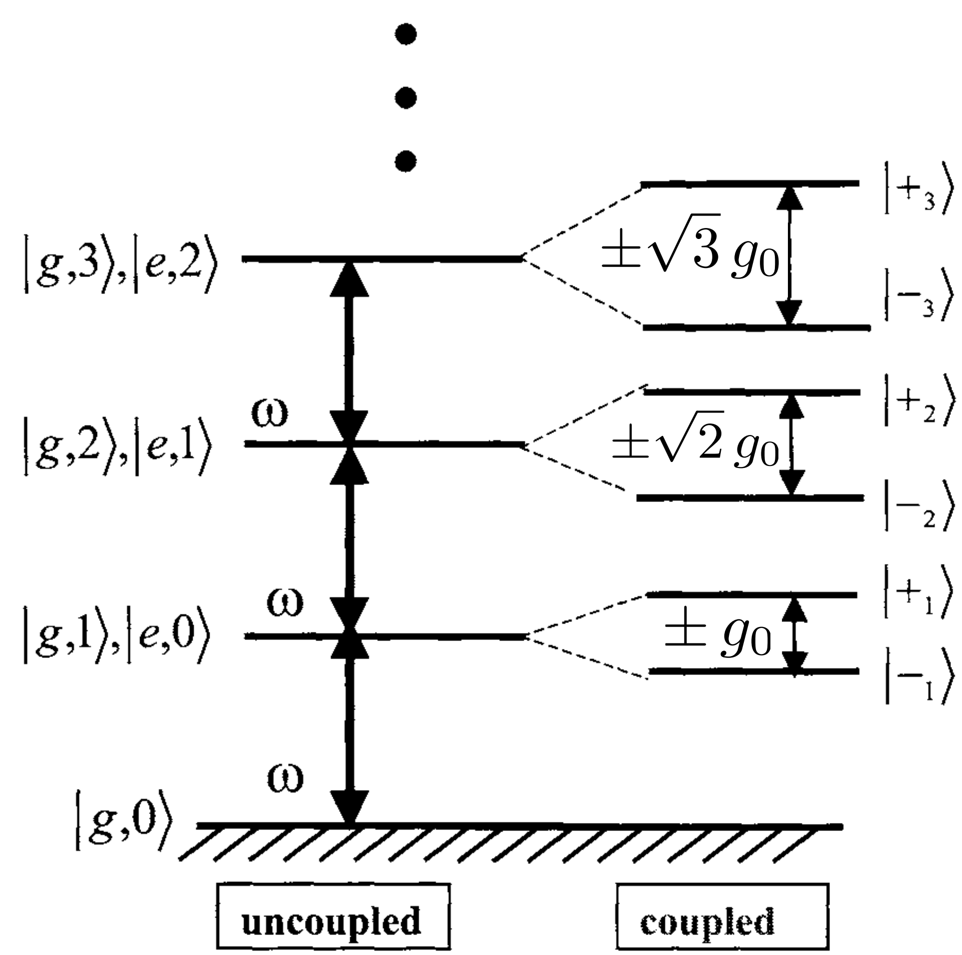


Qubit-Cavity

(Jaynes-Cummings Model)

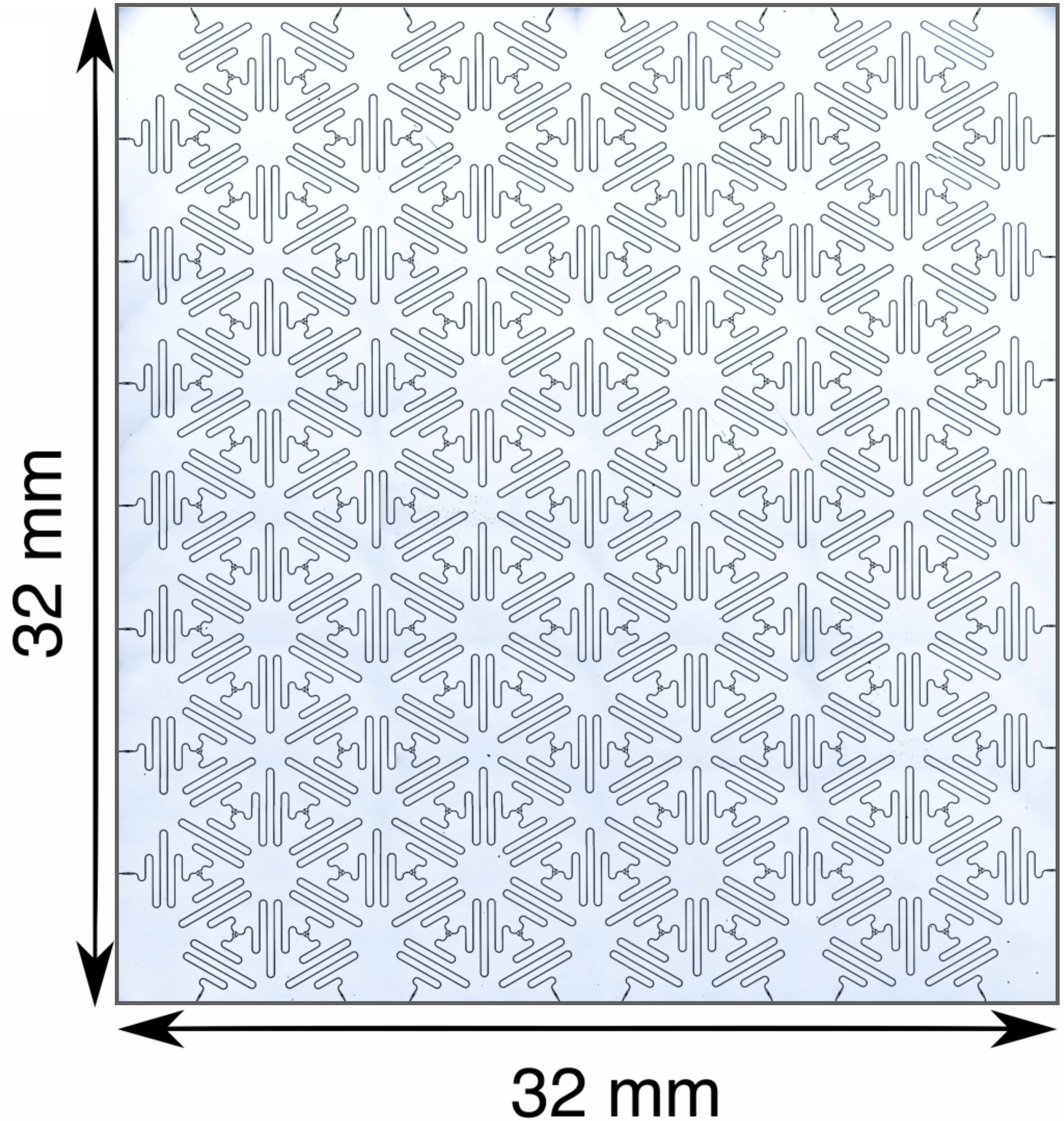
$$H_{JC} = \omega_c a^\dagger a + \frac{1}{2}\omega_q \sigma_z + g_0(a^\dagger \sigma^- + a\,\sigma^+)$$

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



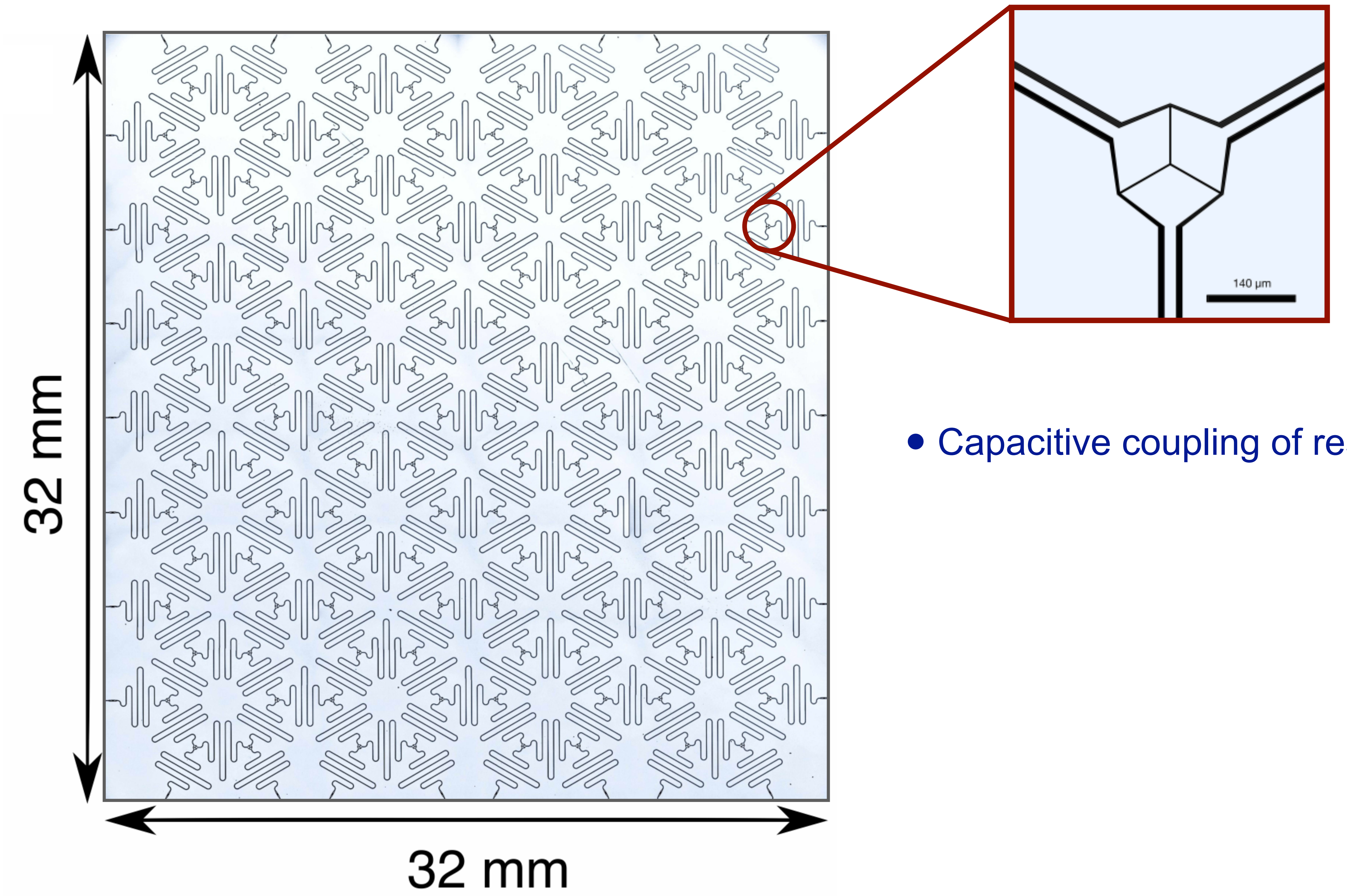
Ye *et al*. Advances in AMO Physics **49** (2003)

CPW Lattices



Houck *et al*. Nat Phys **8**, (2012)
Underwood *et al*. PRA **86**, 023837 (2012)

CPW Lattices



- Capacitive coupling of resonators

Houck *et al*. Nat Phys **8**, (2012)
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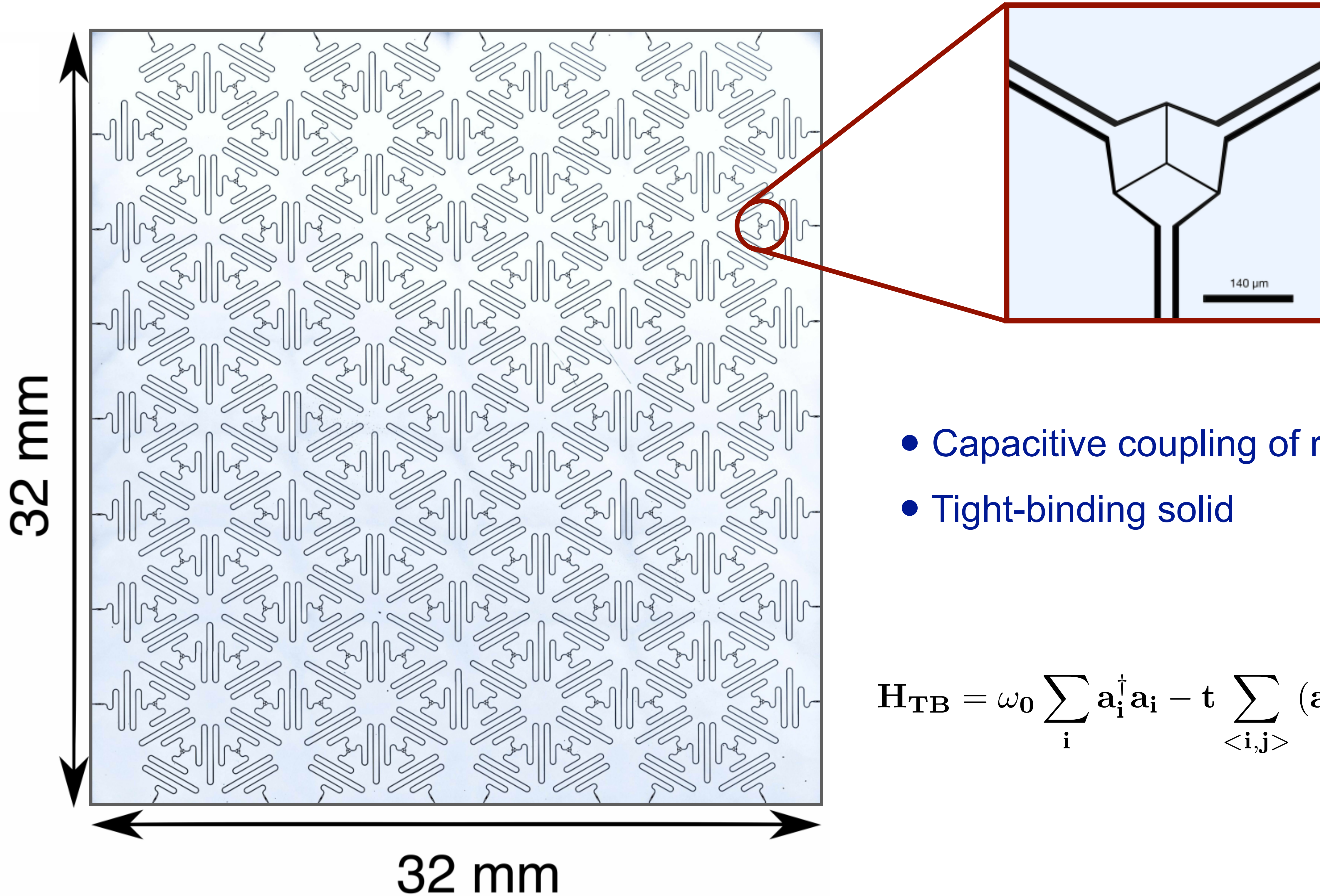
CPW Lattices



- Capacitive coupling of resonators
- Tight-binding solid

$$\mathbf{H_{TB}} = \omega_0 \sum_{\mathbf{i}} \mathbf{a_i^\dagger a_i} - \mathbf{t} \sum_{<\mathbf{i,j}>} (\mathbf{a_i^\dagger a_j} + \mathbf{a_j^\dagger a_i})$$

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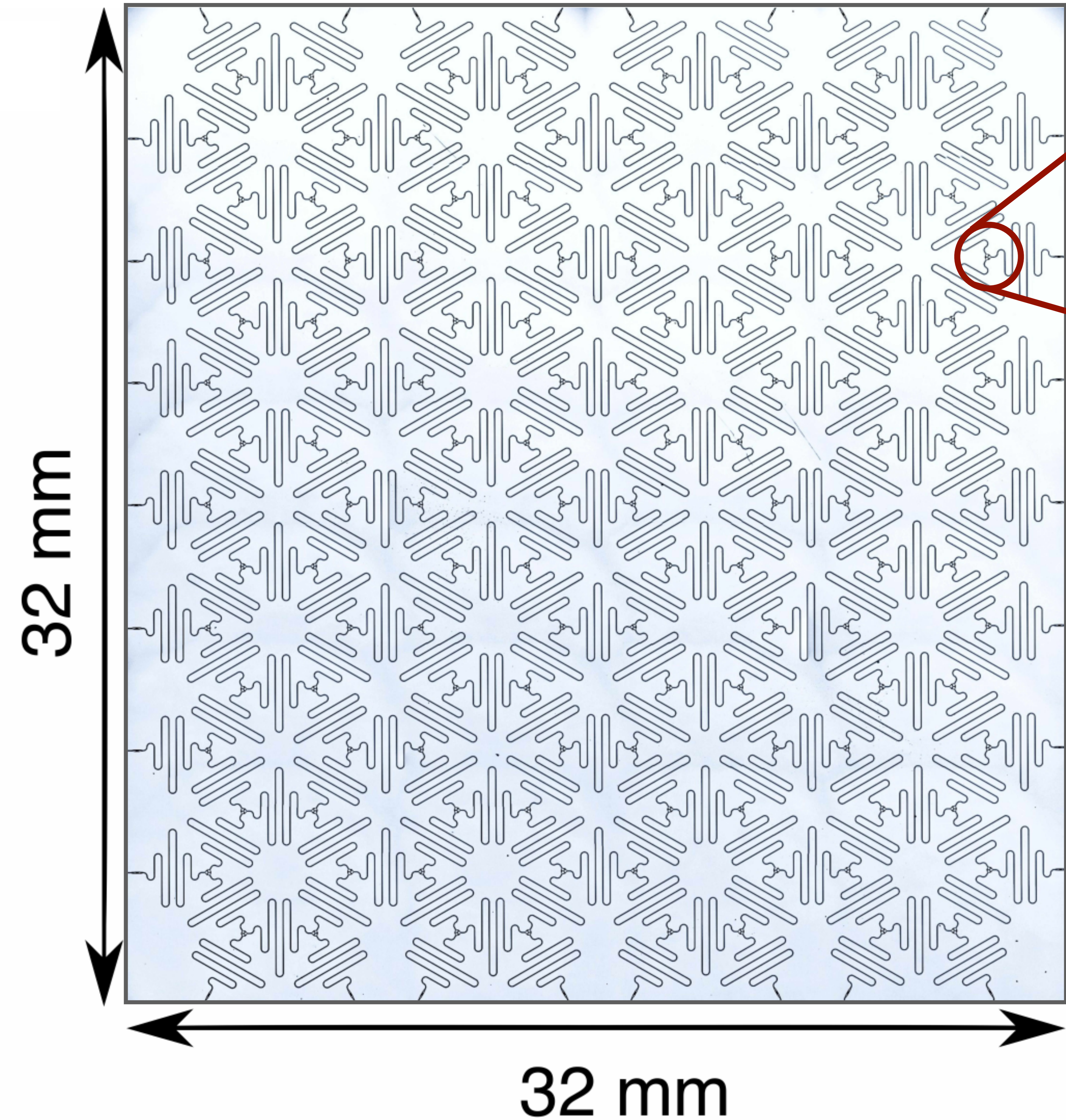
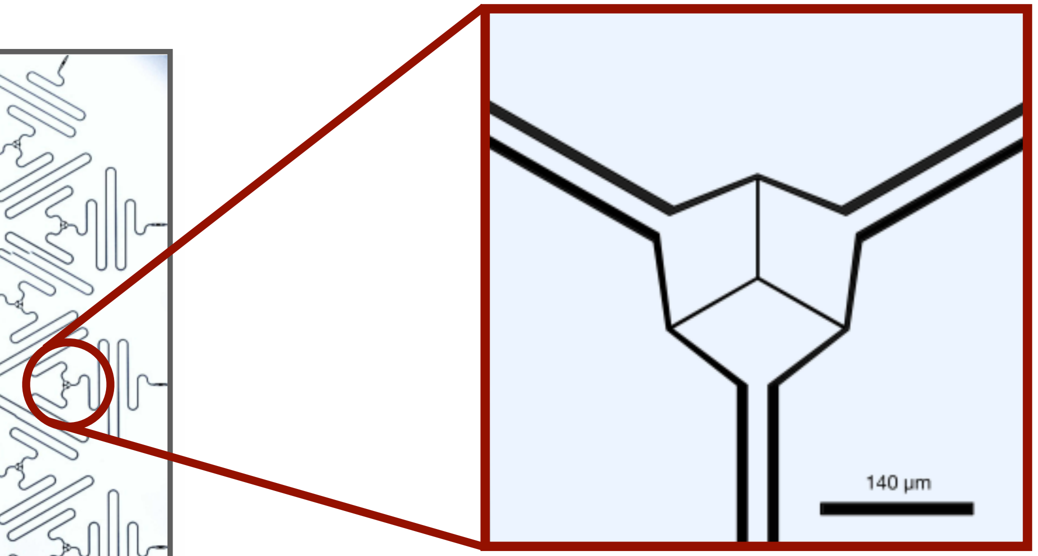
CPW Lattices





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

$$\mathbf{H_{TB}} = \omega_0 \sum_{\mathbf{i}} \mathbf{a_i^\dagger a_i} - \mathbf{t} \sum_{<\mathbf{i,j}>} (\mathbf{a_i^\dagger a_j} + \mathbf{a_j^\dagger a_i})$$

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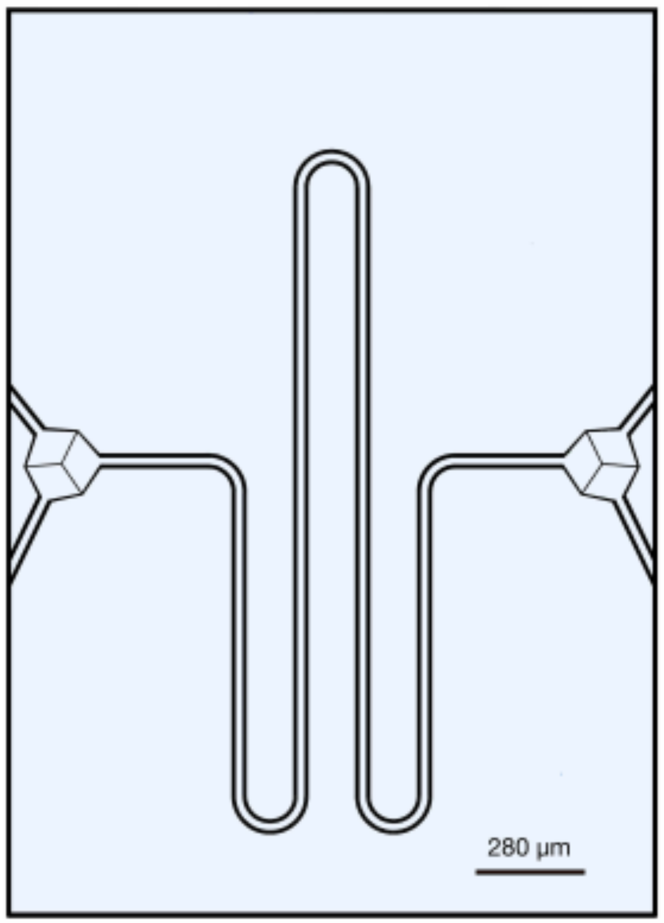
Deformable Resonators



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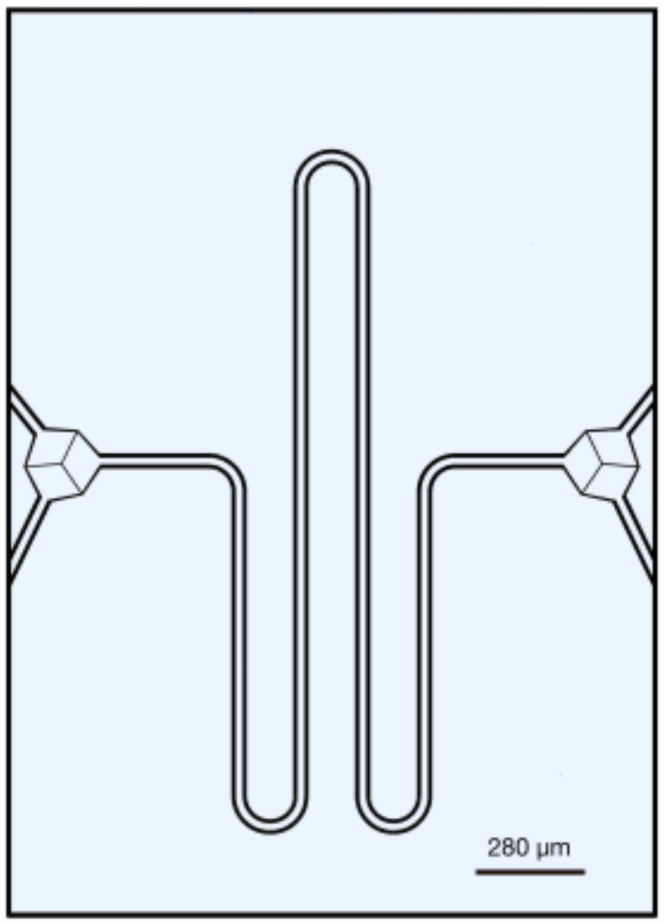
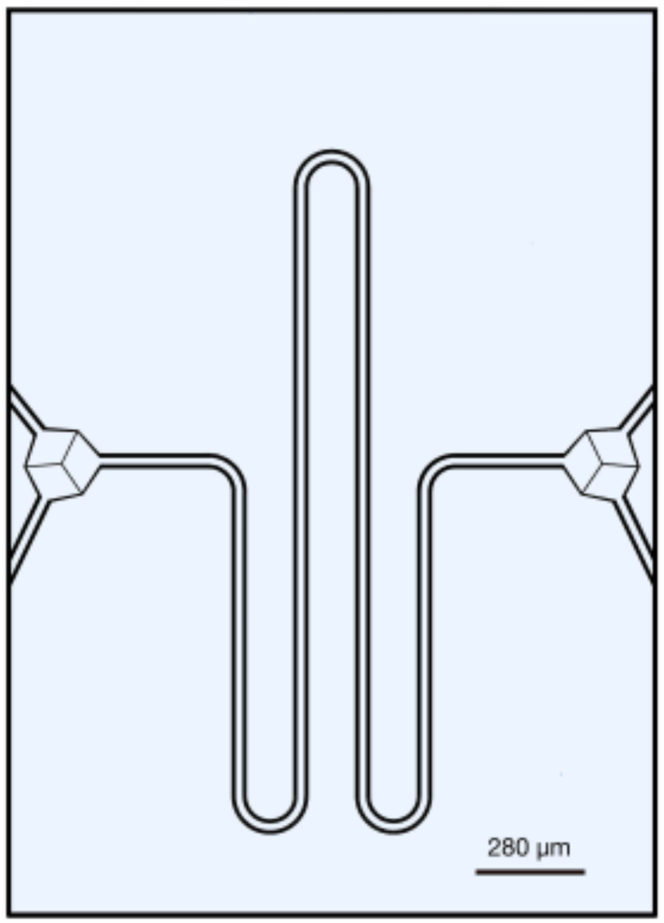


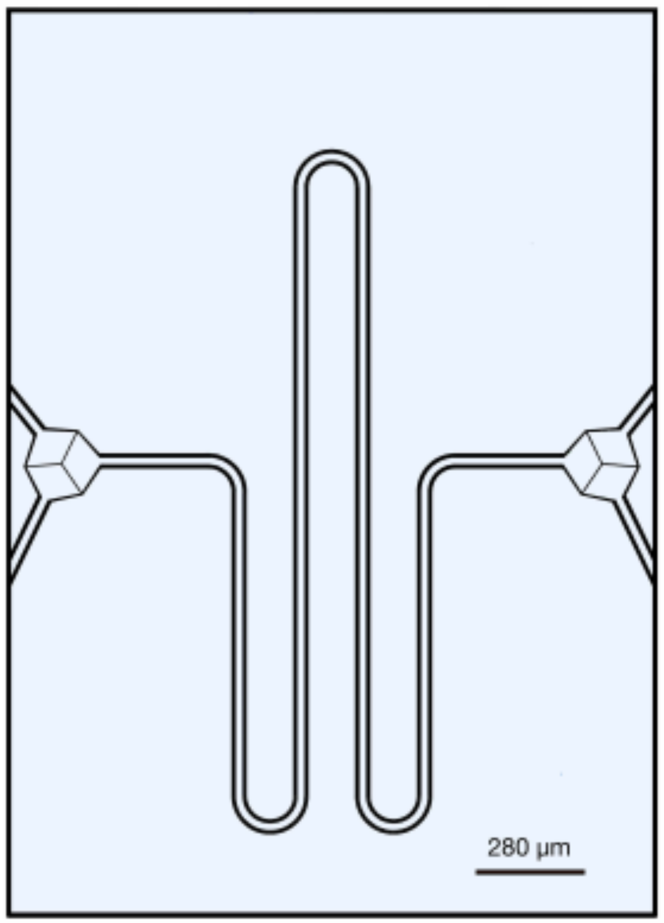
- Frequency depends only on length

Deformable Resonators



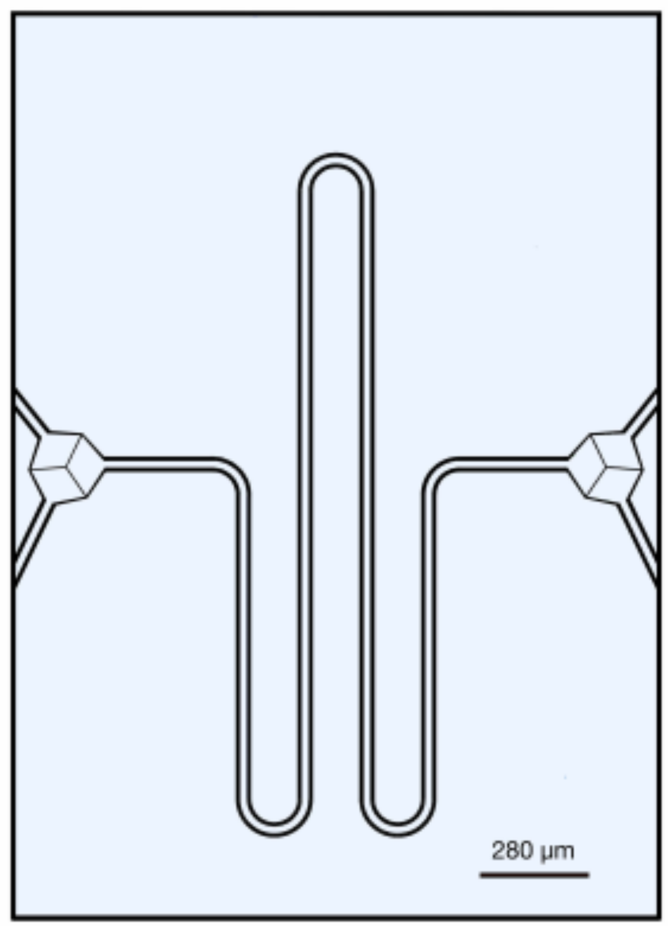
- Frequency depends only on length
- Coupling depends on ends

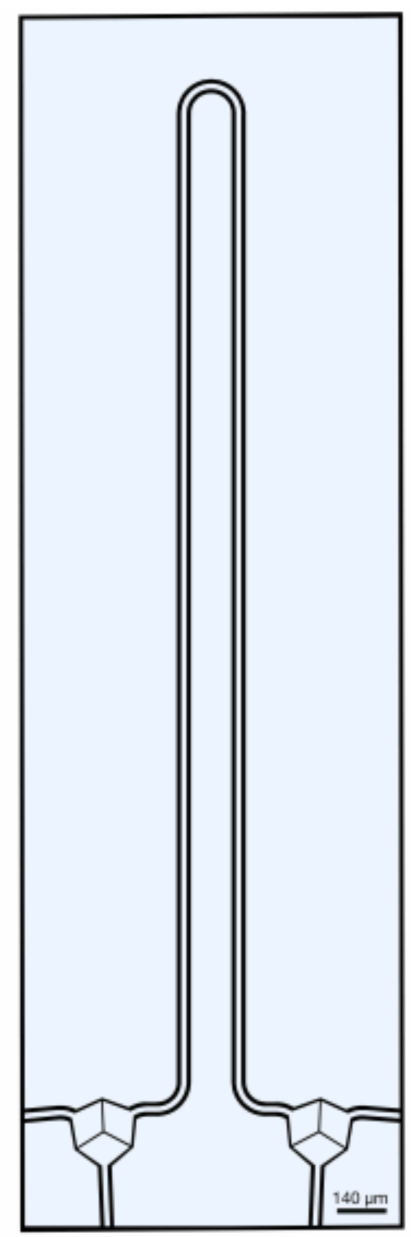
Deformable Resonators



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

Deformable Resonators





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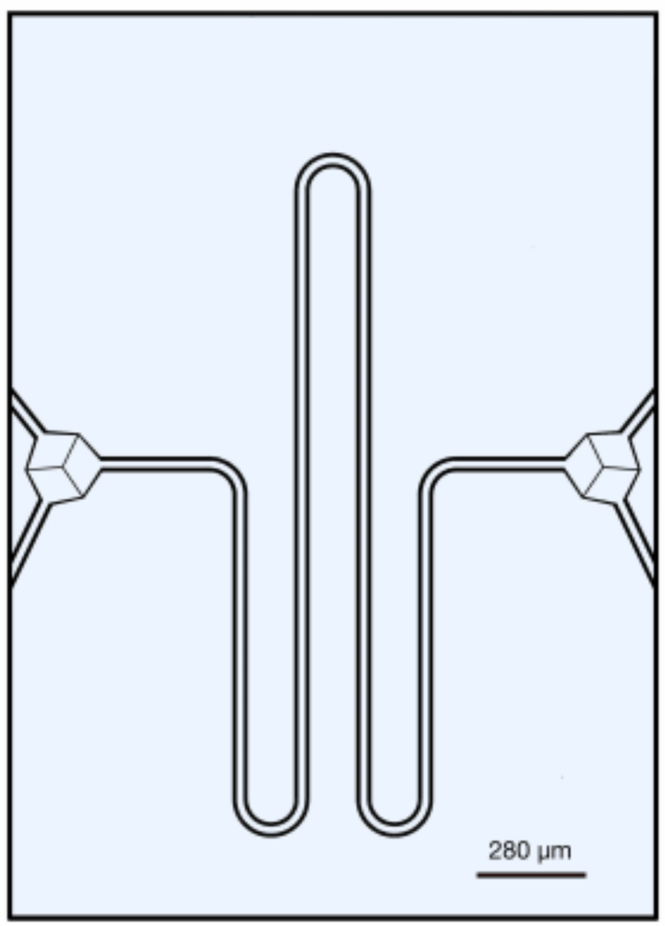

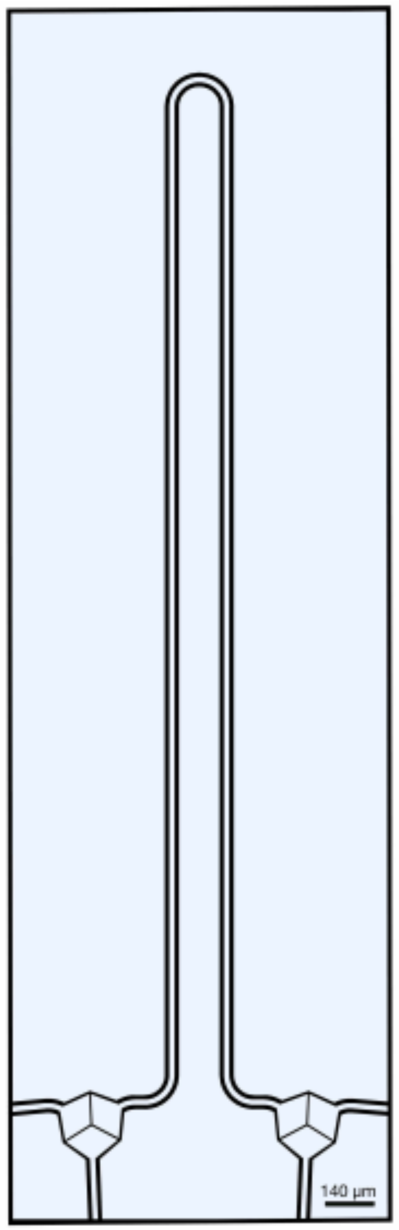

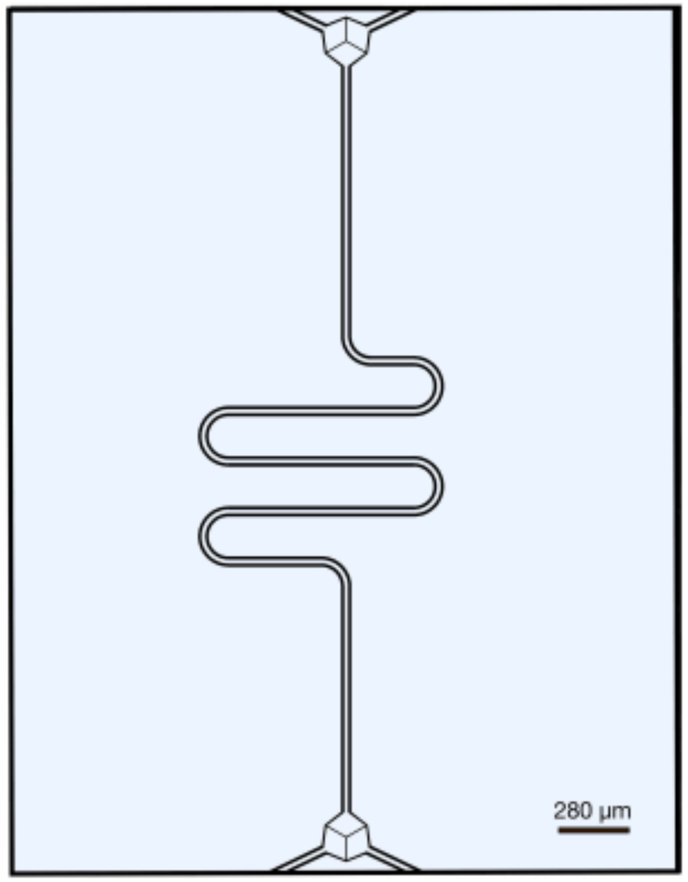

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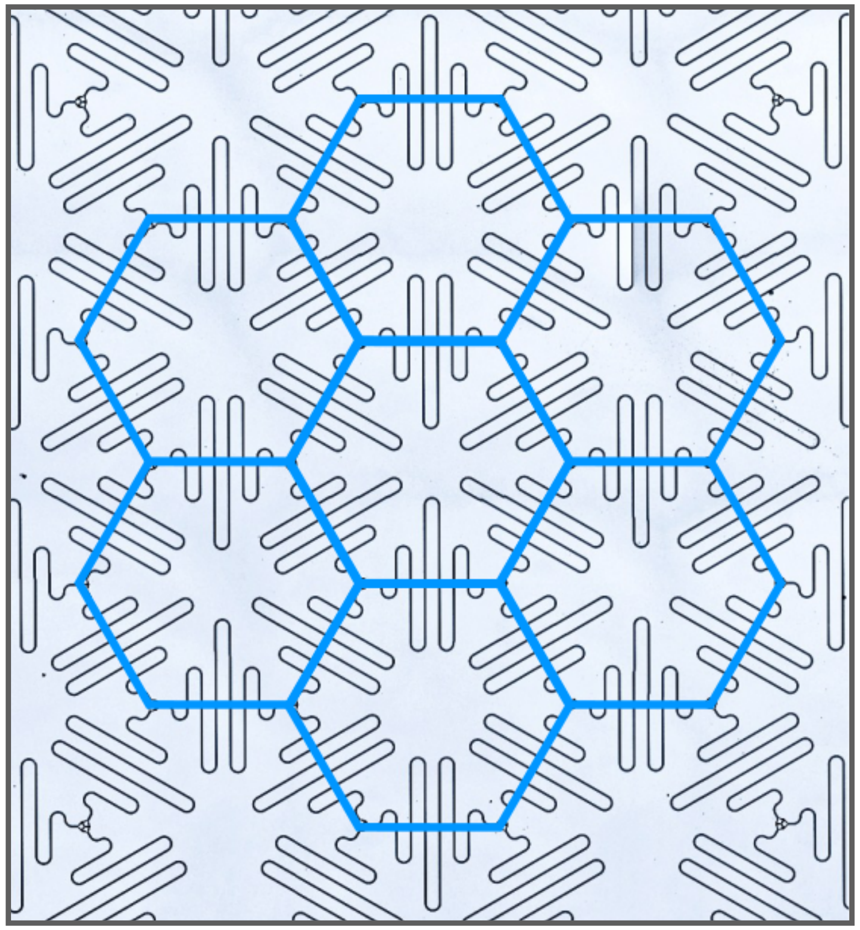
Layout and Effective Lattices

Resonator Lattice



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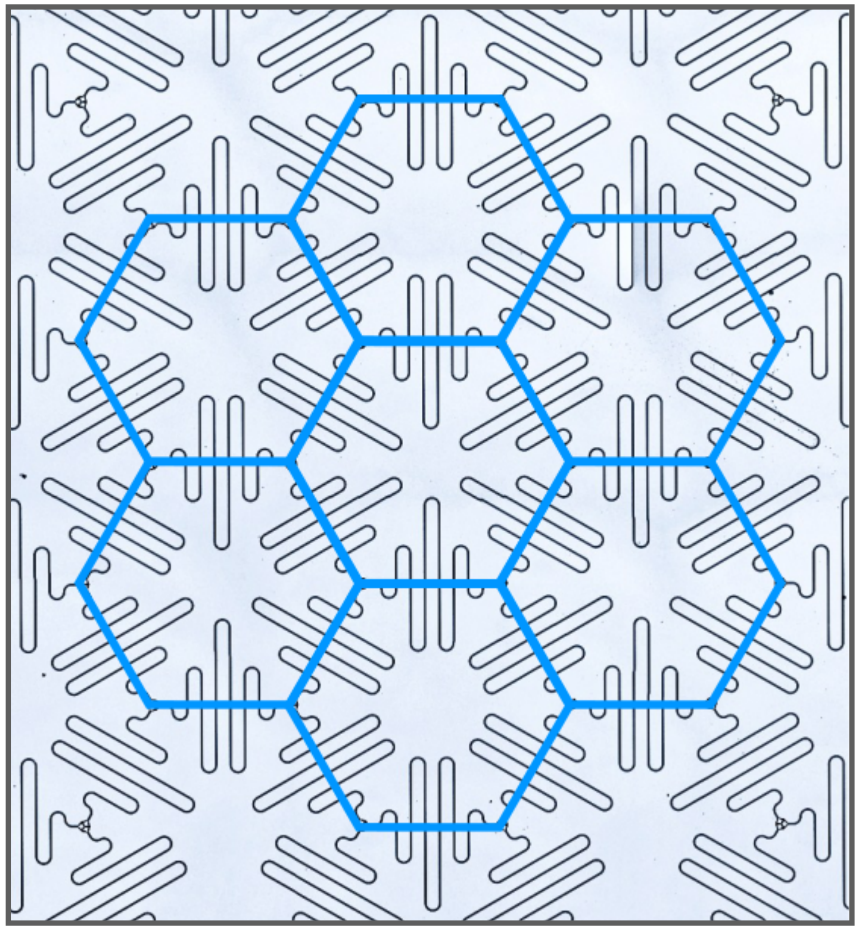
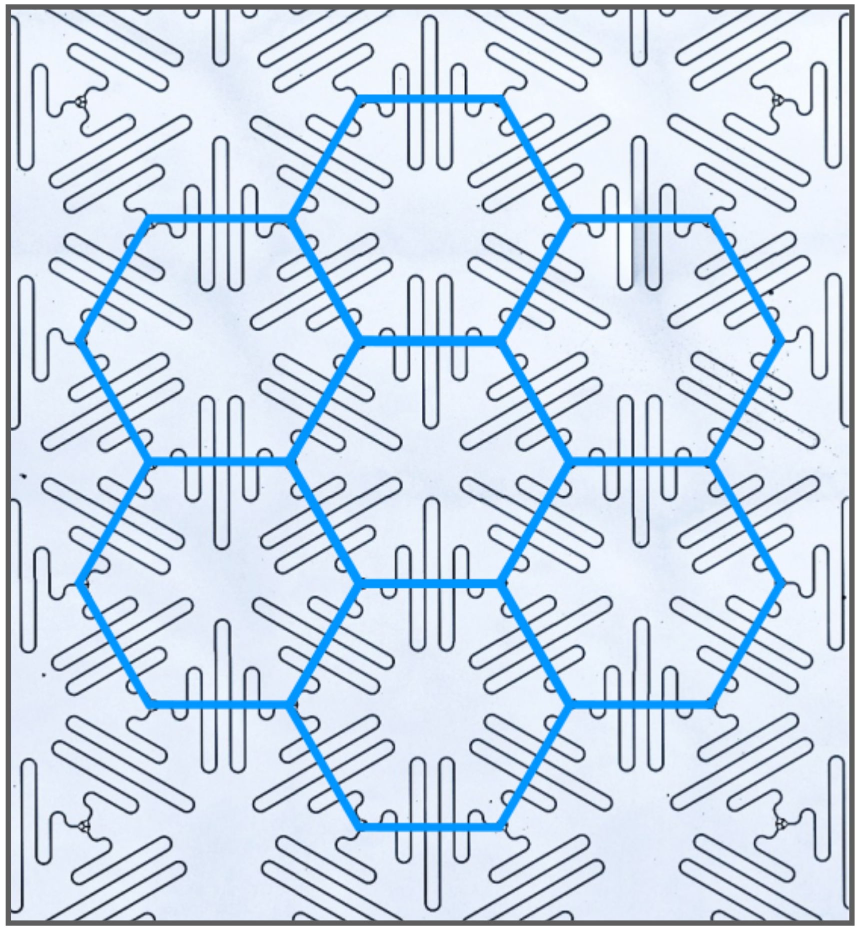


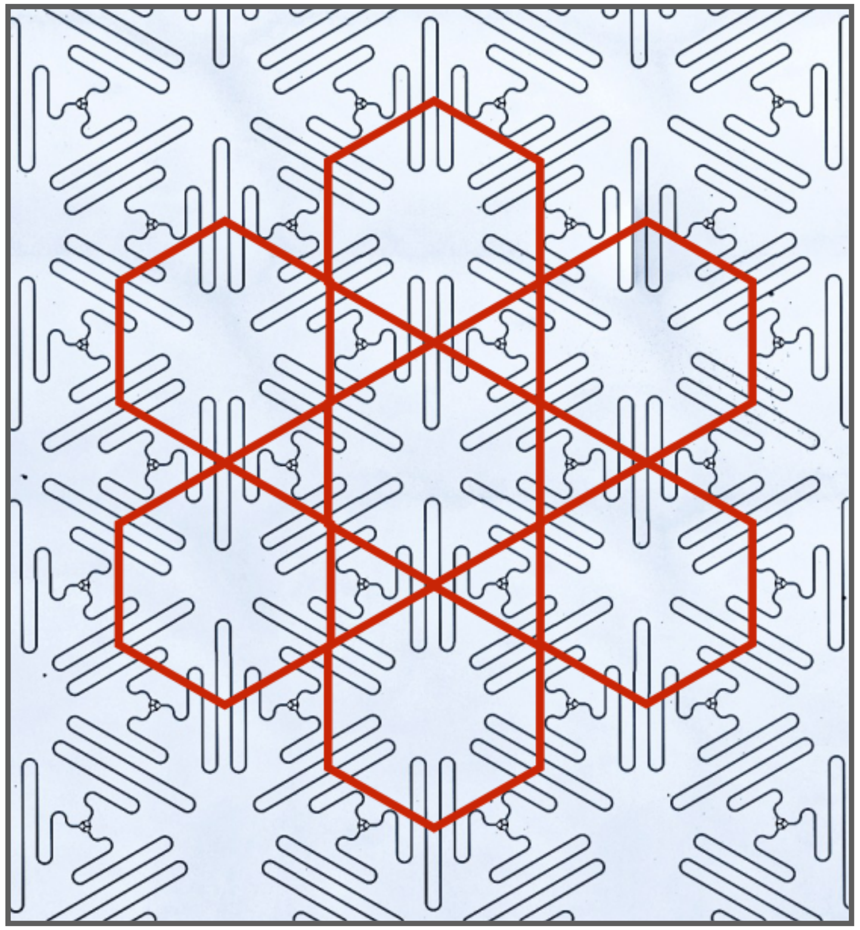
- An *edge* on each resonator

Layout and Effective Lattices

Resonator Lattice



Effective Photonic Lattice



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Layout and Effective Lattices

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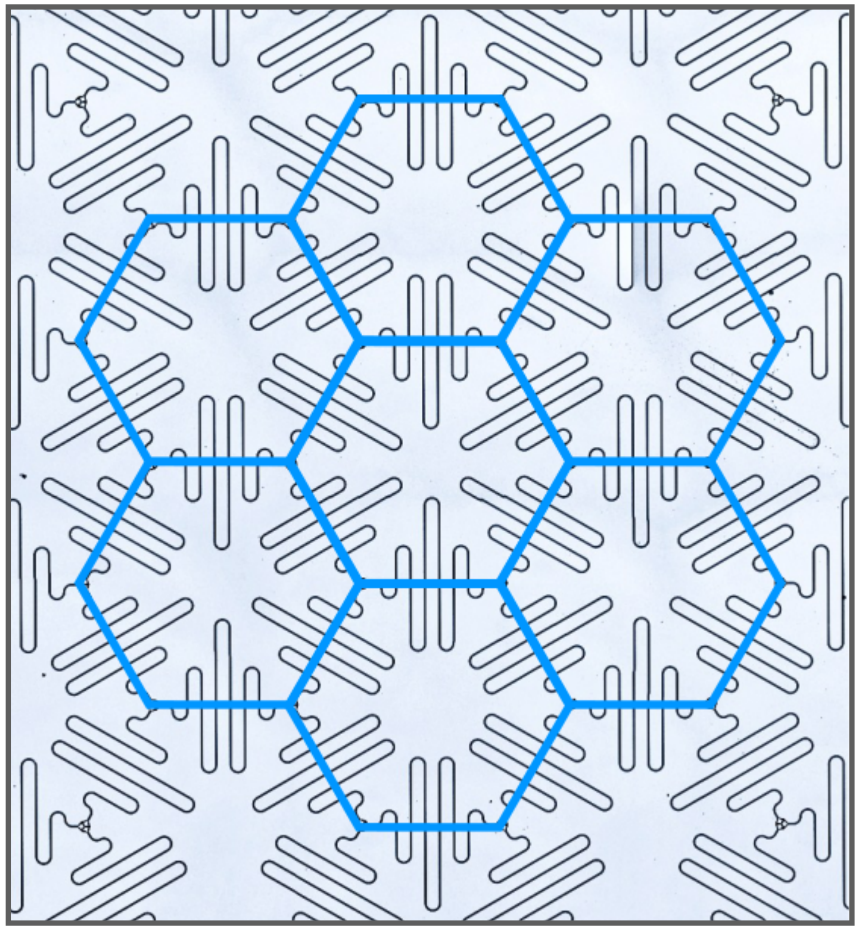

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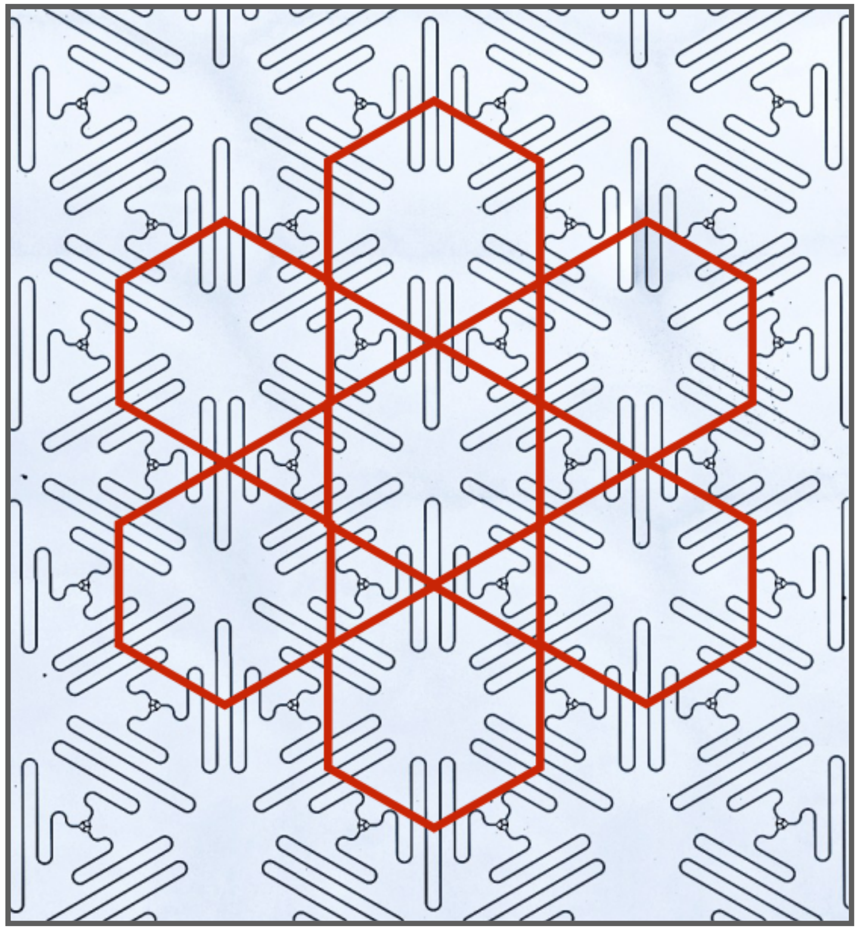
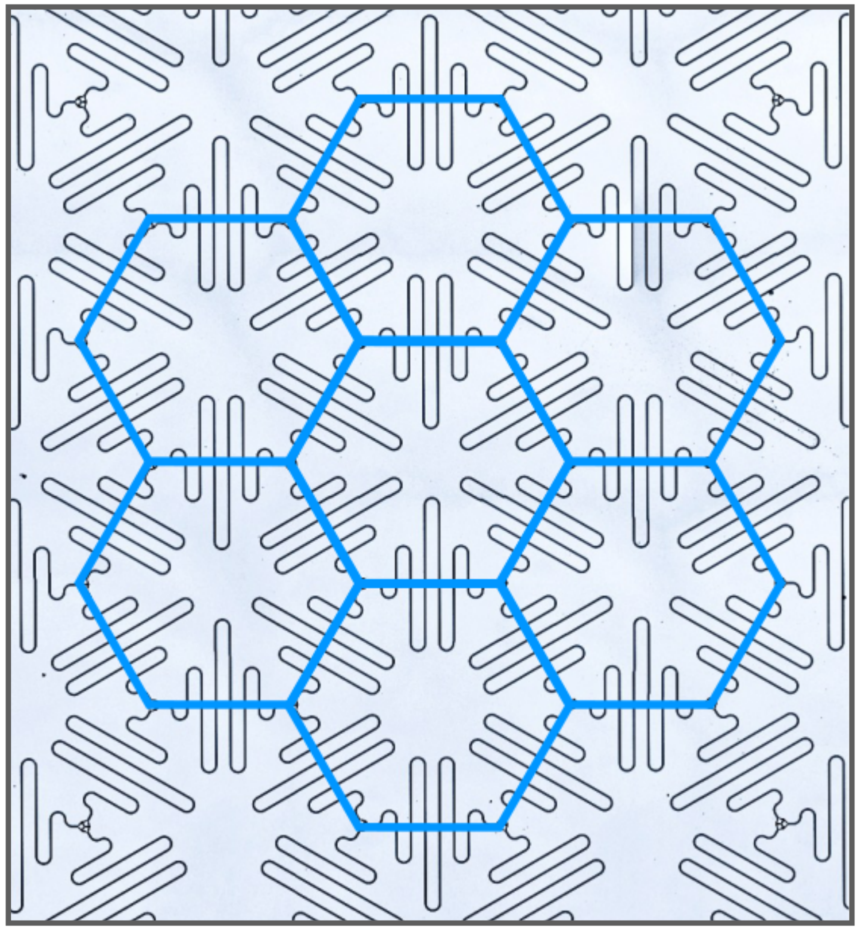


- A *vertex* on each resonator

Layout and Effective Lattices

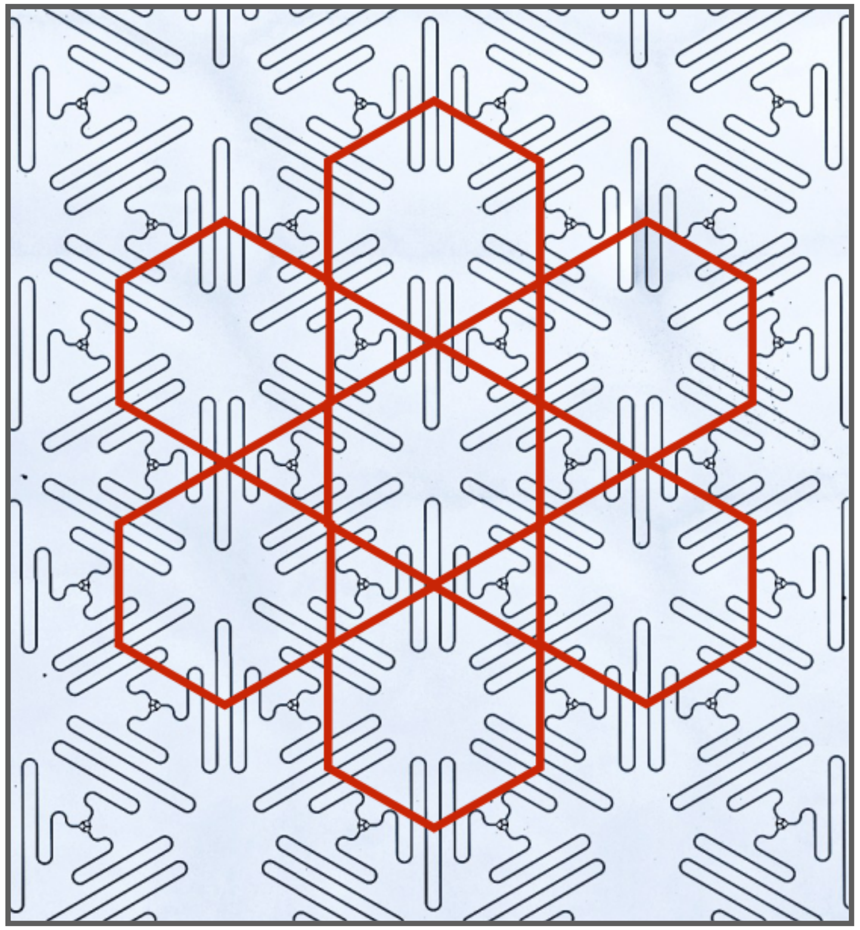
Resonator Lattice



- An *edge* on each resonator

Layout X

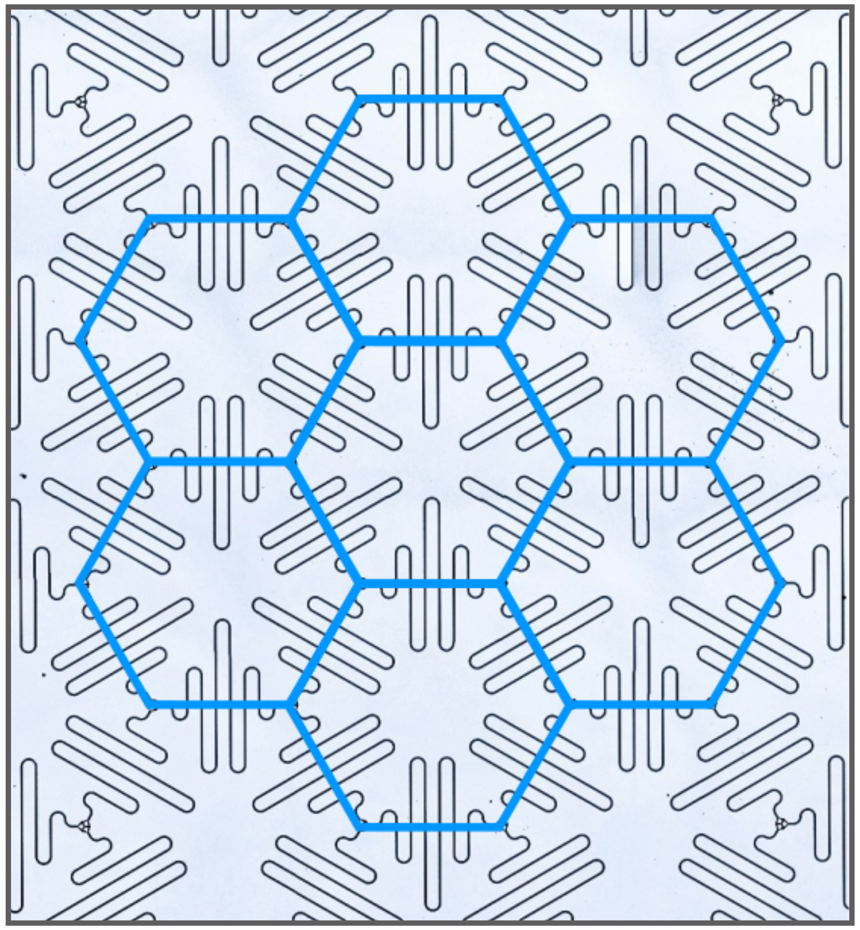
Effective Photonic Lattice



- A *vertex* on each resonator

Layout and Effective Lattices

Resonator Lattice



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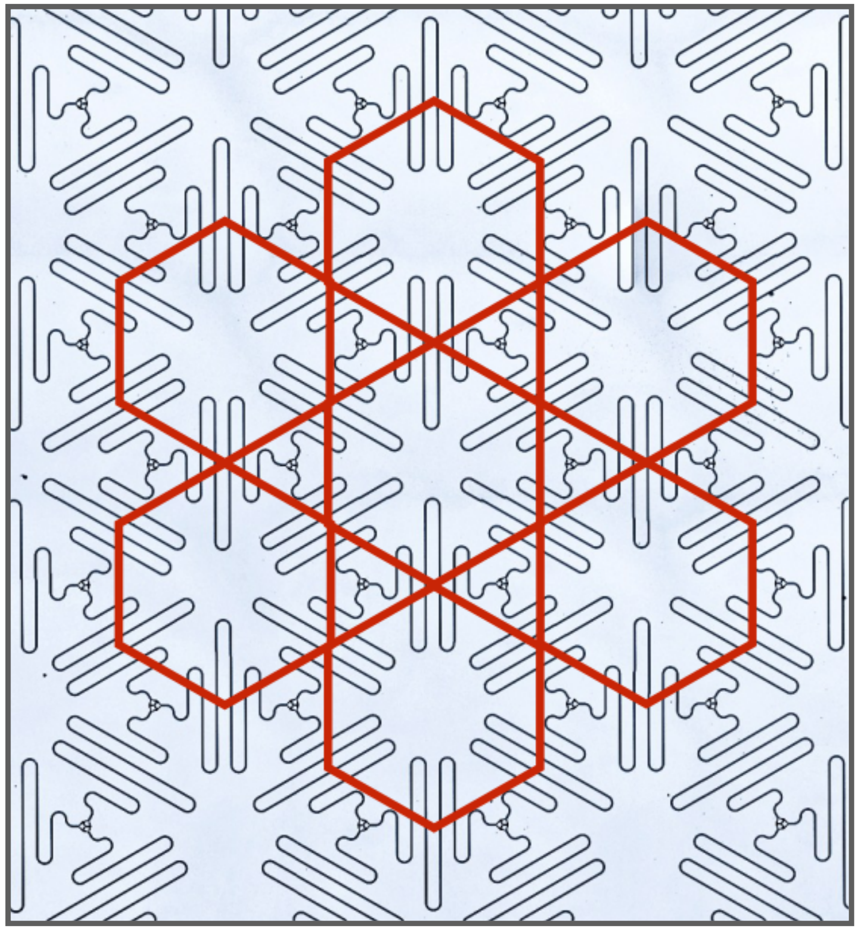

- A *vertex* on each resonator

Line Graph $L(X)$

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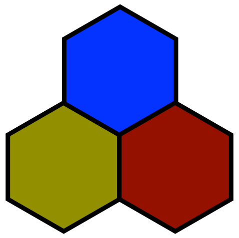
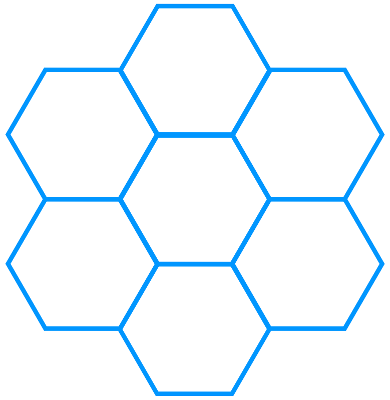
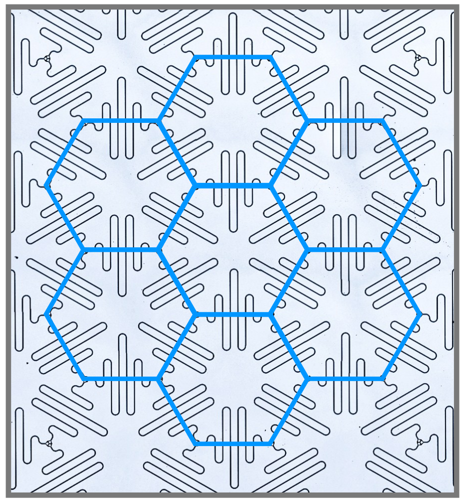
Projecting to Flat 2D

n = 6

flat







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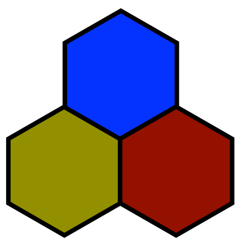
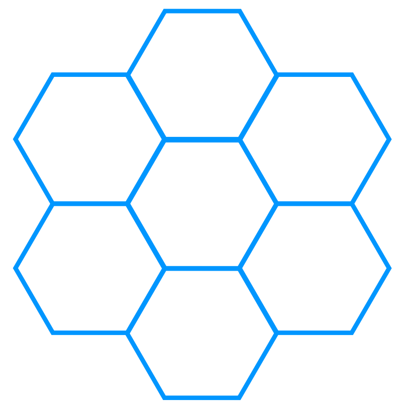
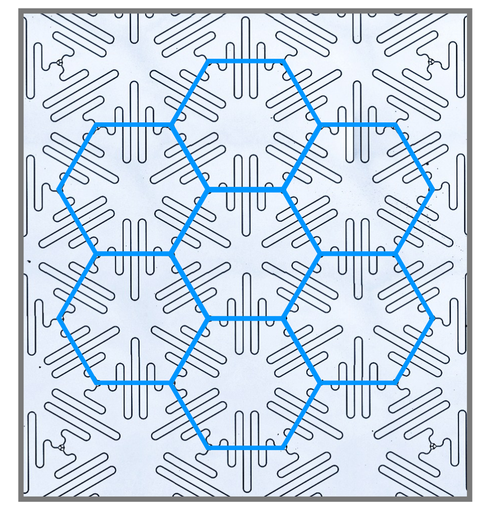
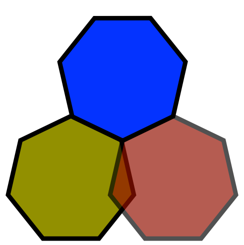


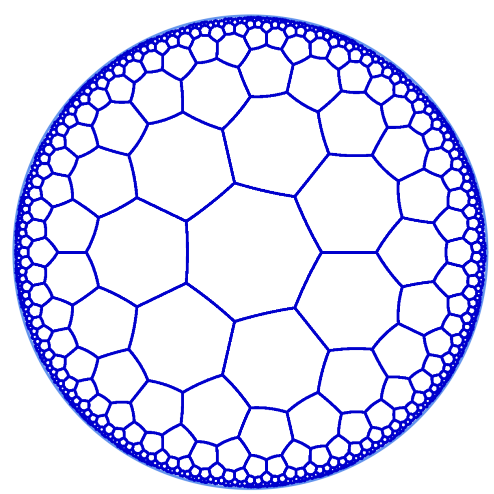


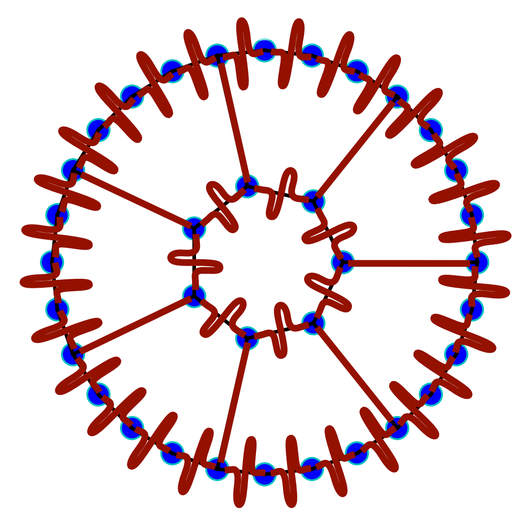


n = 7

hyperbolic







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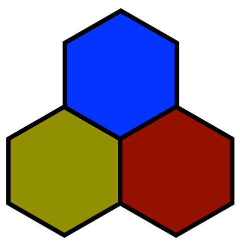
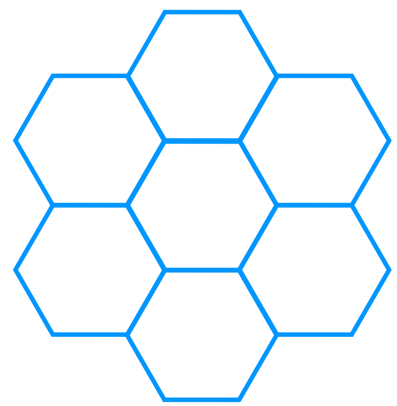
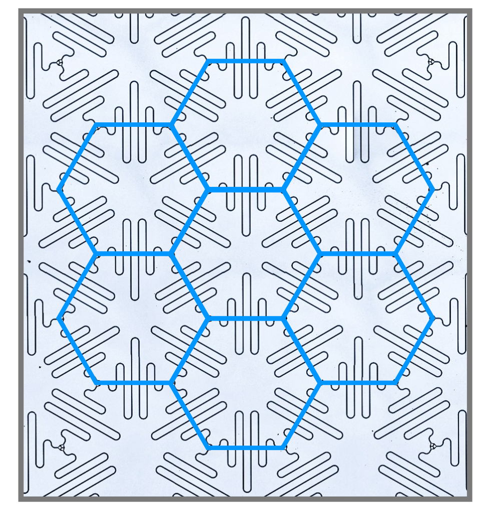
flat







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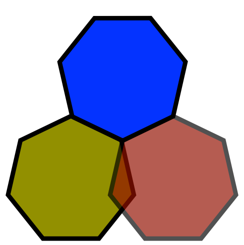
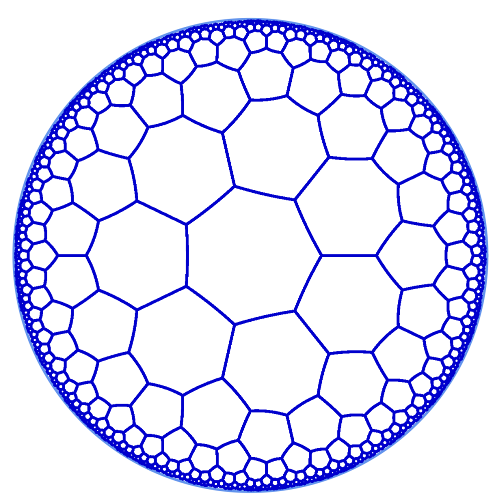
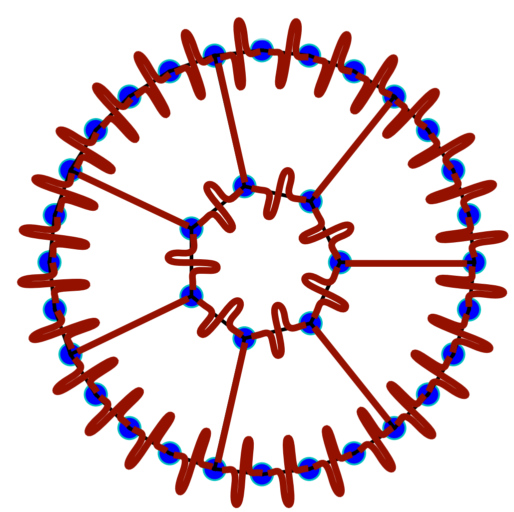
hyperbolic





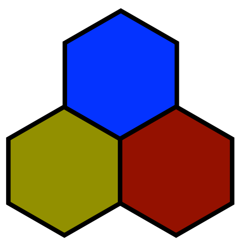


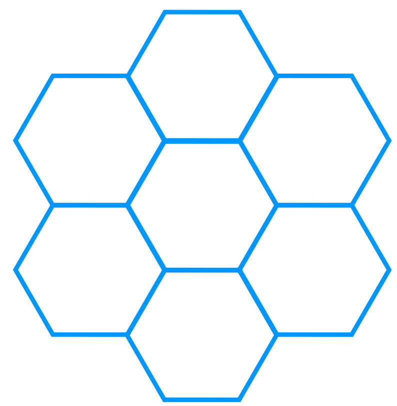
- Distance is not preserved.

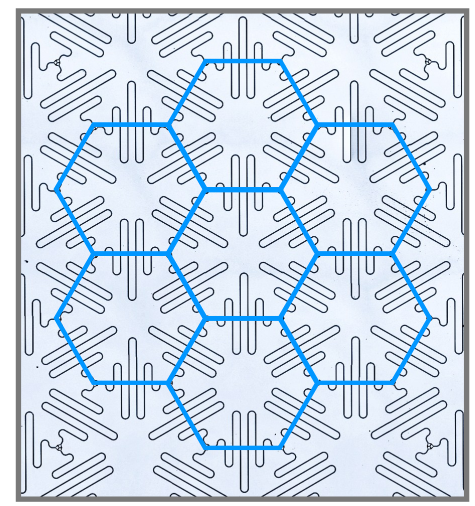
Projecting to Flat 2D

n = 6

flat

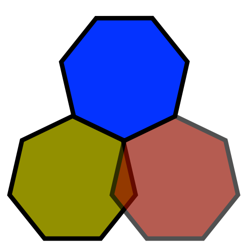


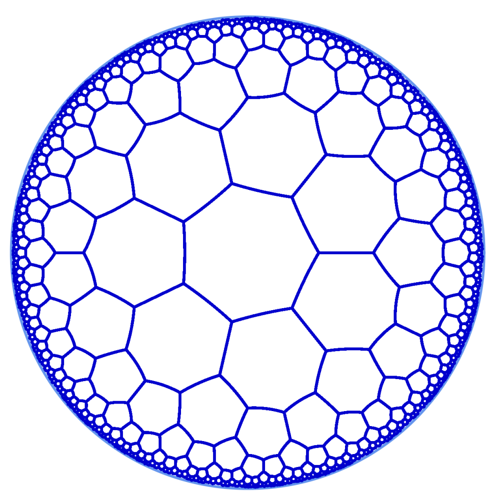


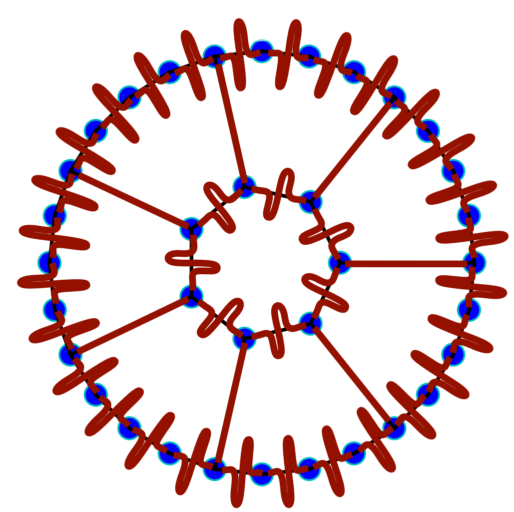


n = 7

hyperbolic





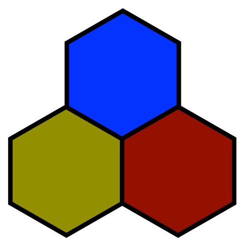


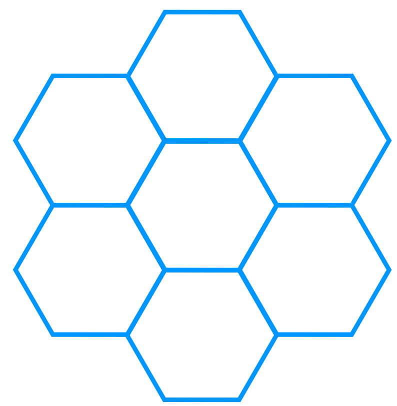
- Distance is not preserved.
- t *is* preserved.

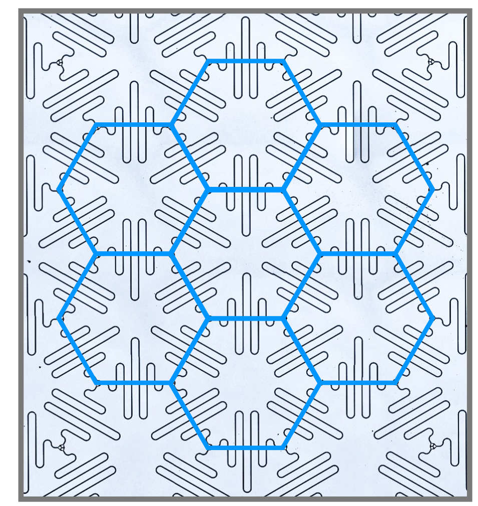
Projecting to Flat 2D

n = 6

flat

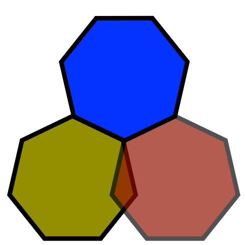


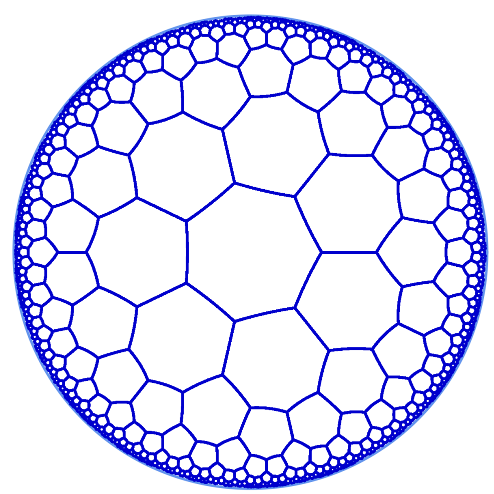


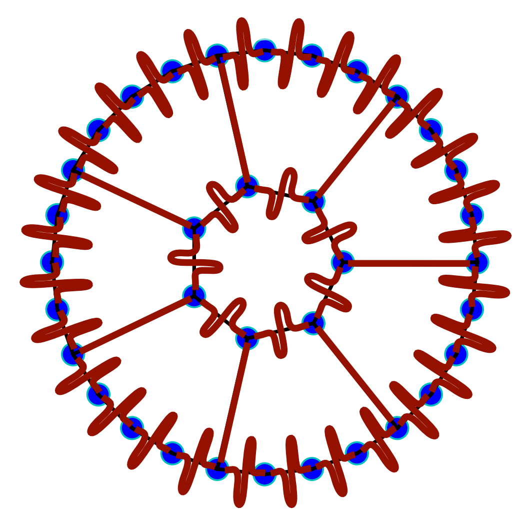


n = 7

hyperbolic

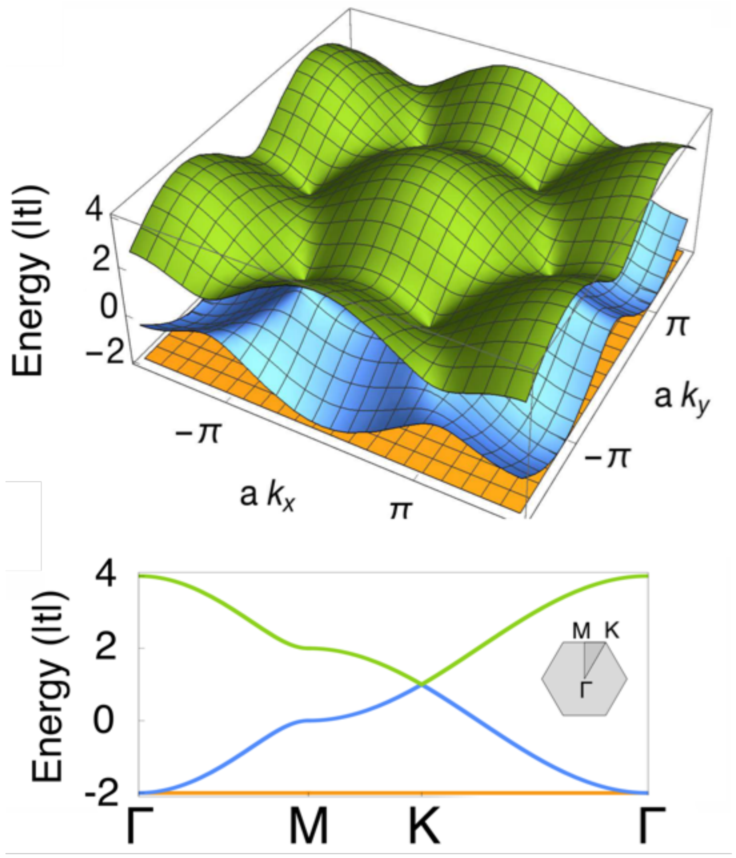






- Distance is not preserved.
- t *is* preserved.
- H *is* preserved.

Band Structure Calculations



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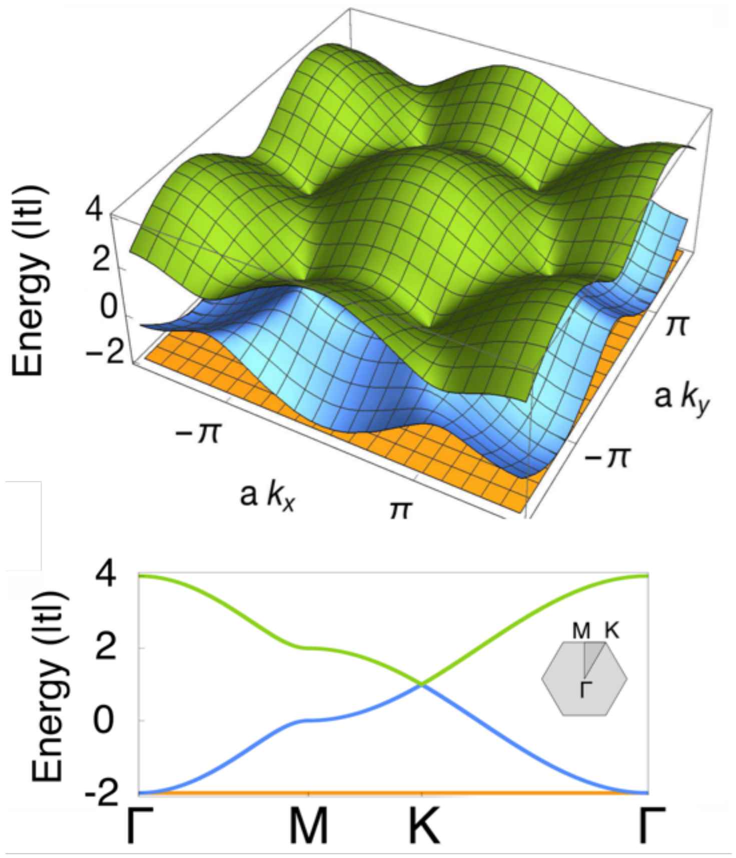

Hyperbolic geometry is non-commutative

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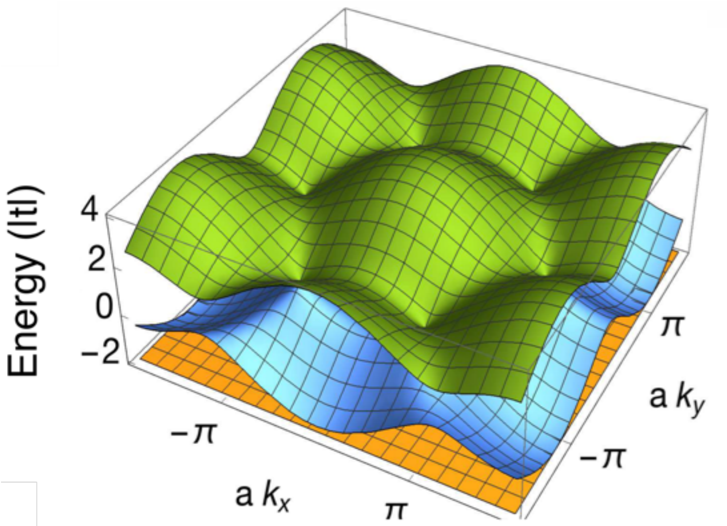
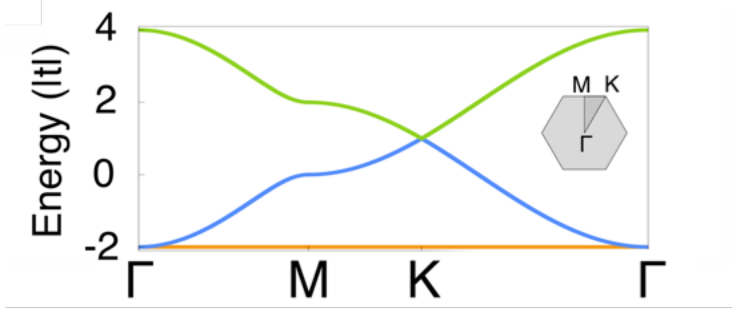
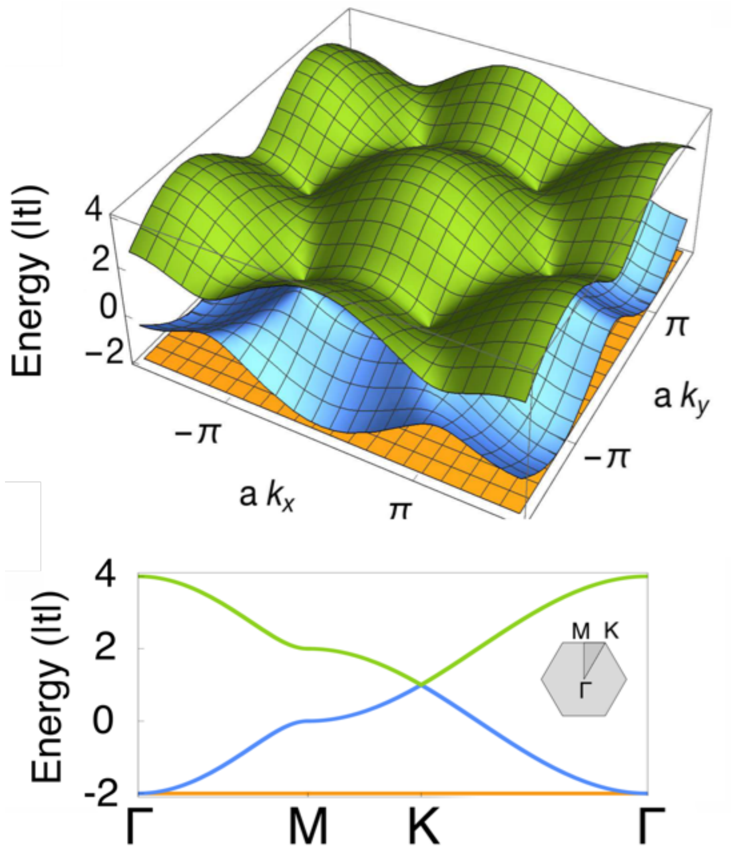




Hyperbolic geometry is non-commutative

- No Bravais lattice

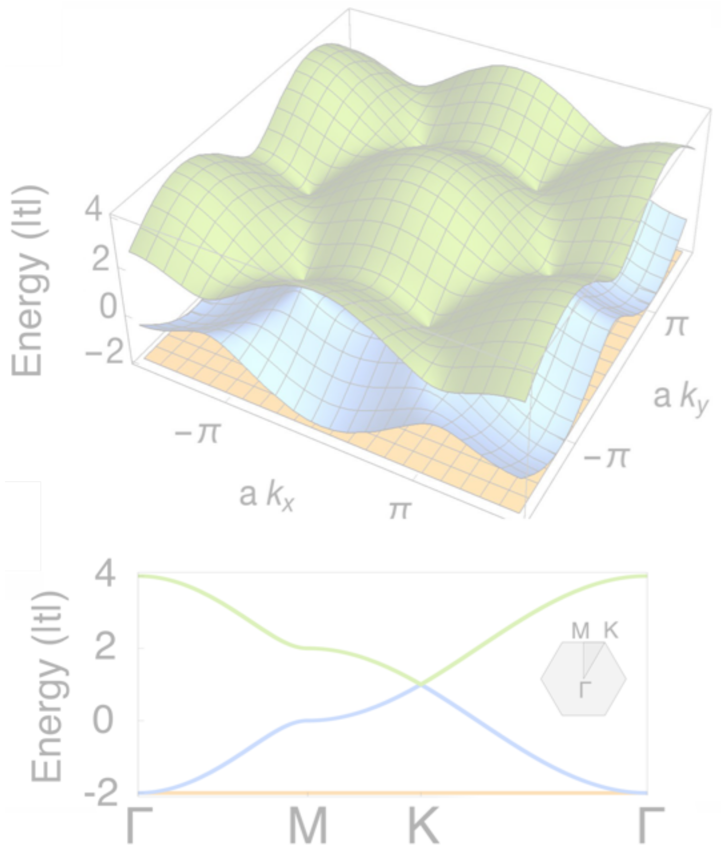
Band Structure Calculations



Hyperbolic geometry is non-commutative

- No Bravais lattice
- No Bloch theory

Band Structure Calculations



Hyperbolic geometry is non-commutative

- No Bravais lattice
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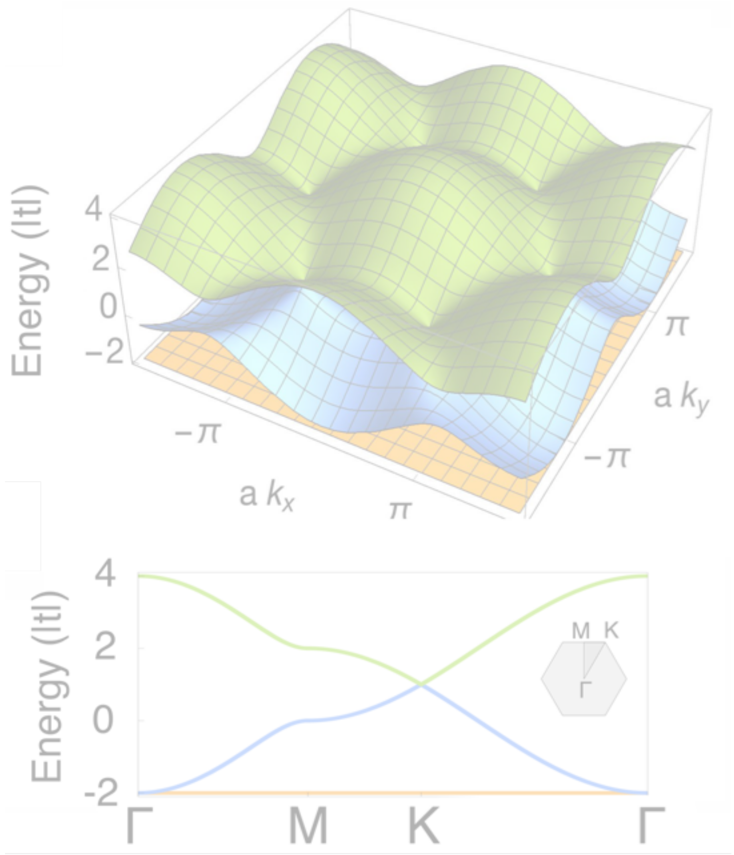
Band Structure Calculations



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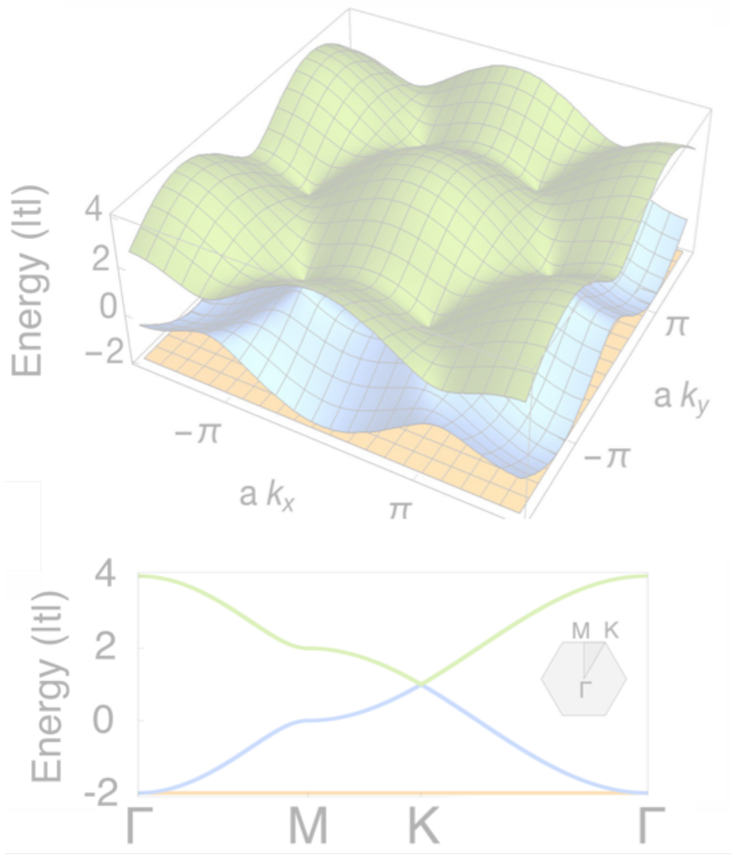

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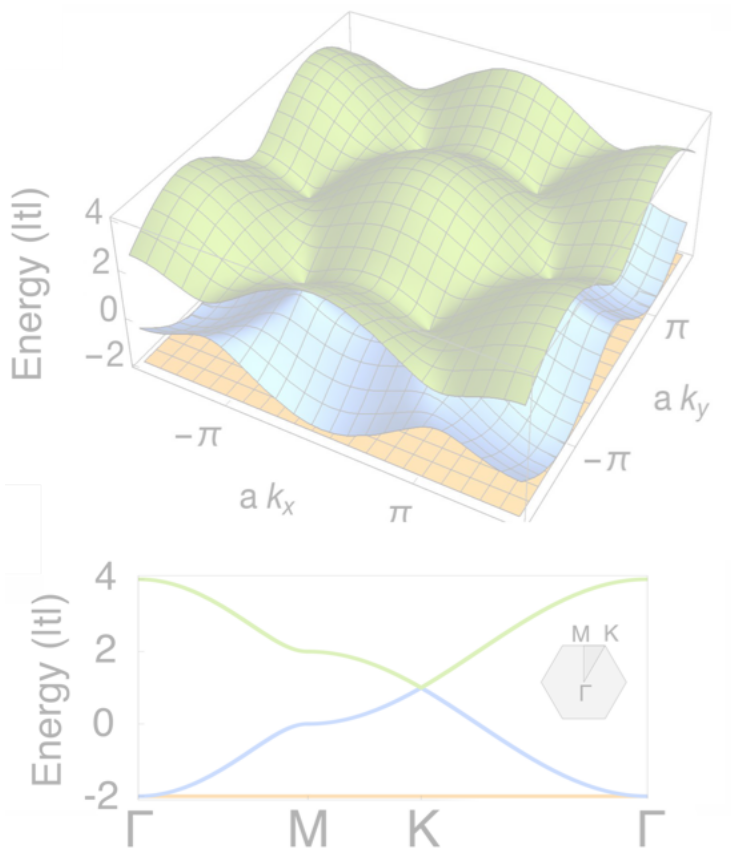

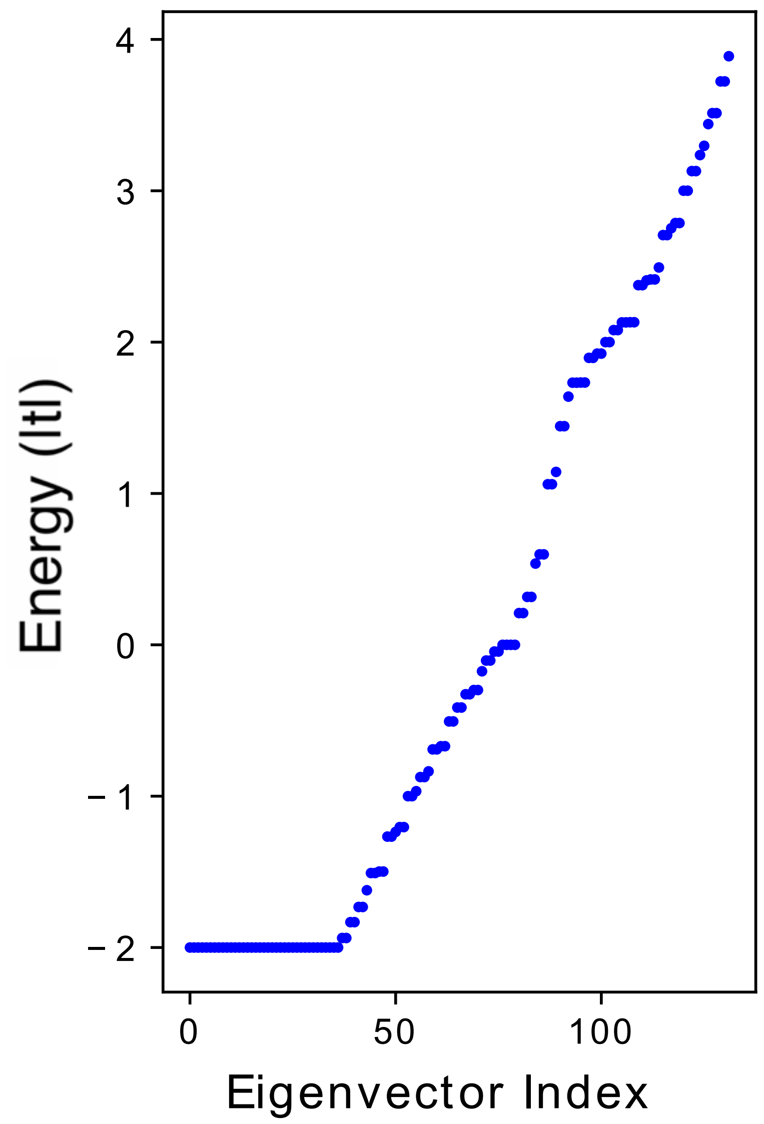

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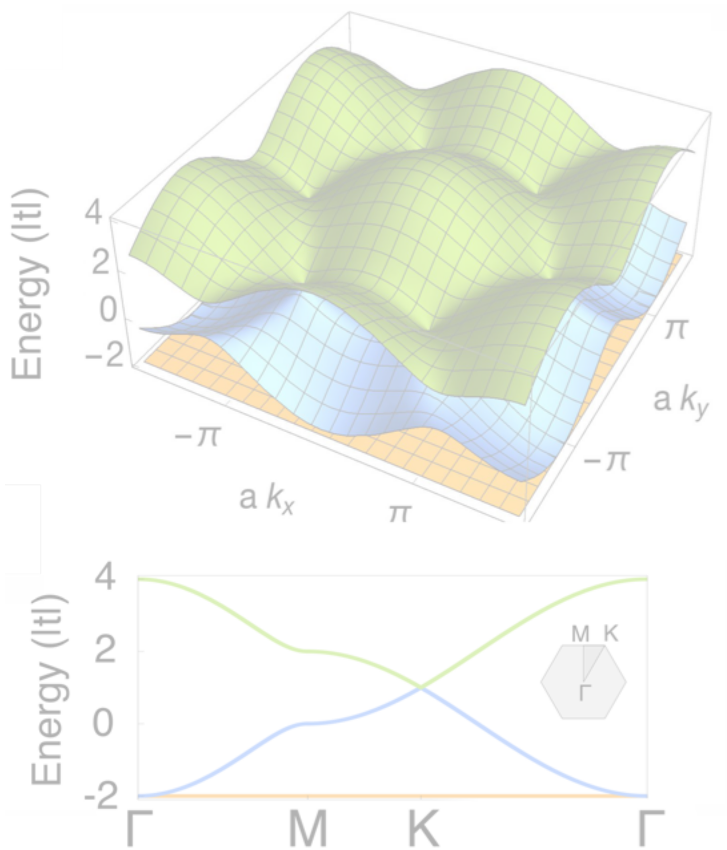

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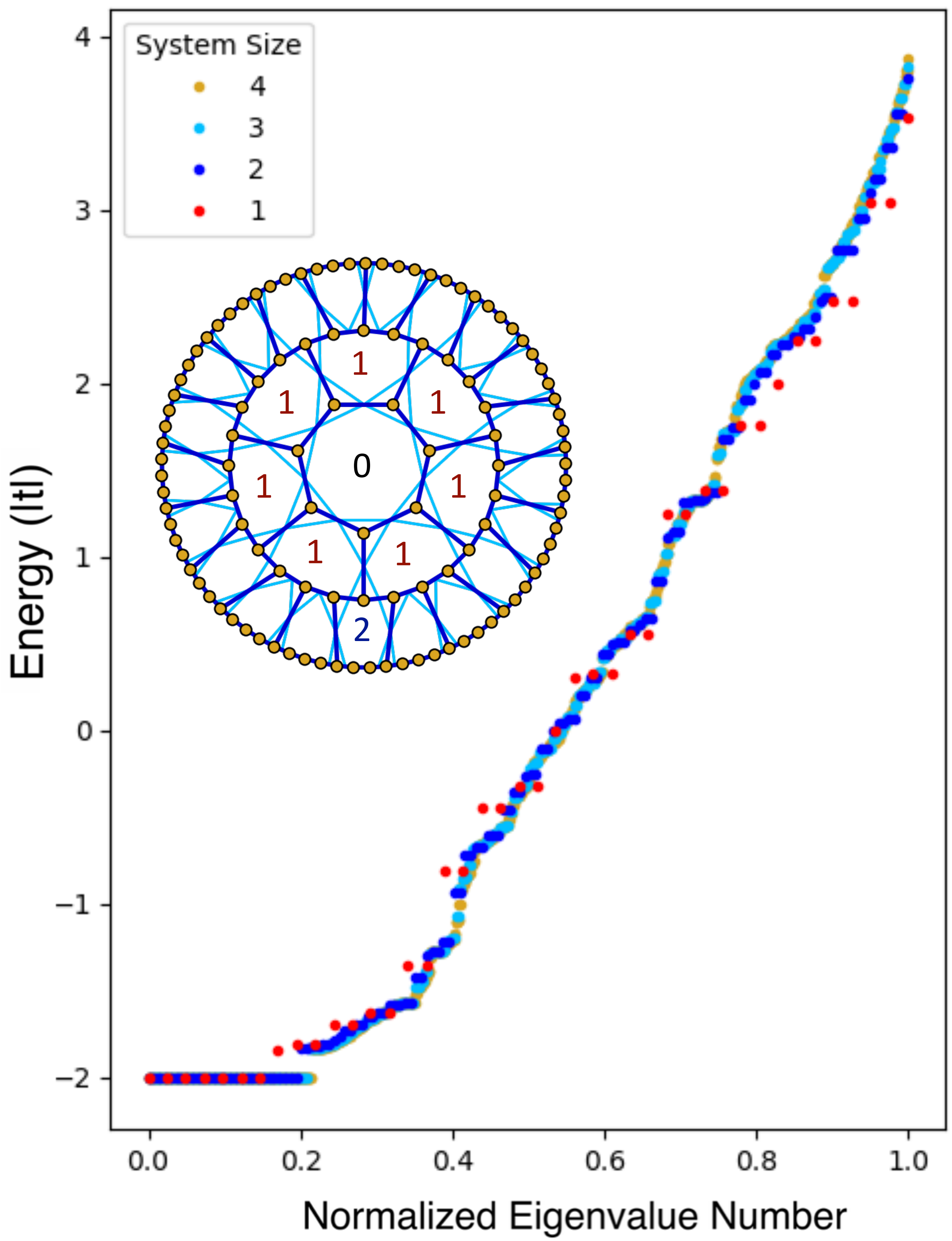

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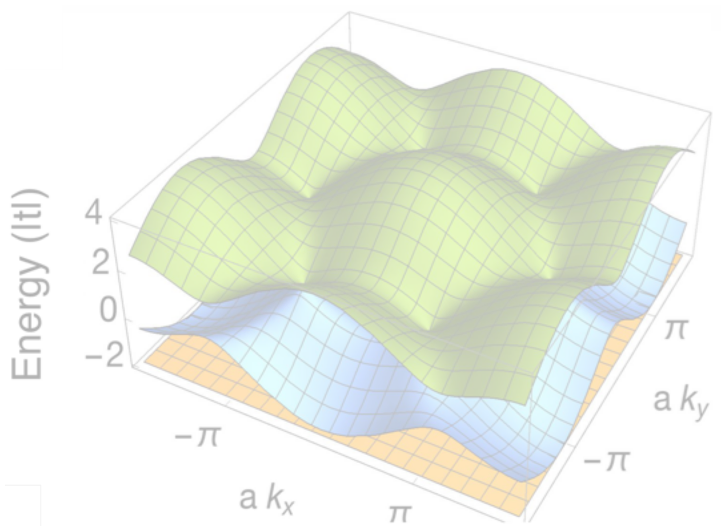

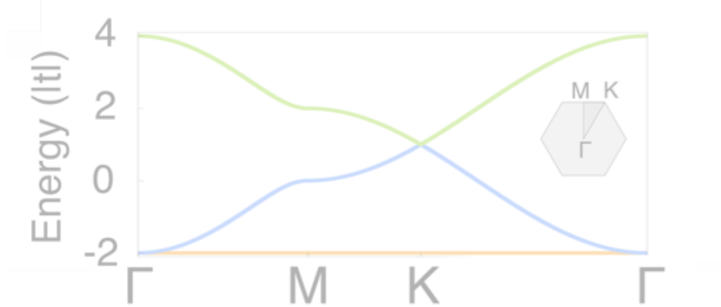

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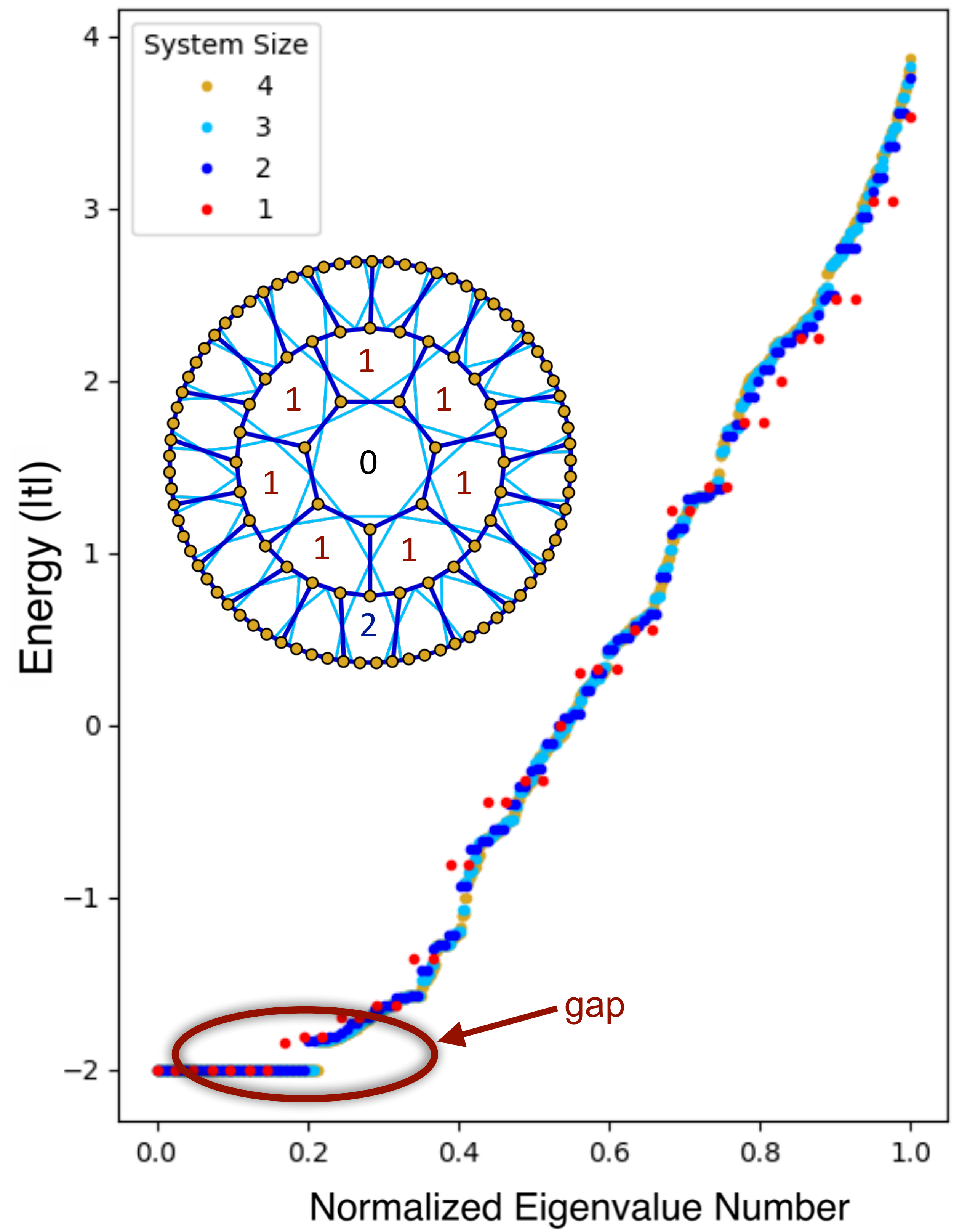
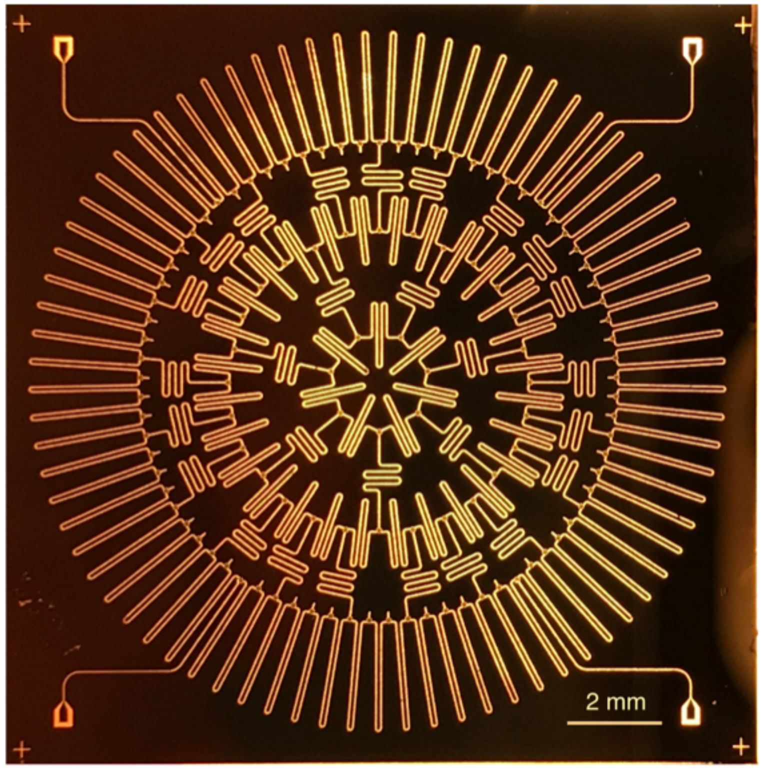


Heptagon-Kagome Device



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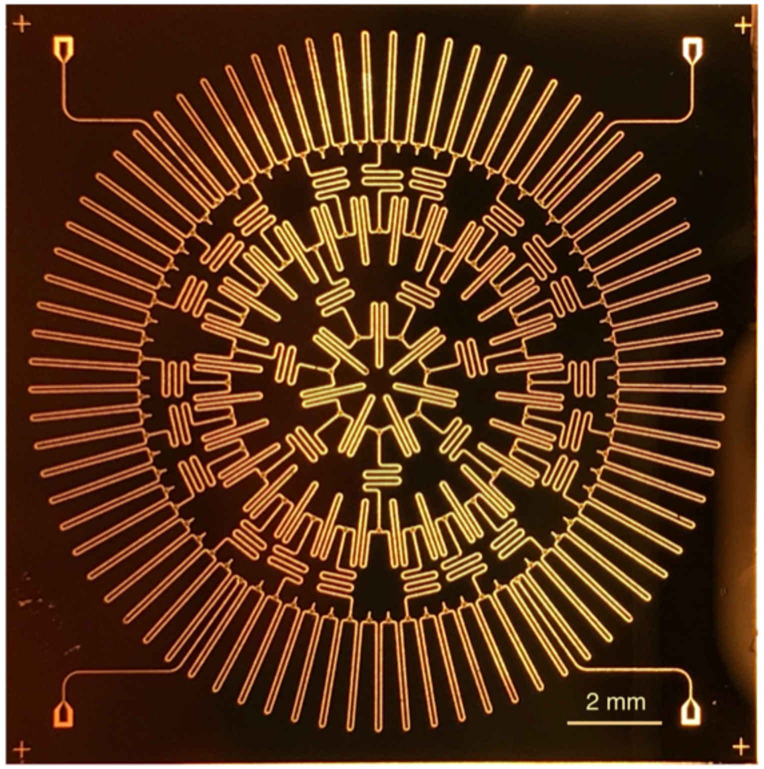
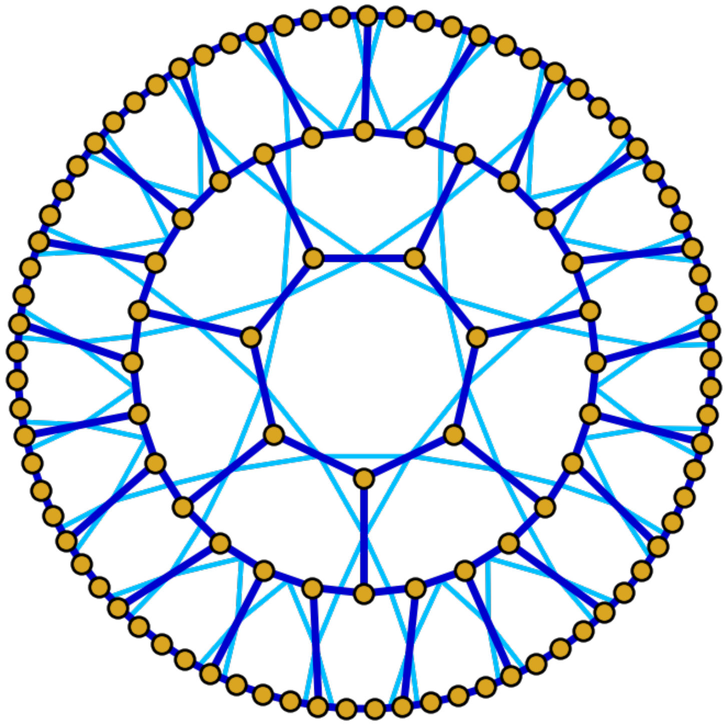
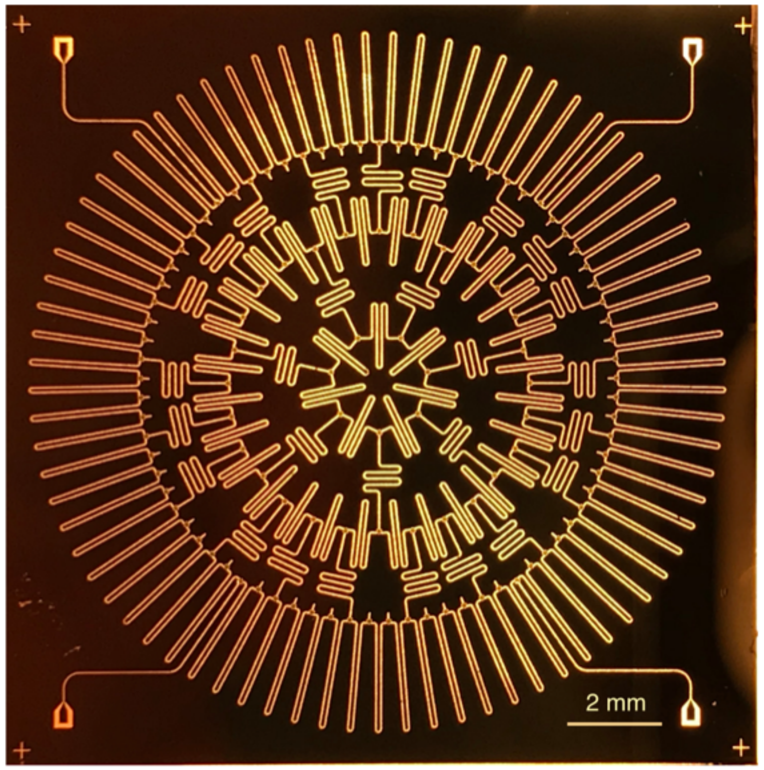
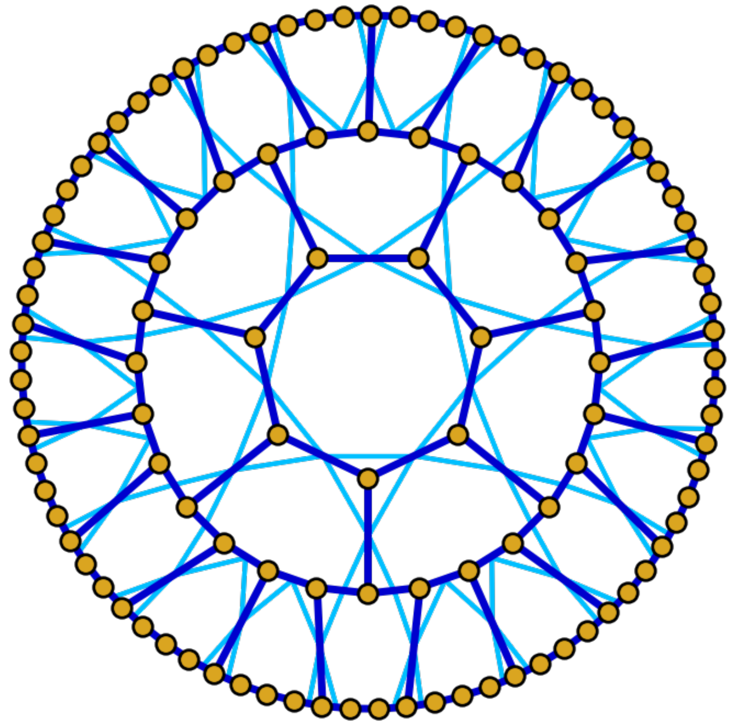




- 2 shells

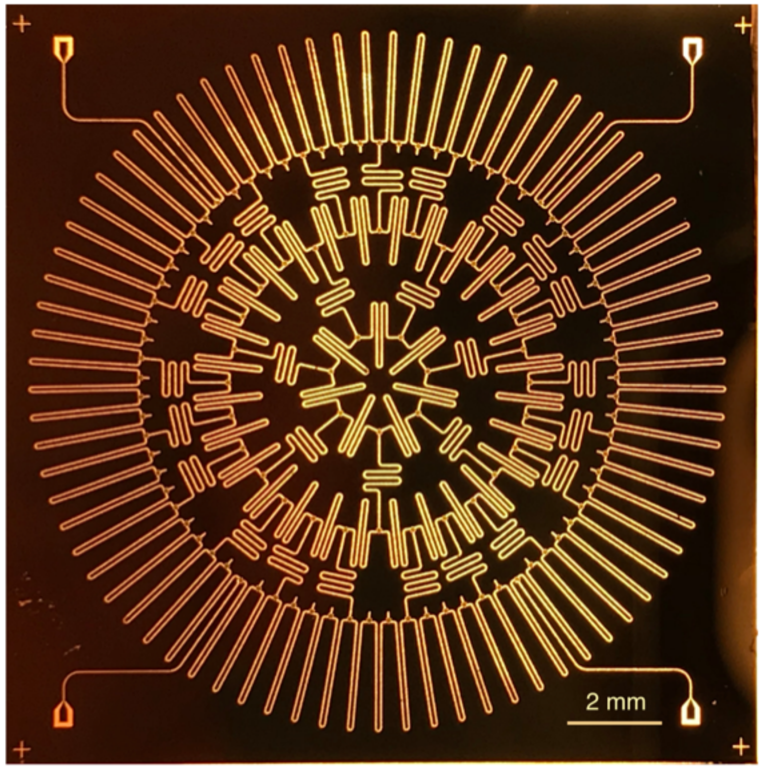
Heptagon-Kagome Device

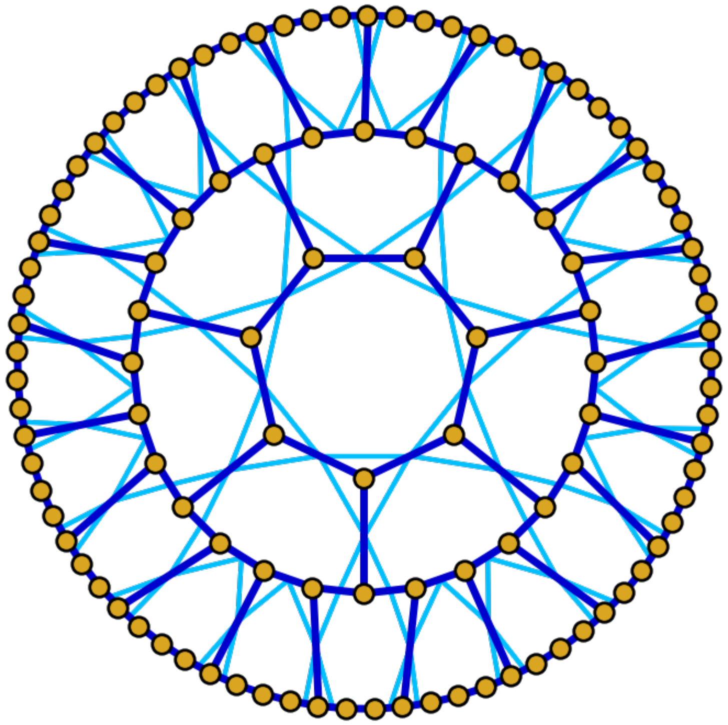




- 2 shells
- Operating frequency: 16 GHz

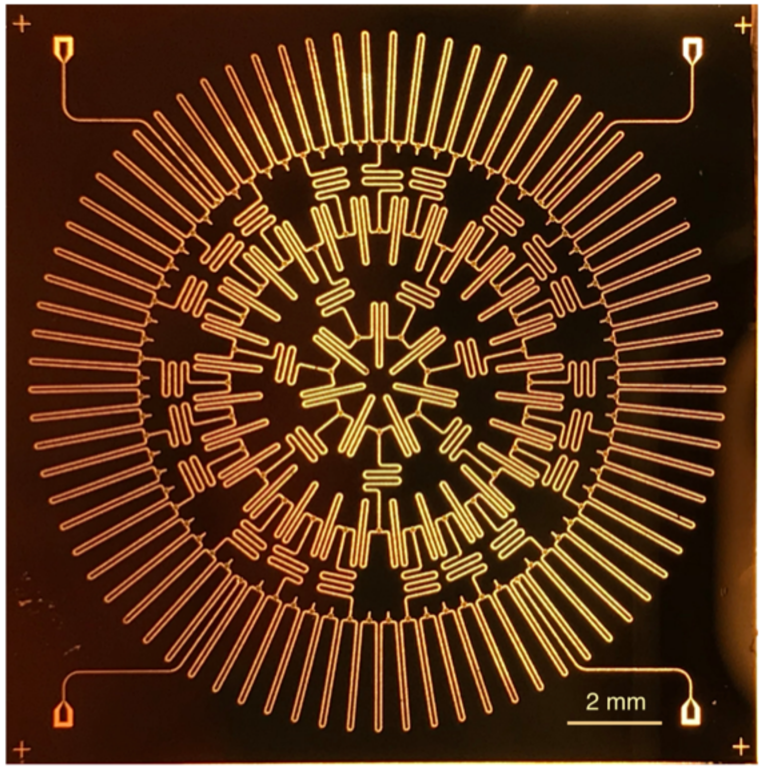
Heptagon-Kagome Device

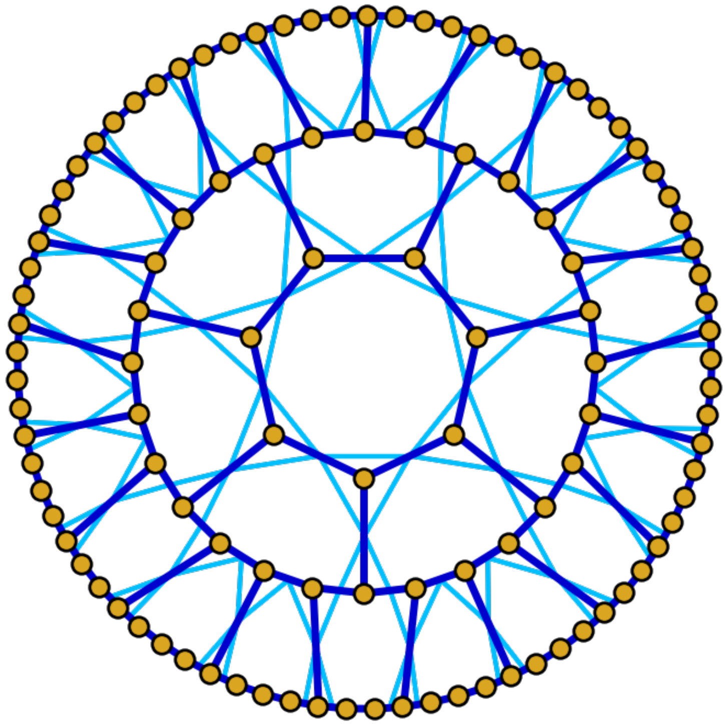




- 2 shells
- Operating frequency: 16 GHz
- 4 input-output ports

Heptagon-Kagome Device





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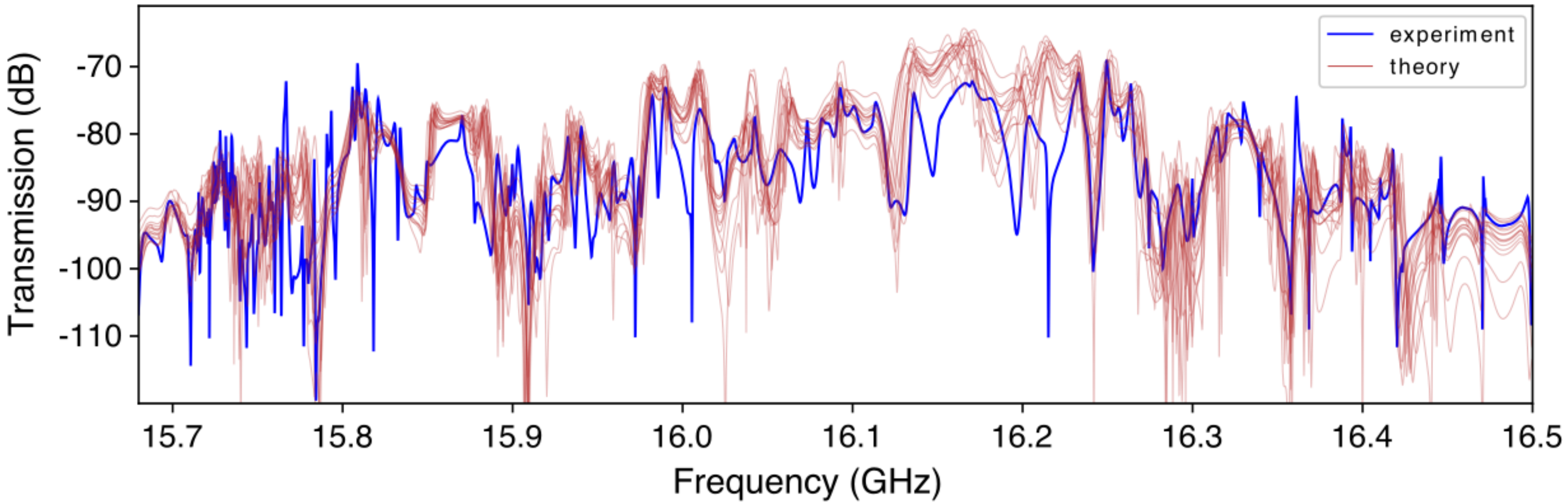
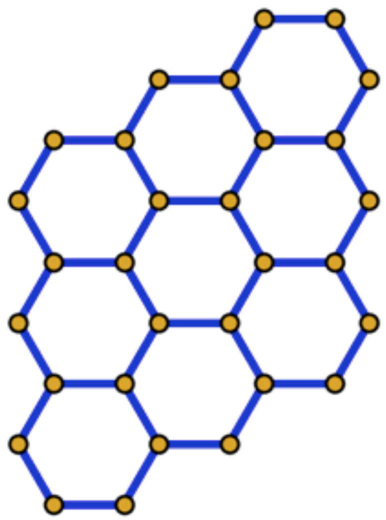
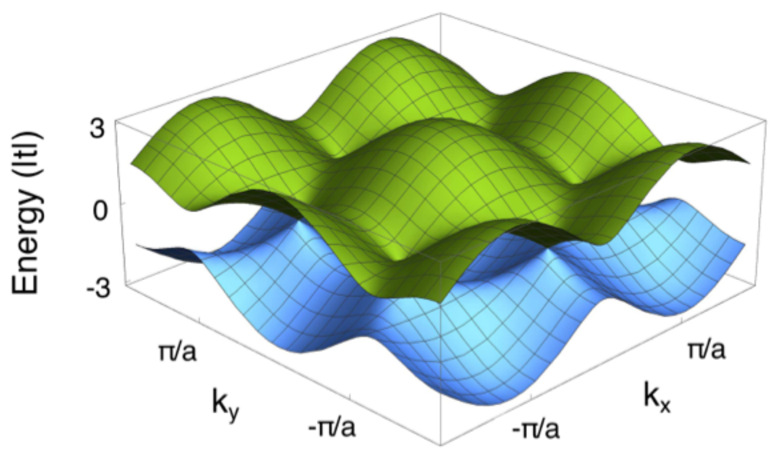


Kollár *et al*. arXiv:1802.09549 (2018)

Band Structure Correspondence

Layout X





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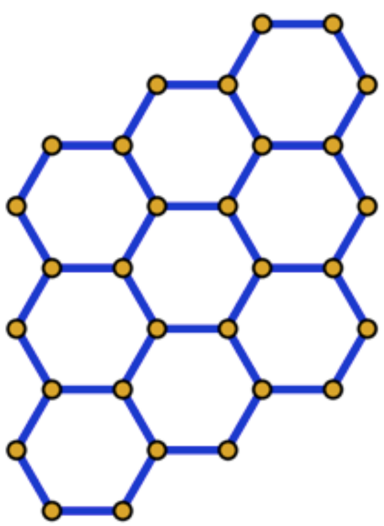
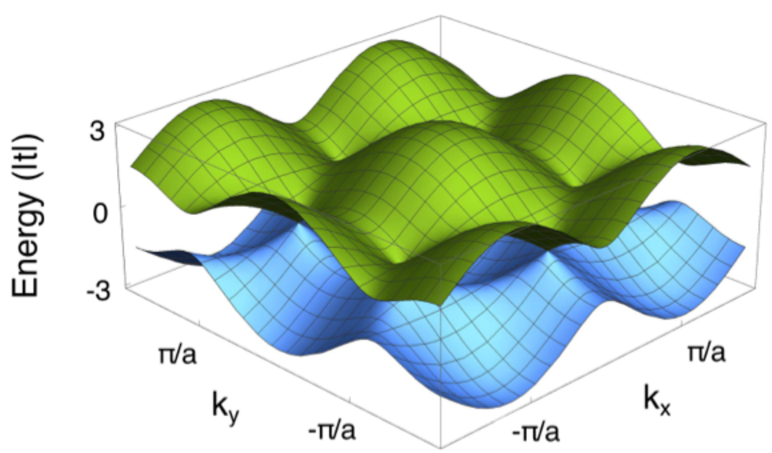
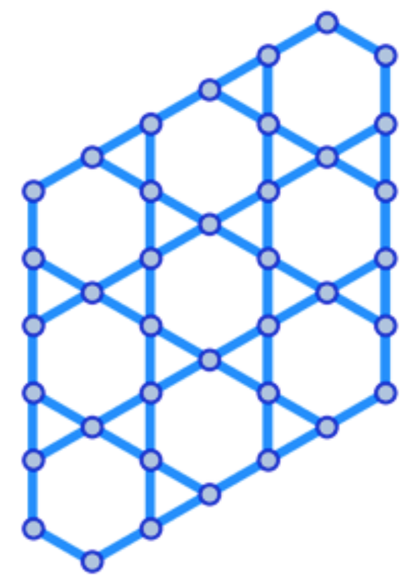
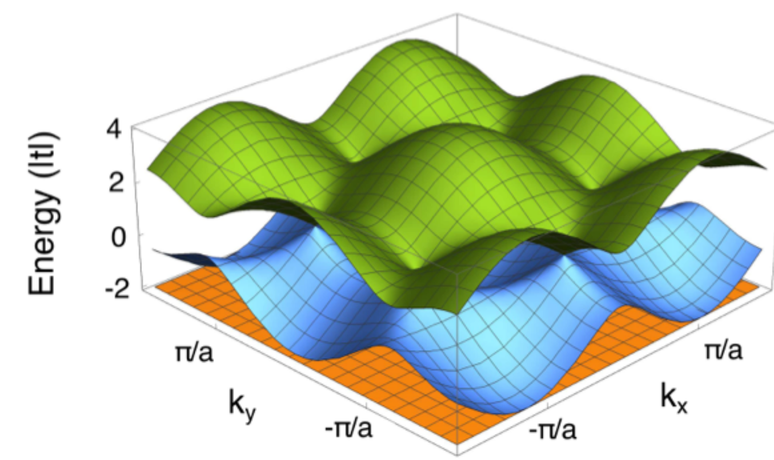




Line Graph $L(X)$





Band Structure Correspondence

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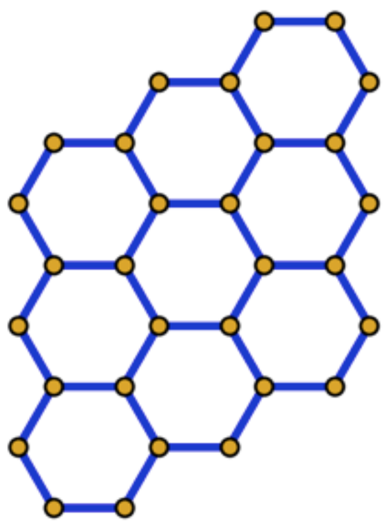
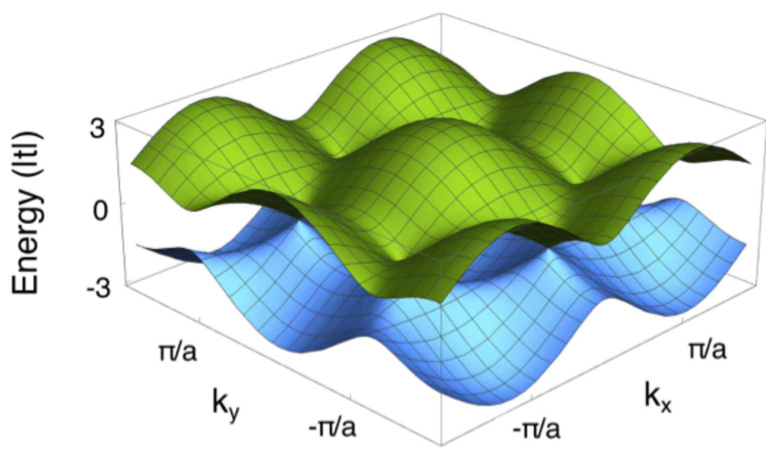
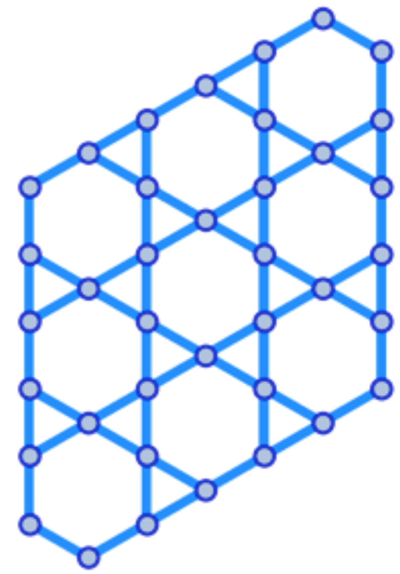
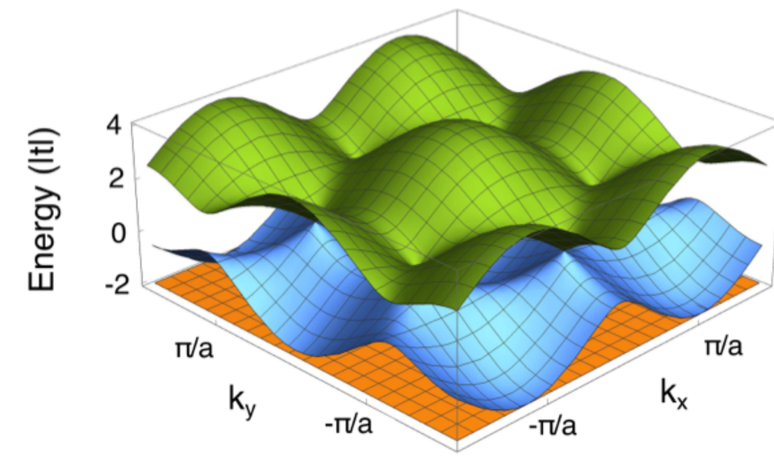
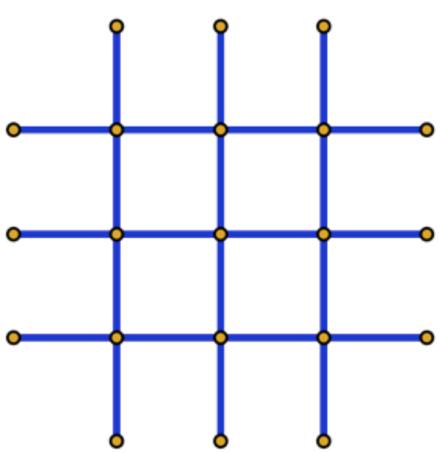
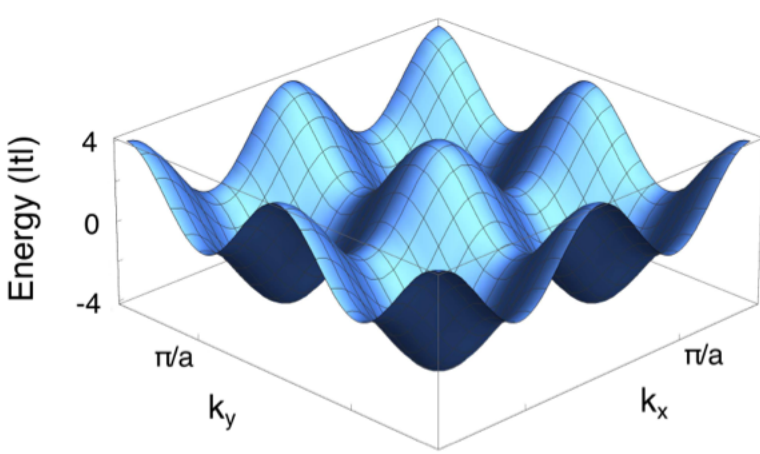






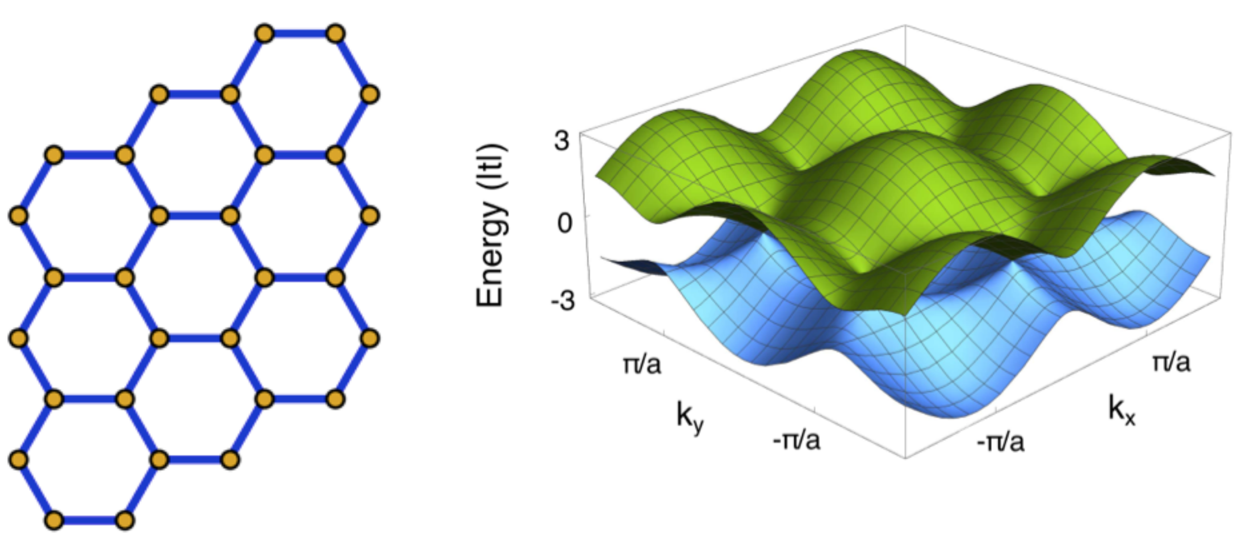


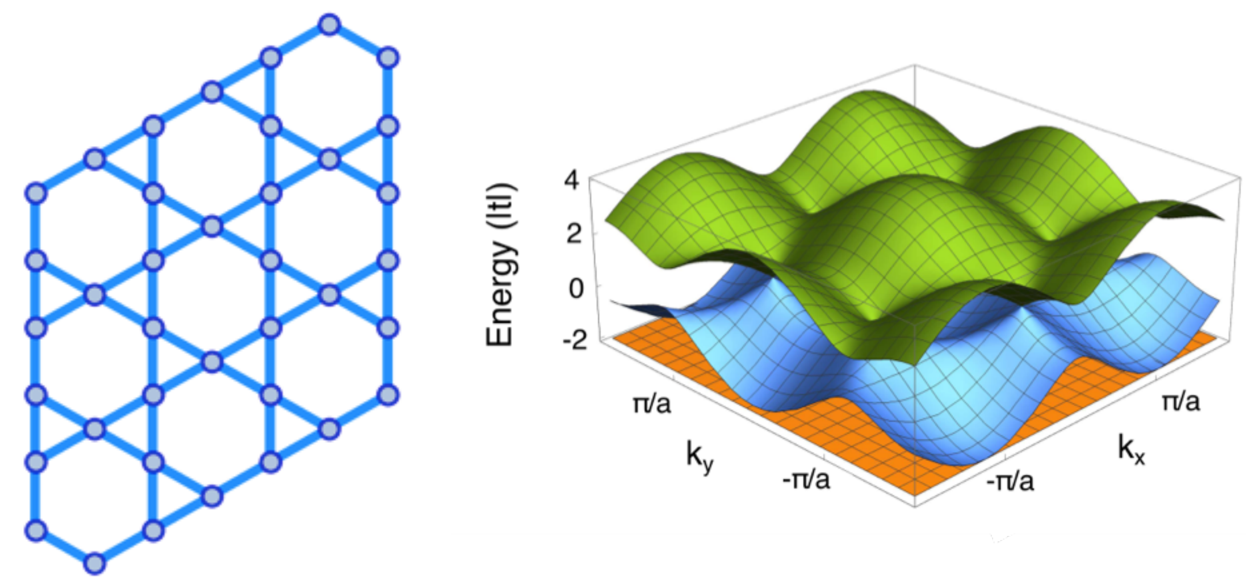


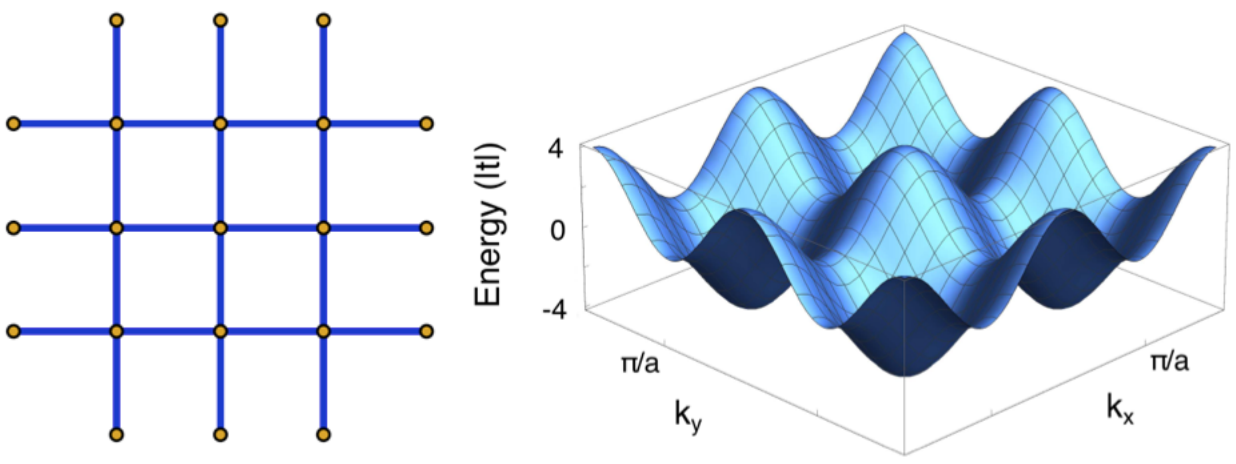


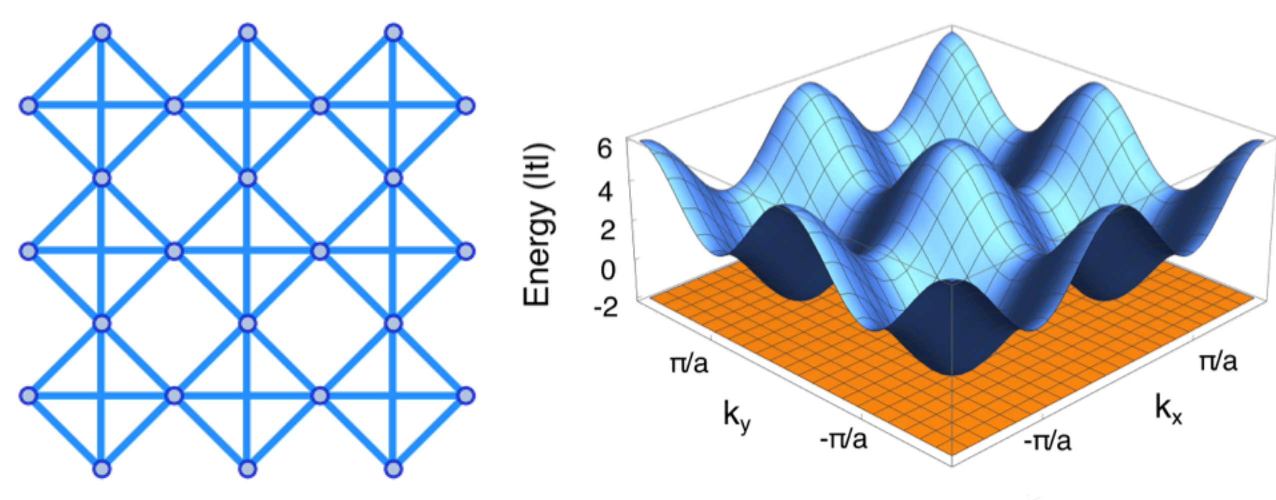
Band Structure Correspondence

Layout X **Line Graph** $L(X)$









Band Structure Correspondence

Layout Tight-Binding Hamiltonian

- Bounded self-adjoint operator on X

$$H_X$$

Kollár *et al*. arXiv:1902.02794 (2019)

Band Structure Correspondence

Layout Tight-Binding Hamiltonian

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$$H_X$$

Effective Hamiltonian

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

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Band Structure Correspondence

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Incidence Operator

- From X to L(X)

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

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

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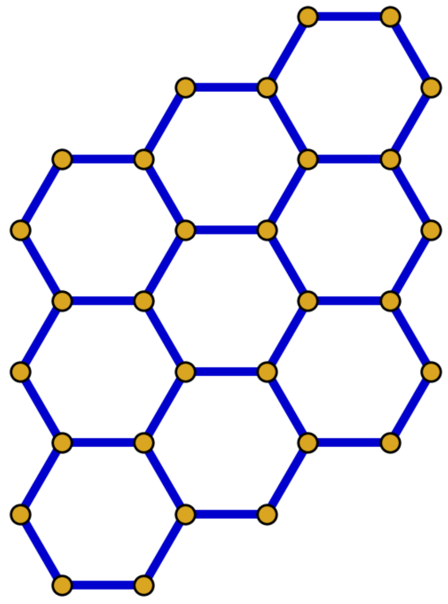
$$D_X + H_X \simeq 2I + \bar{H}_s(X)$$

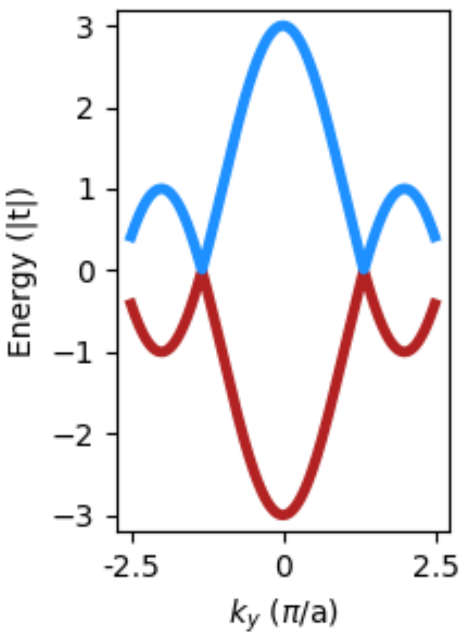
$$E_{\bar{H}_s} = \begin{cases} d - 2 + E_{H_X} \\ -2 \end{cases}$$

Kollár *et al*. arXiv:1902.02794 (2019)

Subdivision Graphs and Optimally Gapped Flat Bands

X





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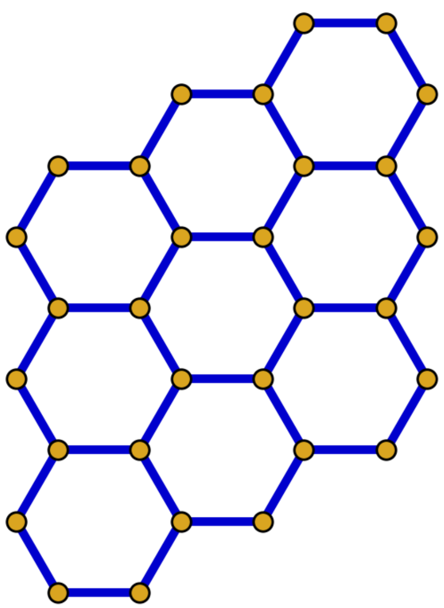
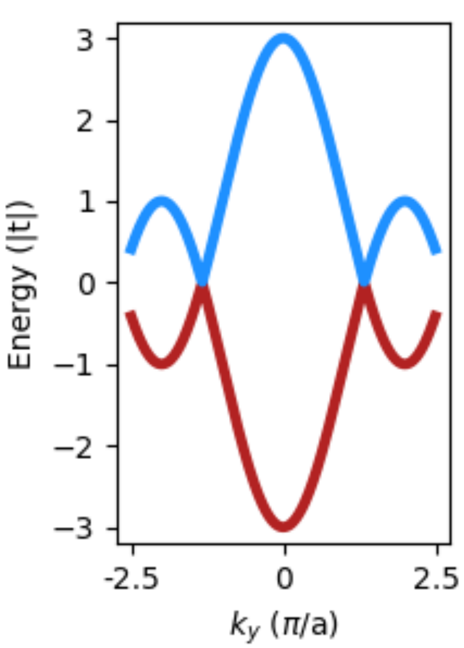
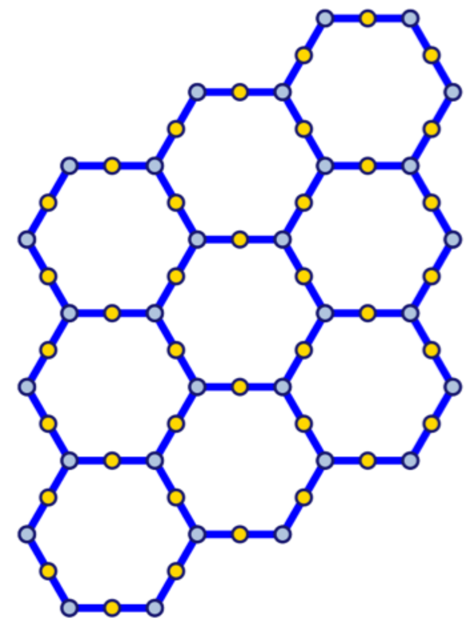
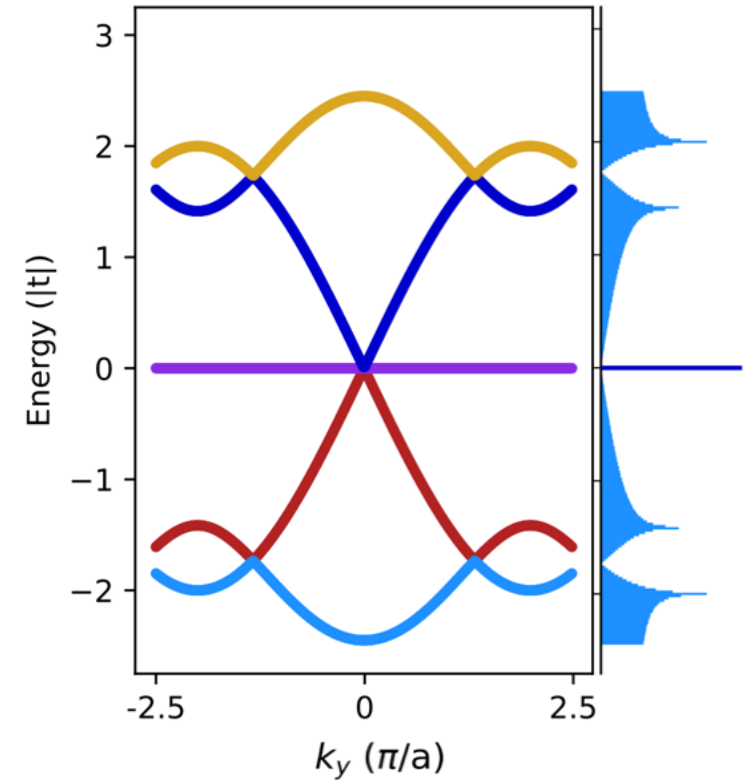




$$E_{\mathbb{S}(X)} = \begin{cases} \pm\sqrt{E_X + 3} \\ 0 \end{cases}$$

$\mathbb{S}(X)$





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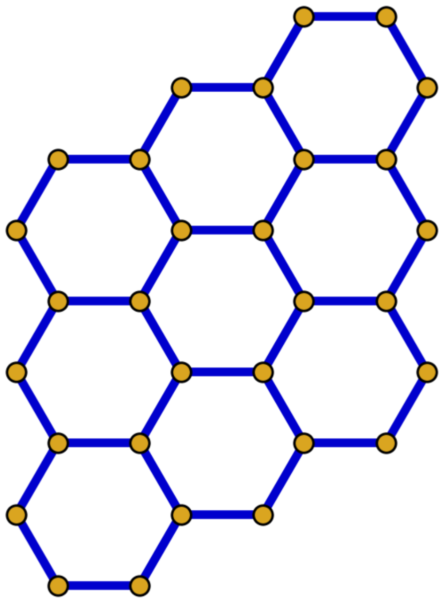

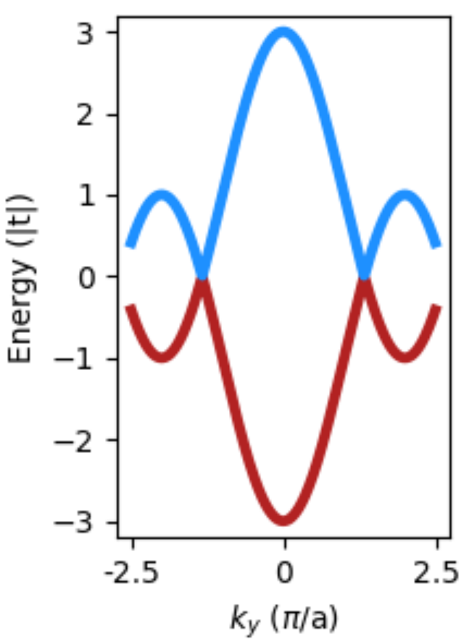

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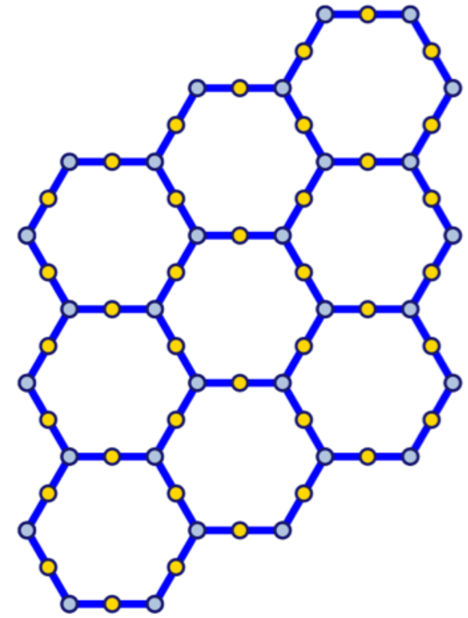
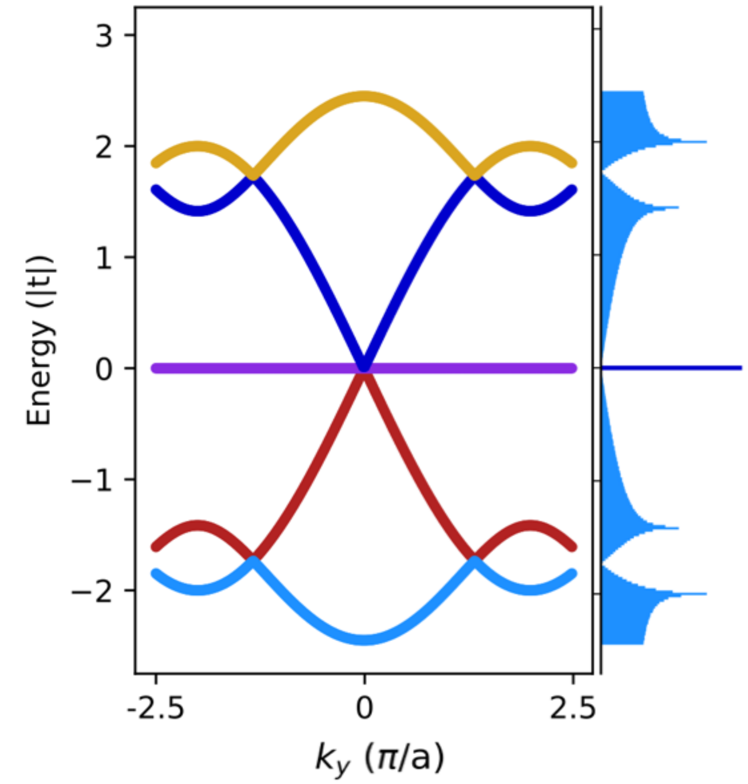
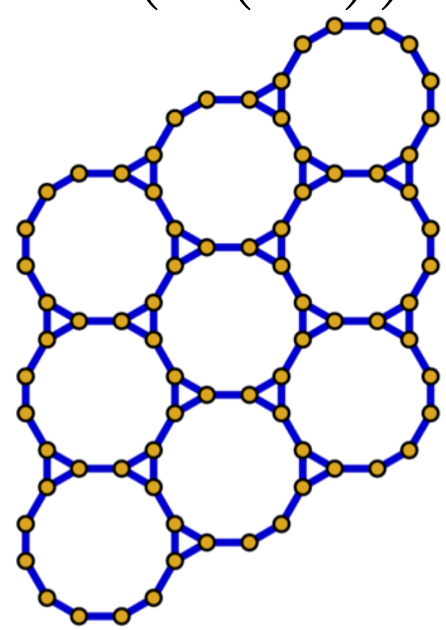
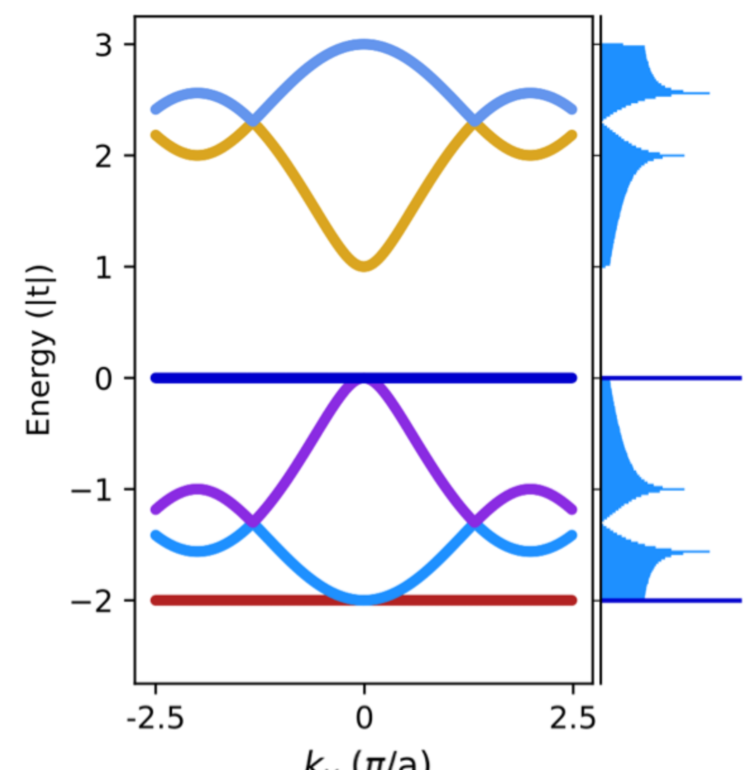




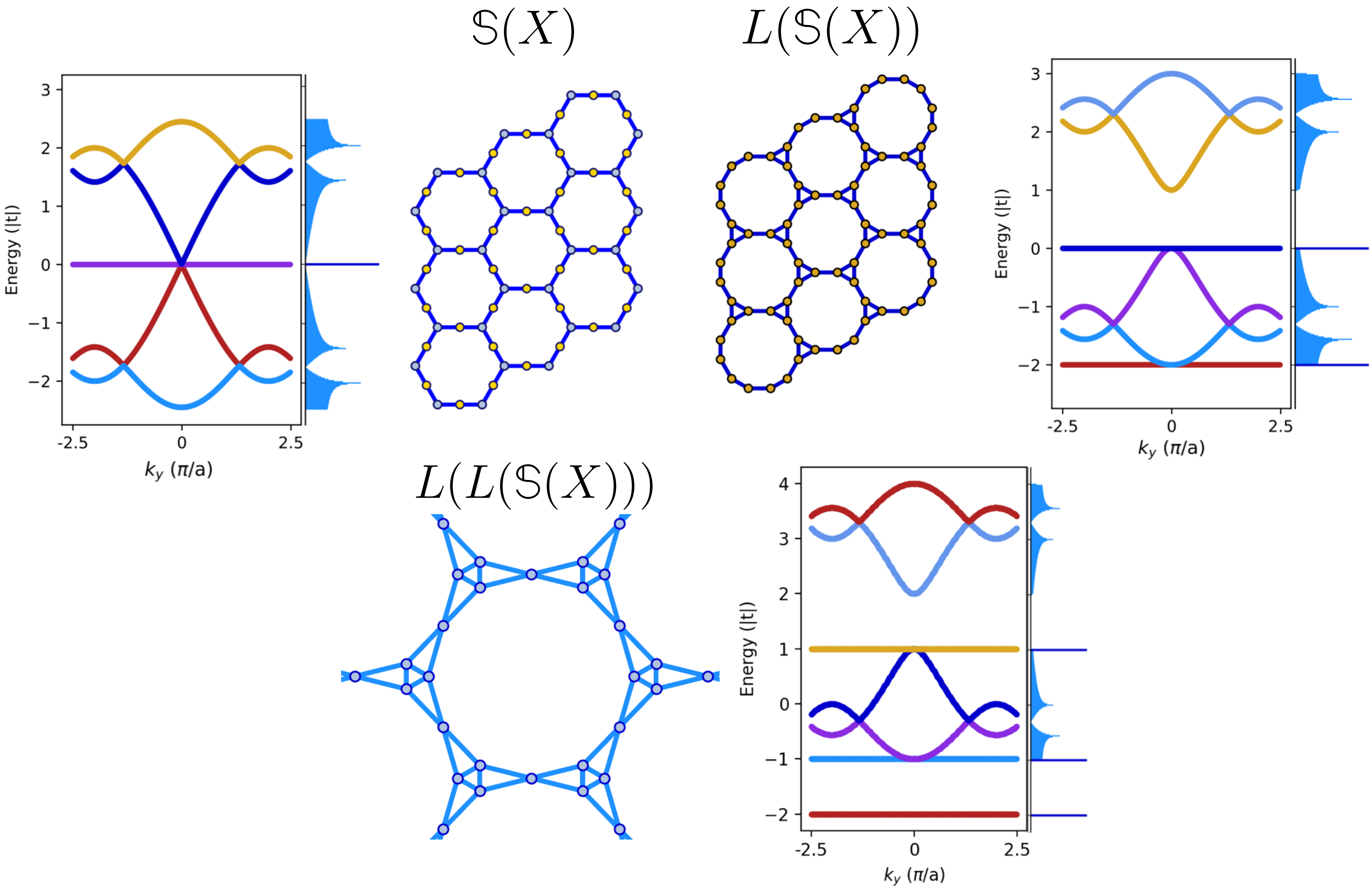
$$E_{L(\mathbb{S}(X))} = \begin{cases} \frac{1 \pm \sqrt{1 + 4(E_X + 3)}}{2} \\ 0 \\ -2 \end{cases}$$

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

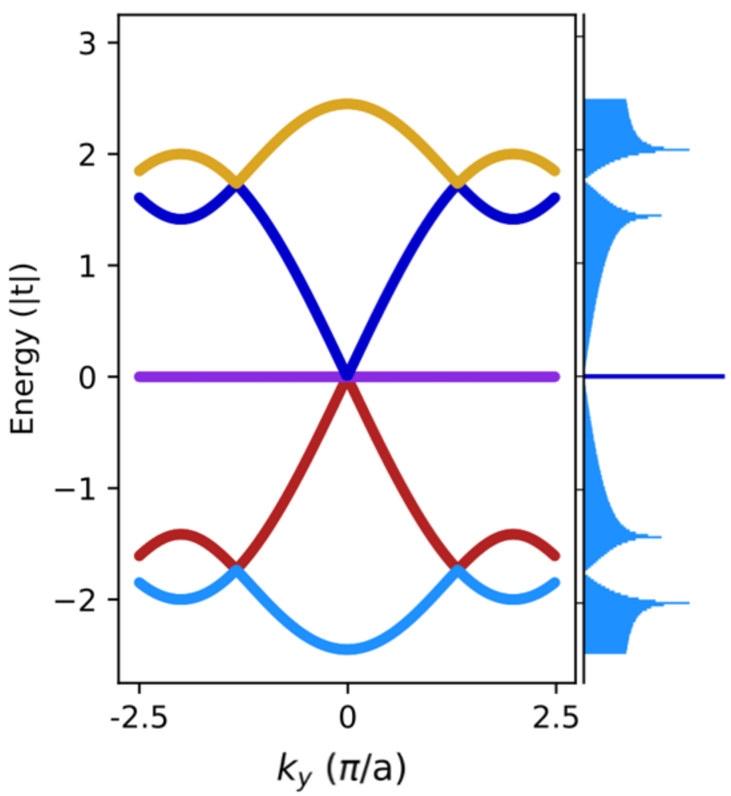




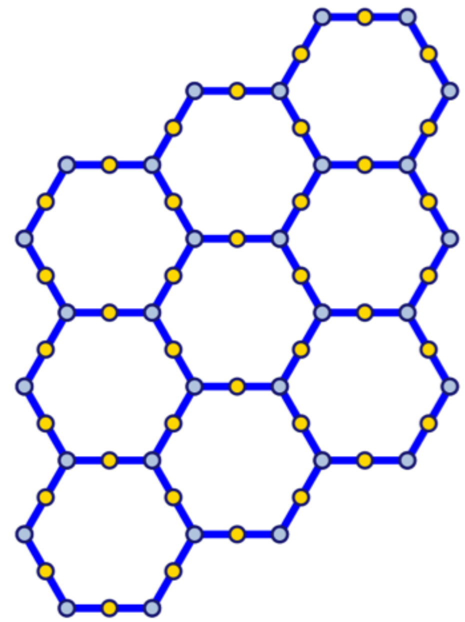
Subdivision Graphs and Optimally Gapped Flat Bands



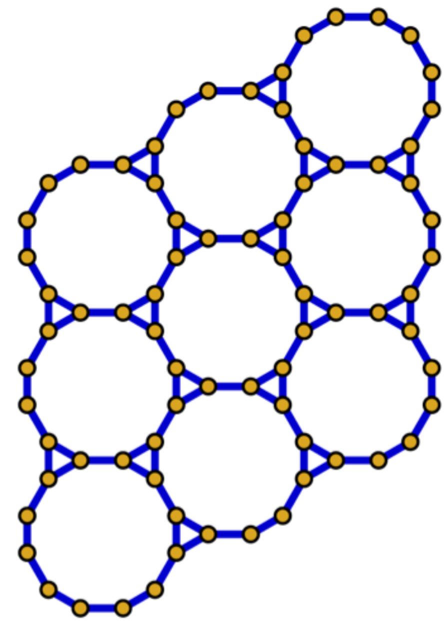
Subdivision Graphs and Optimally Gapped Flat Bands

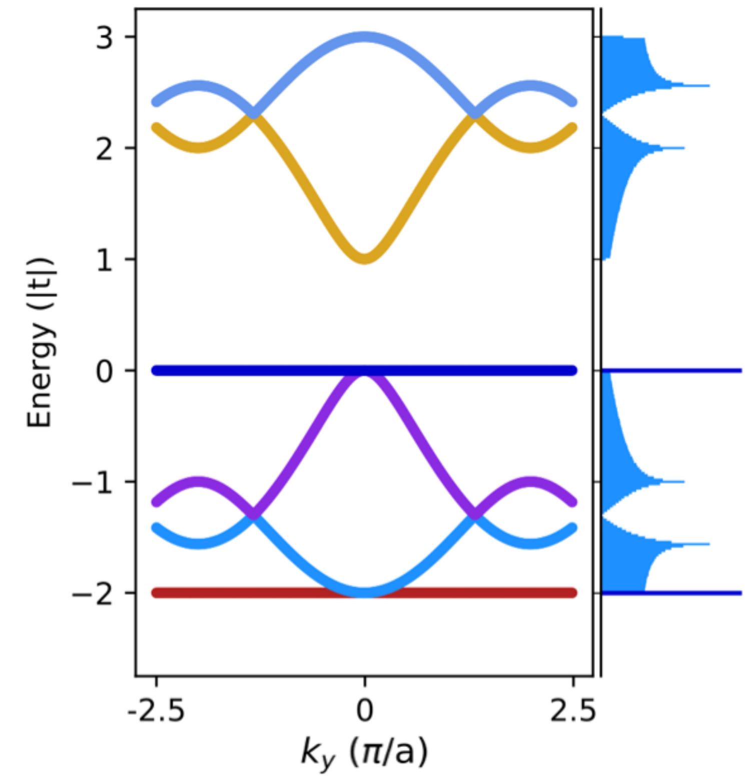


$\mathbb{S}(X)$

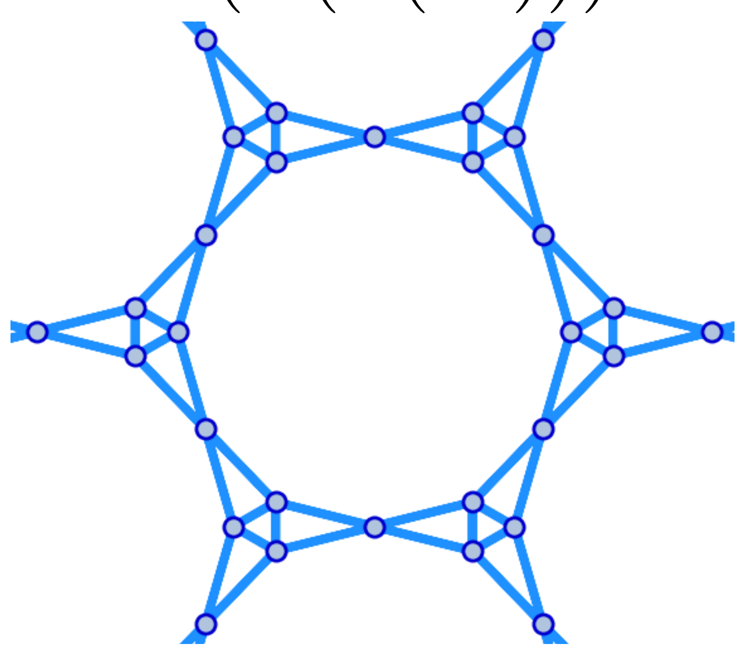


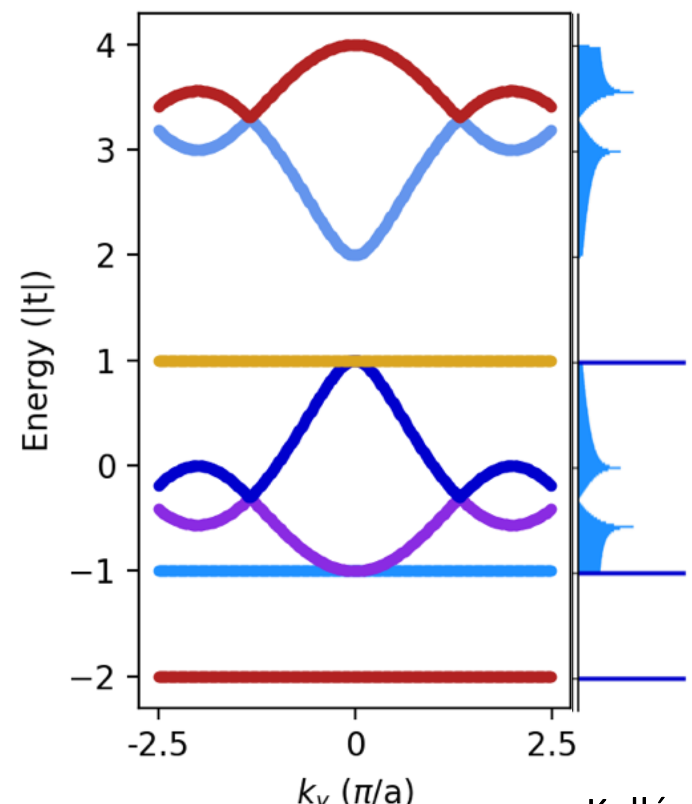
$L(\mathbb{S}(X))$





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





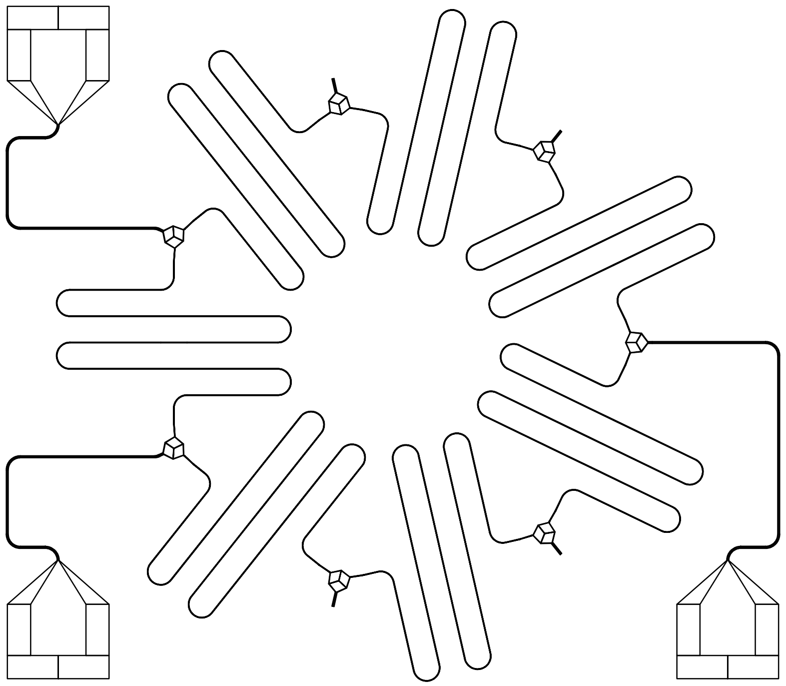
Kollár *et al.* arXiv:1902.02794 (2019)

Outline

- Coplanar Waveguide (CPW) Lattices
  - Interacting photons
- Hyperbolic lattices
  - Projection to flat space
  - Deformable resonators
- Flat-band lattices
  - Line graphs
  - Maximal gaps
- Non-linear lattices
  - Limit cycles
  - Chaos

Small-Scale Lattice Device

Heptagonal Ring

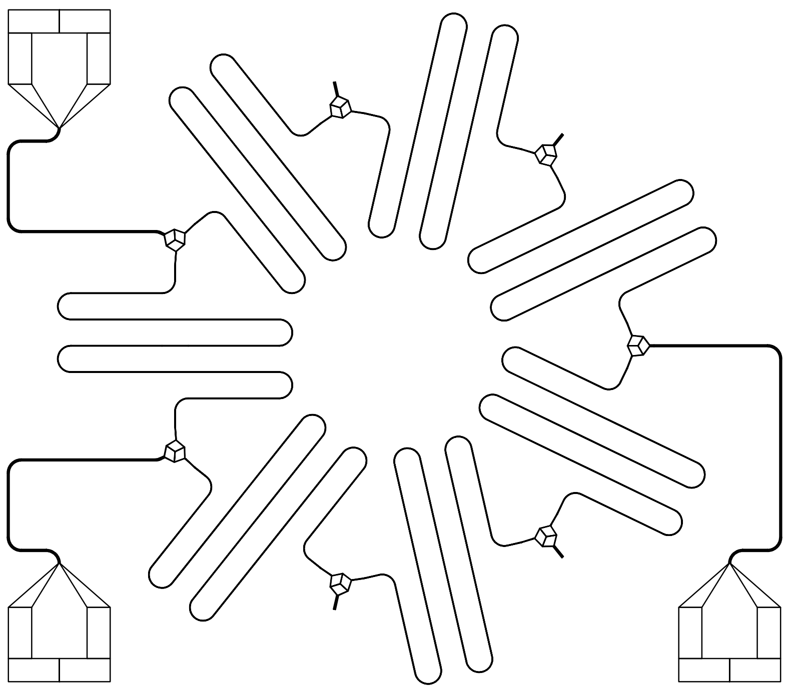


Niobium TiN

- Kinetic Inductor
- Kerr-nonlinear

Small-Scale Lattice Device

Heptagonal Ring



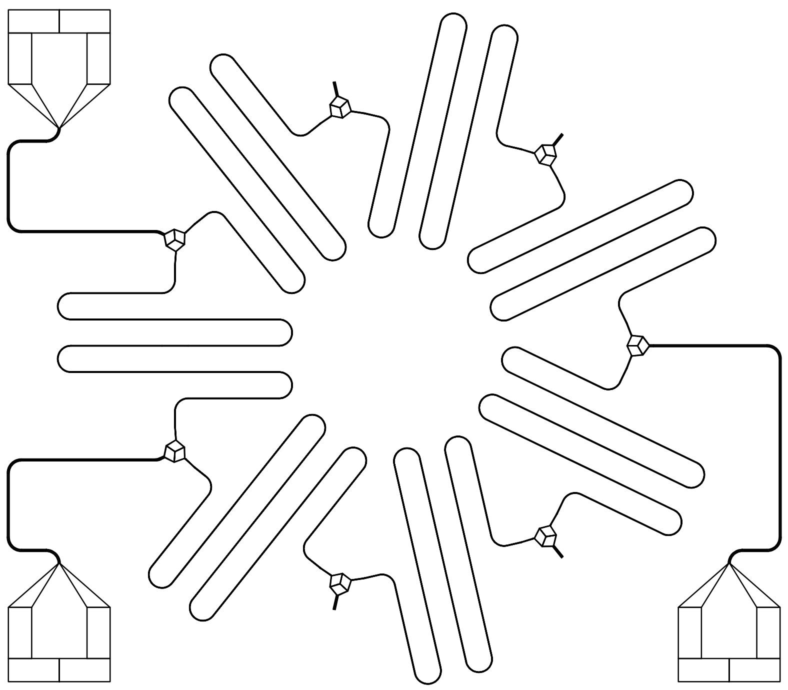
Niobium TiN

- Kinetic Inductor
- Kerr-nonlinear

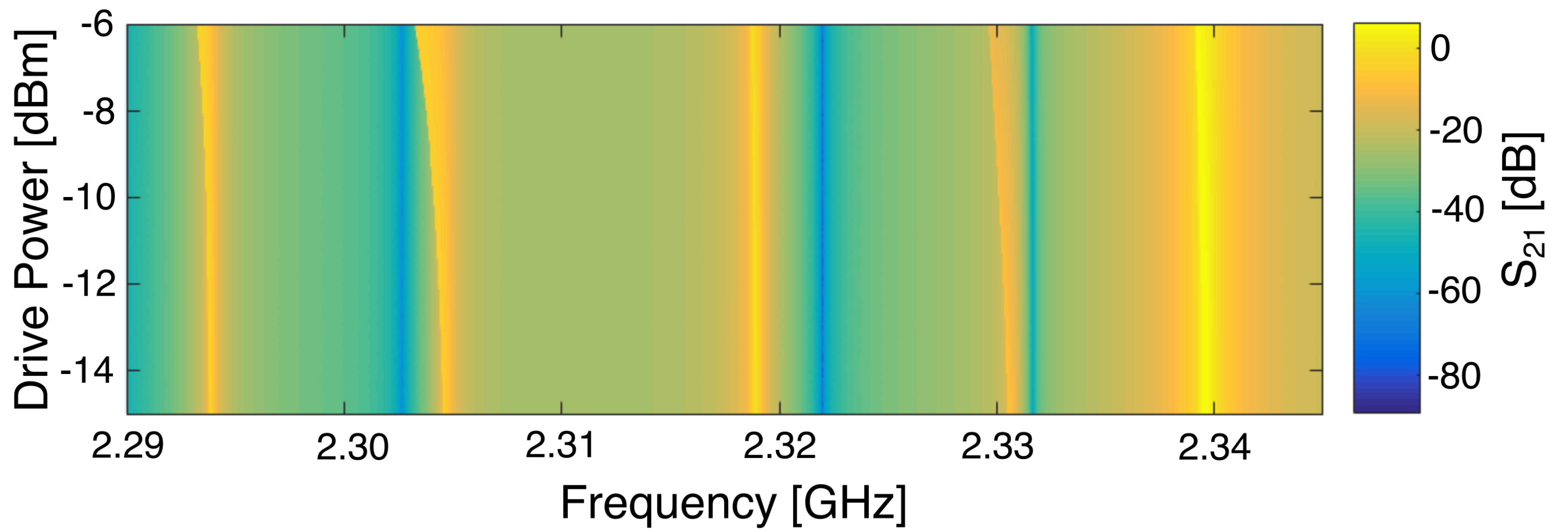
$$\mathbf{H_{TB}} = \omega_0 \sum_{\mathbf{i}} \mathbf{a_i^\dagger a_i} - \mathbf{t} \sum_{\langle \mathbf{i,j} \rangle} (\mathbf{a_i^\dagger a_j} + \mathbf{a_j^\dagger a_i}) + \mathbf{U} \sum_{\mathbf{i}} \mathbf{a_i^\dagger a_i^\dagger a_i a_i}$$

Small-Scale Lattice Device

Heptagonal Ring



Transmission



Niobium TiN

- Kinetic Inductor
- Kerr-nonlinear

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

$$+ \mathbf{U} \sum_i \mathbf{a}_i^\dagger \mathbf{a}_i^\dagger \mathbf{a}_i \mathbf{a}_i$$

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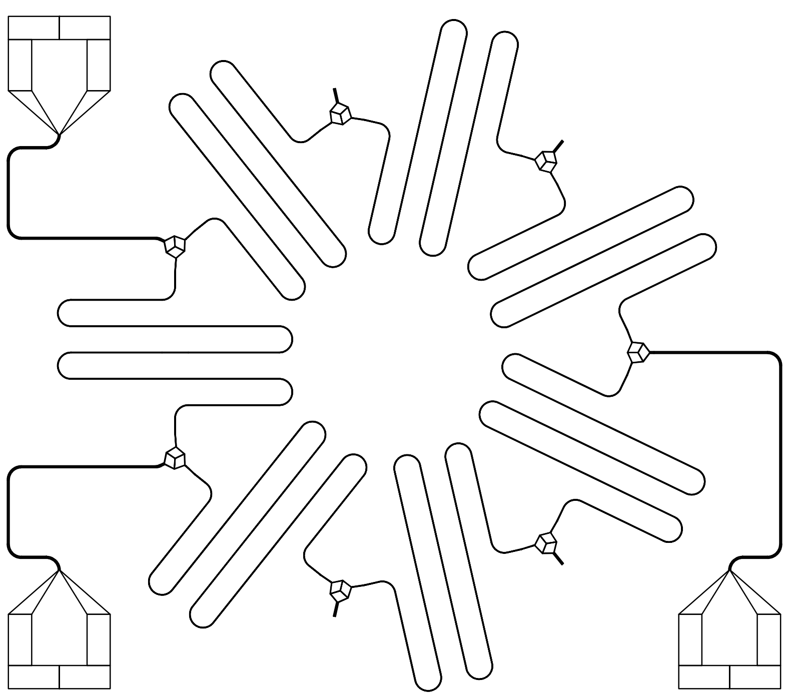

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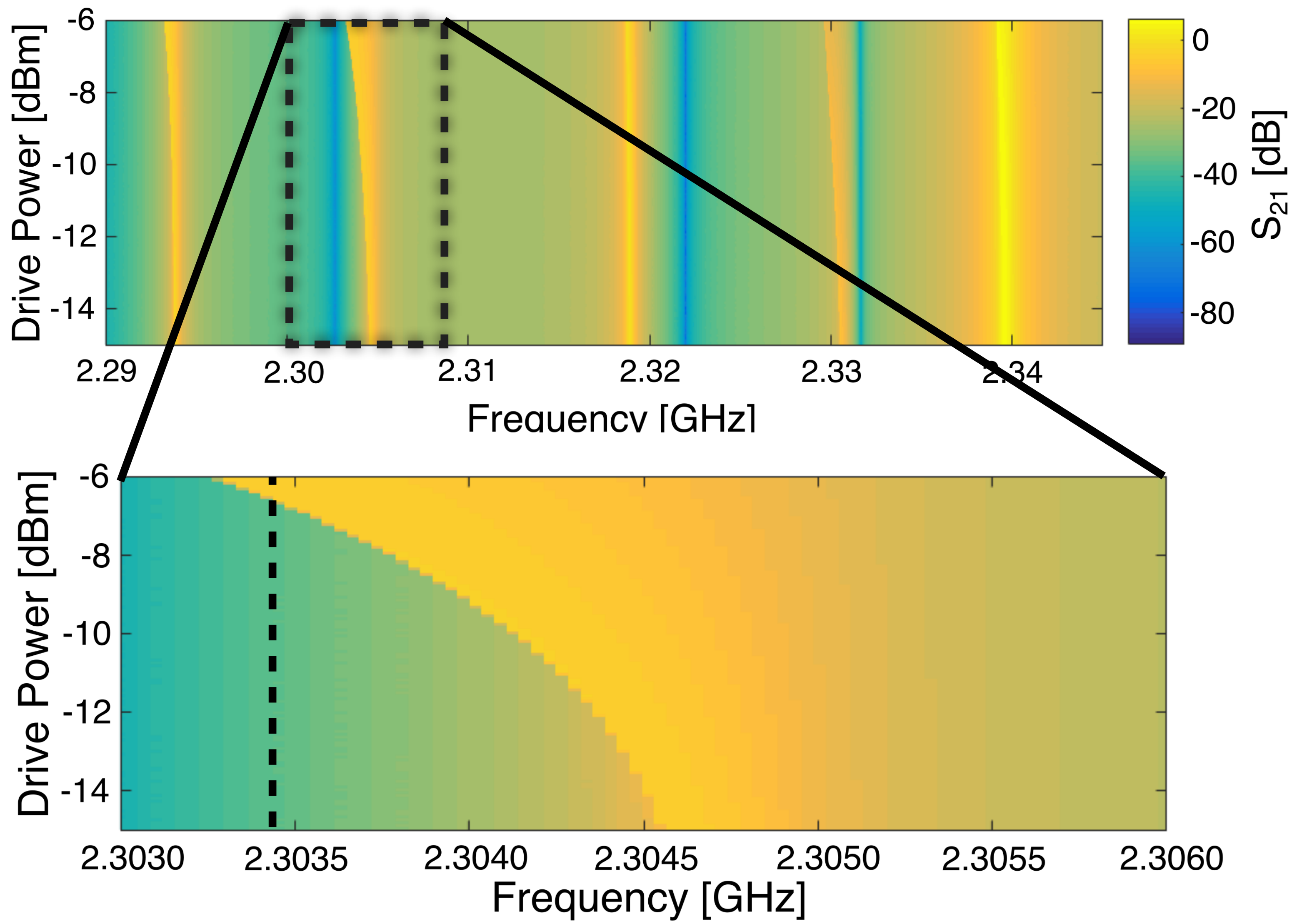
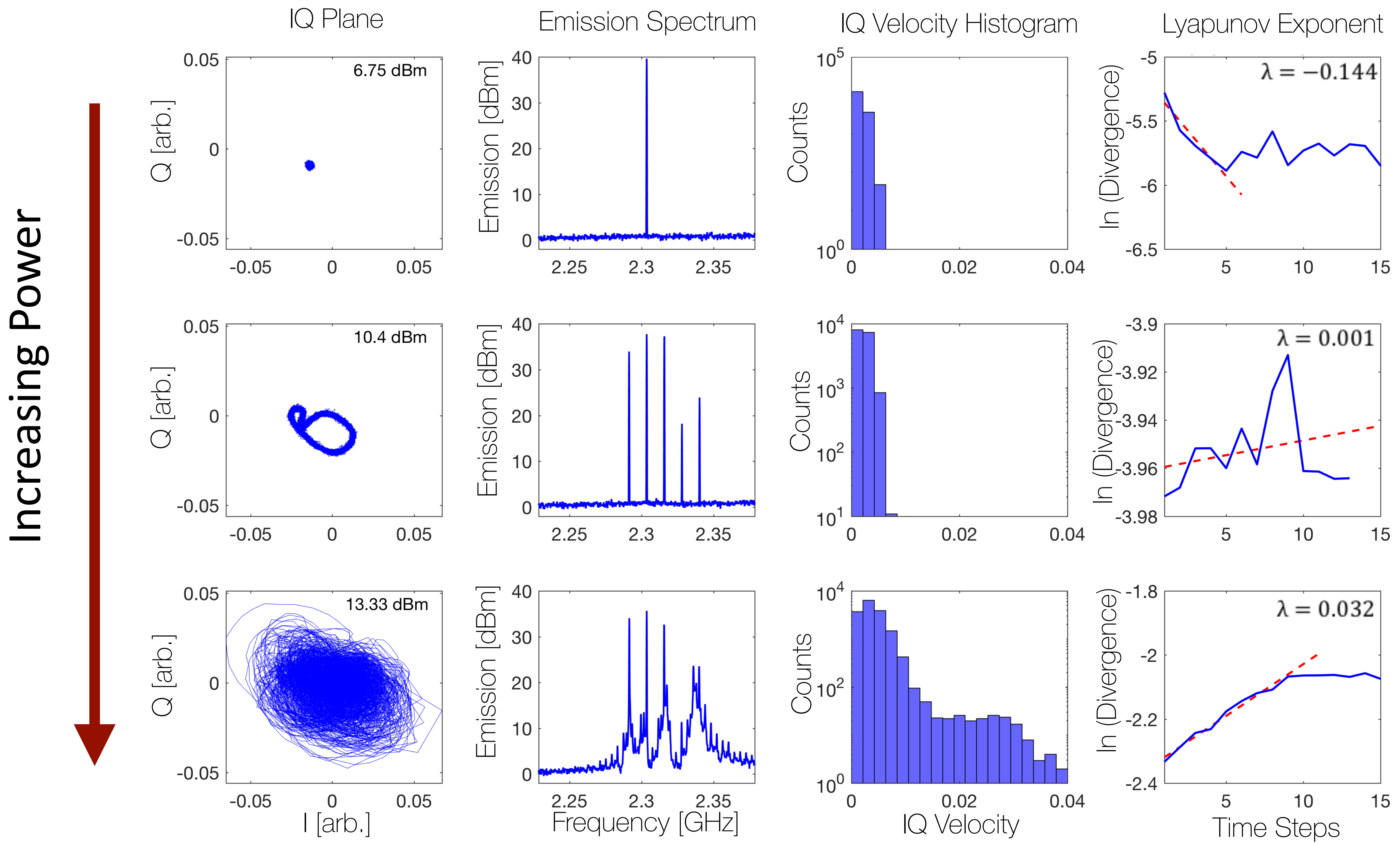
Transmission



Linear and Non-linear Response



Equations of Motion and Linear Stability

Equation of Motion

$$d\psi = -iH_{TB}\psi - \kappa\psi + D - iR(\psi)$$

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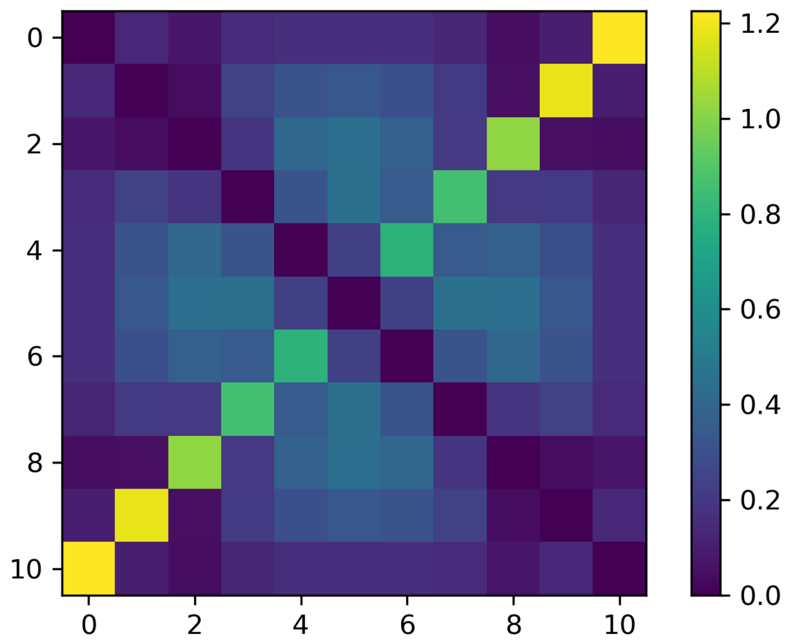
- Effective Hamiltonian

$$H_{eff} = H_{TB} - i\kappa + i\tilde{D} + \tilde{R}(\psi)$$

Propagator, “Effective” Hamiltonian

Limit Cycle

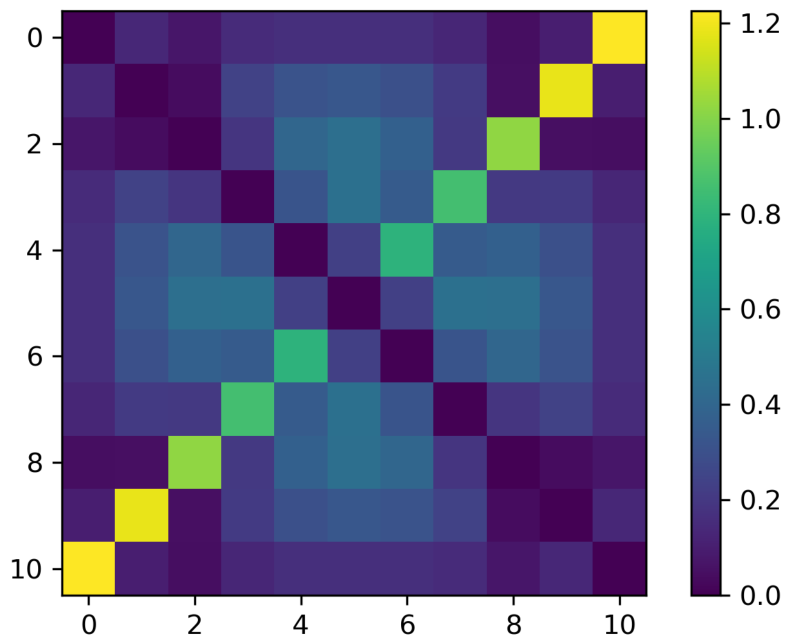
Sample Propagator



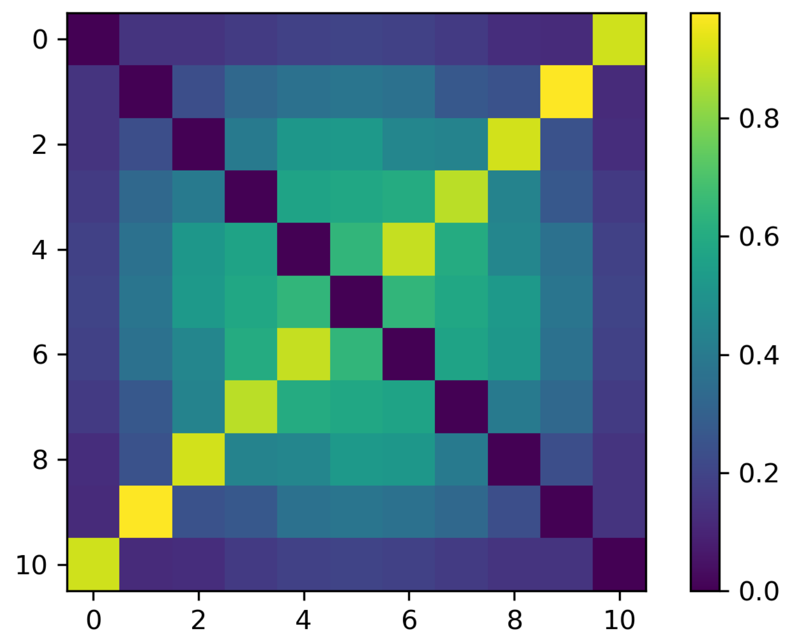
Propagator, “Effective” Hamiltonian

Limit Cycle

Sample Propagator



Average Propagator



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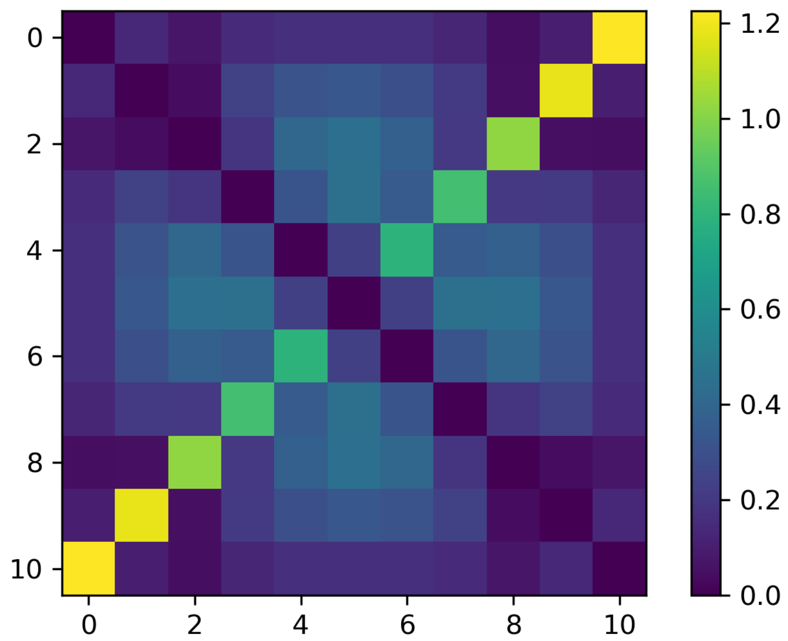

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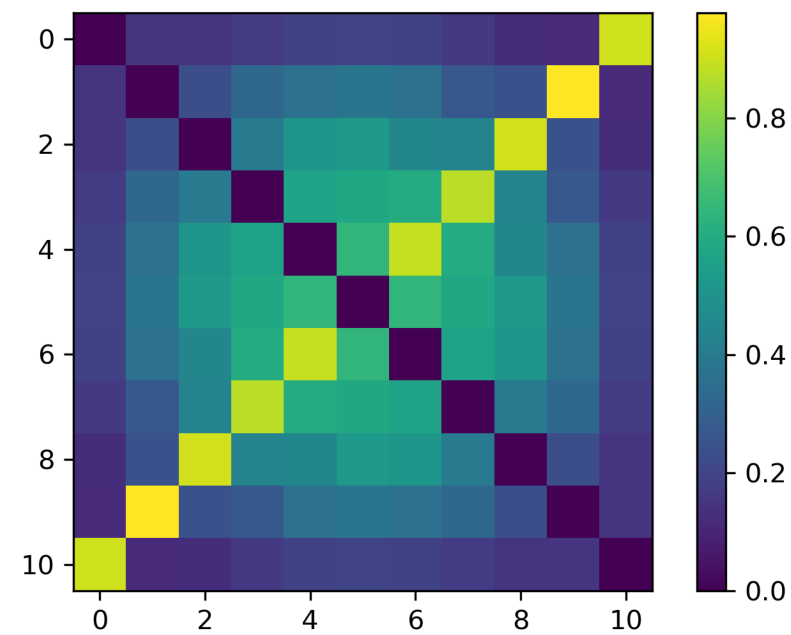
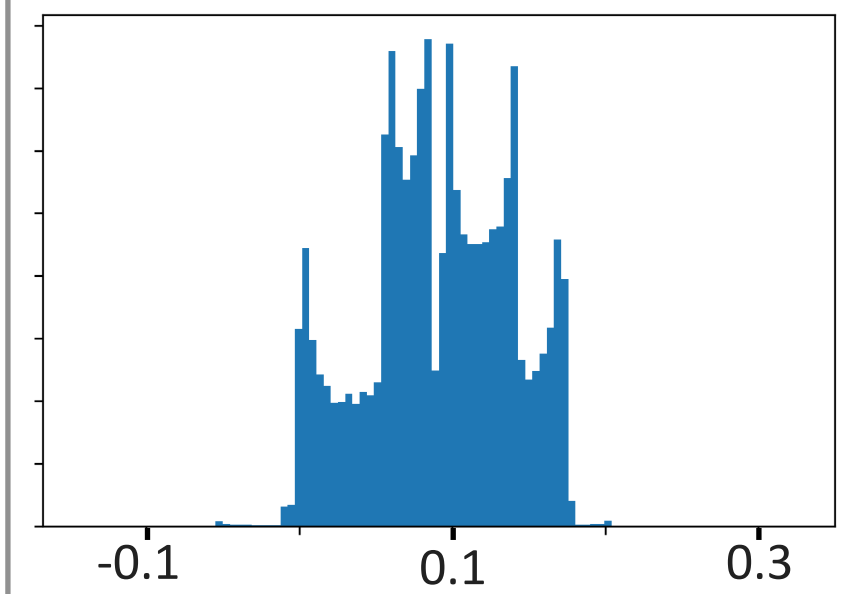


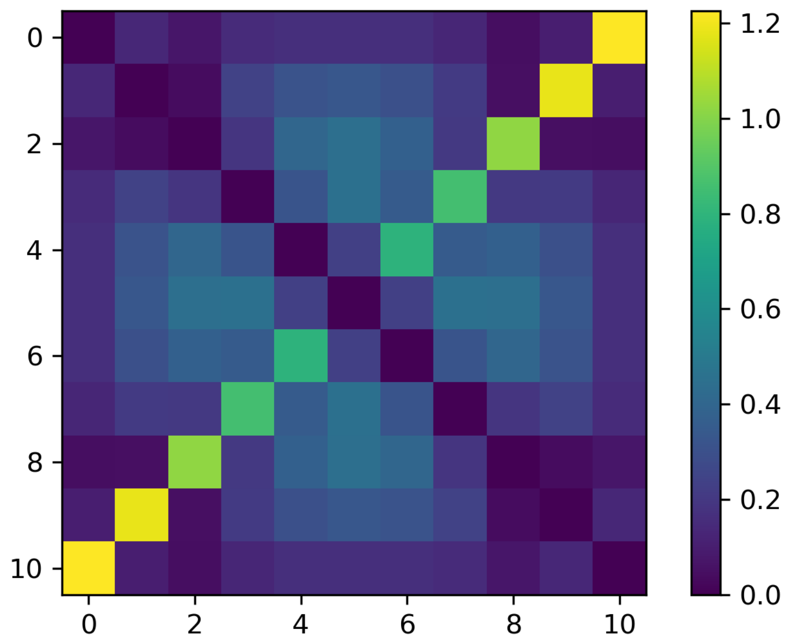
Sample Element Distribution

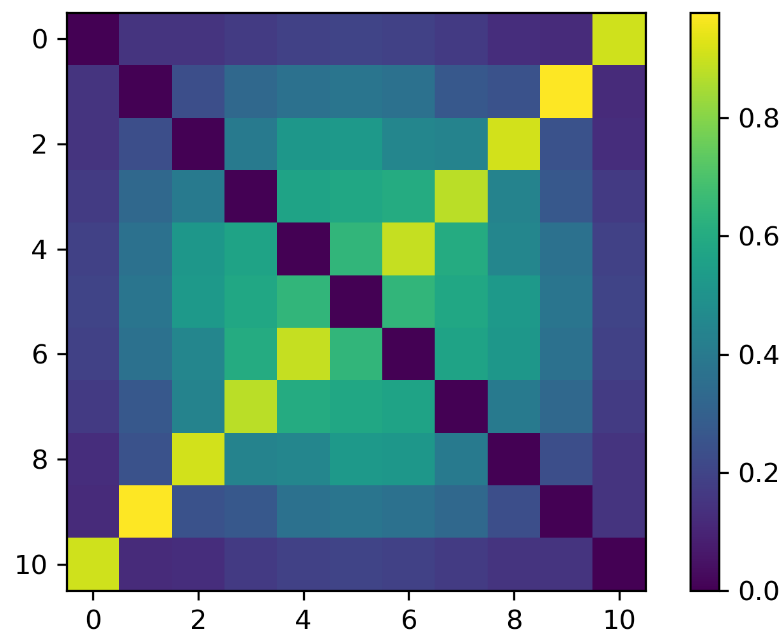


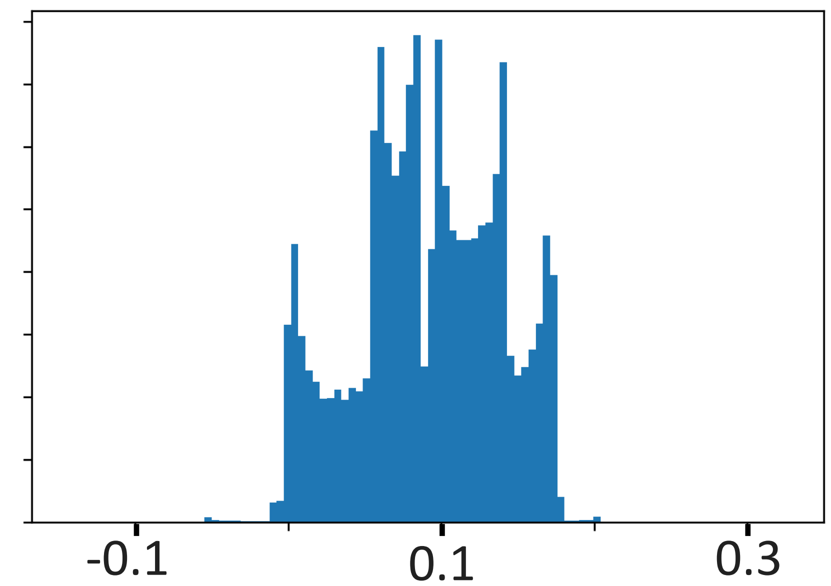
Propagator, "Effective" Hamiltonian

Sample Propagator | Average Propagator | Sample Element Distribution

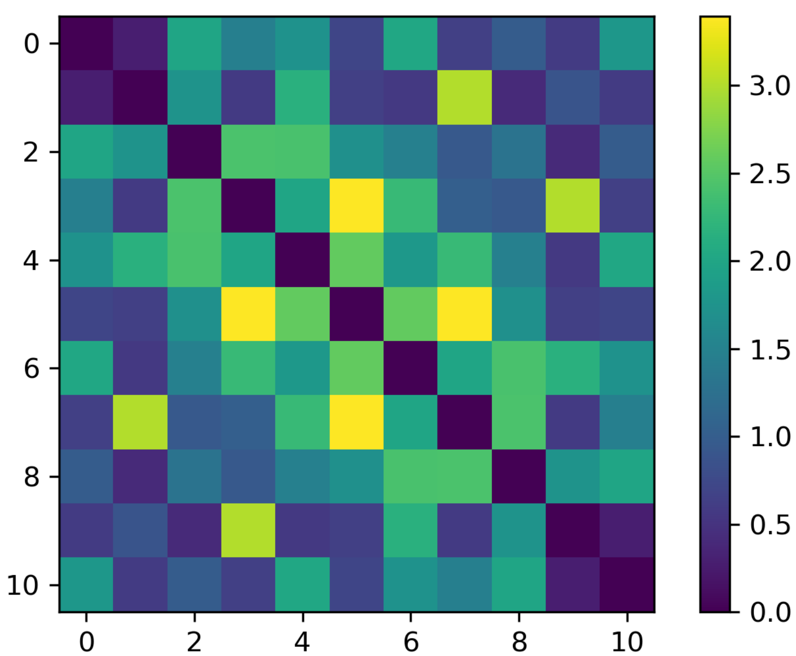
Limit Cycle







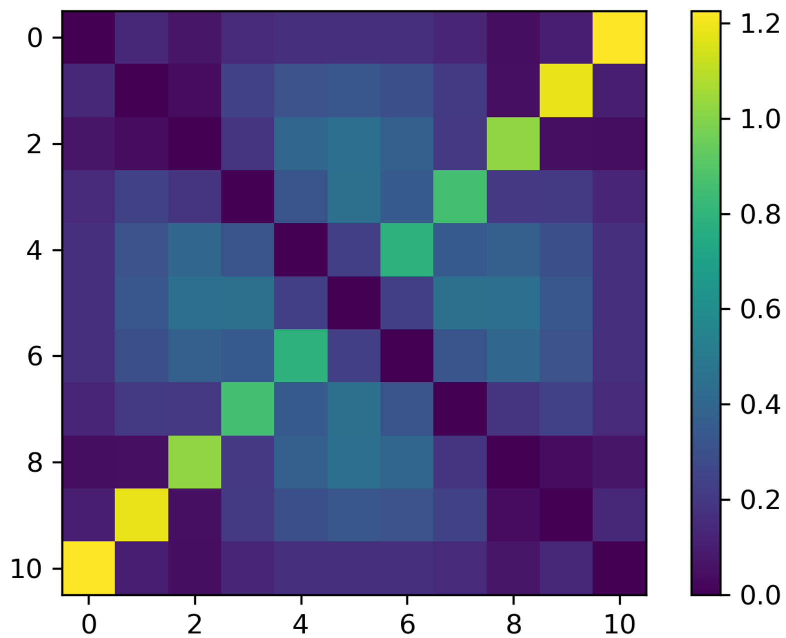
Chaos

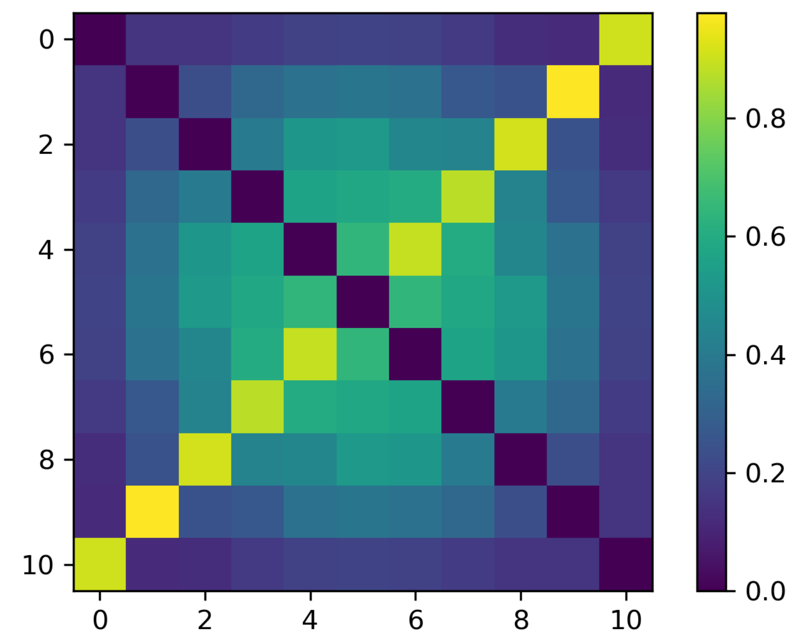


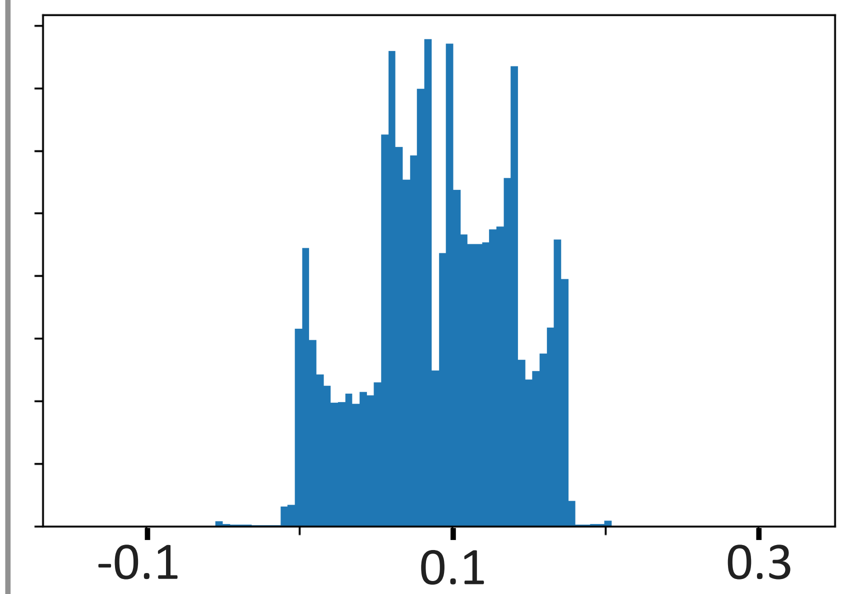
Propagator, “Effective” Hamiltonian

Sample Propagator | **Average Propagator** | **Sample Element Distribution**

Limit Cycle







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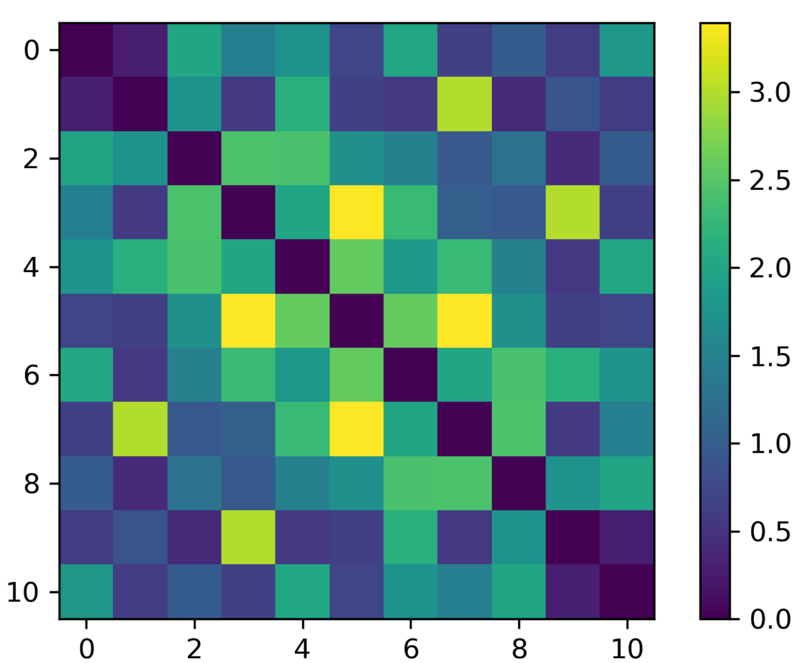
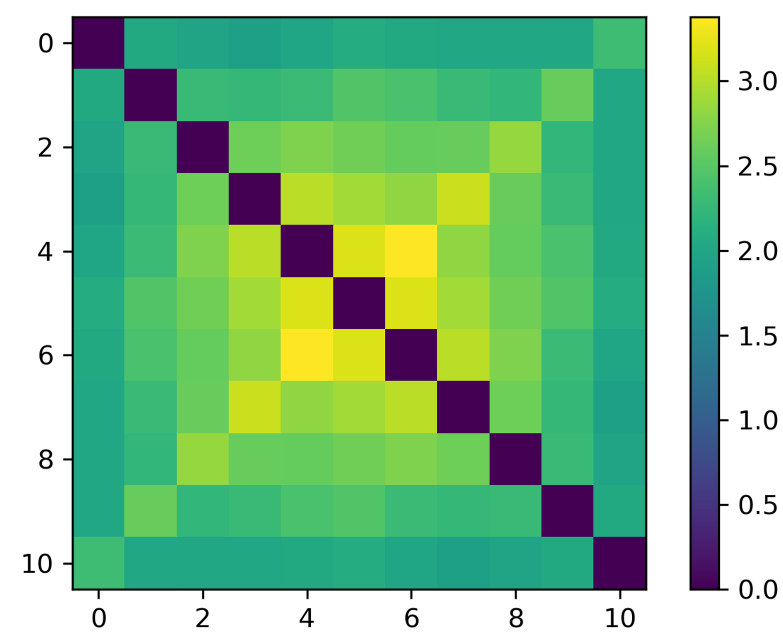
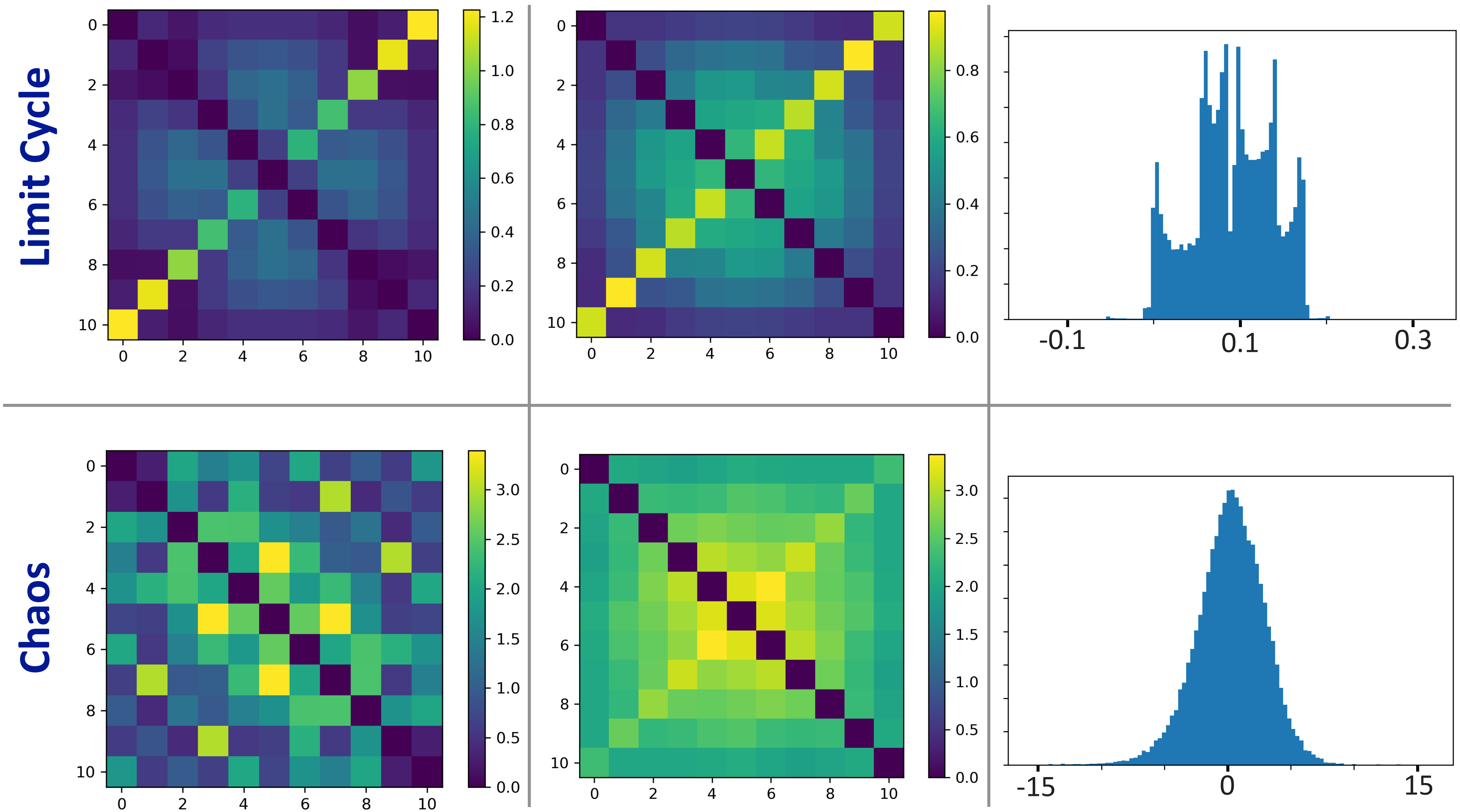




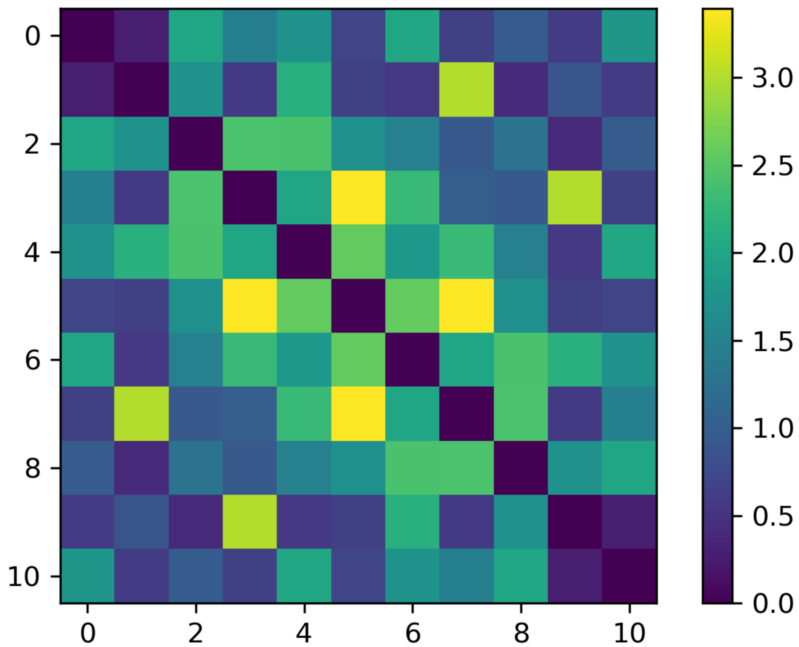
Propagator, “Effective” Hamiltonian

Sample Propagator | **Average Propagator** | **Sample Element Distribution**

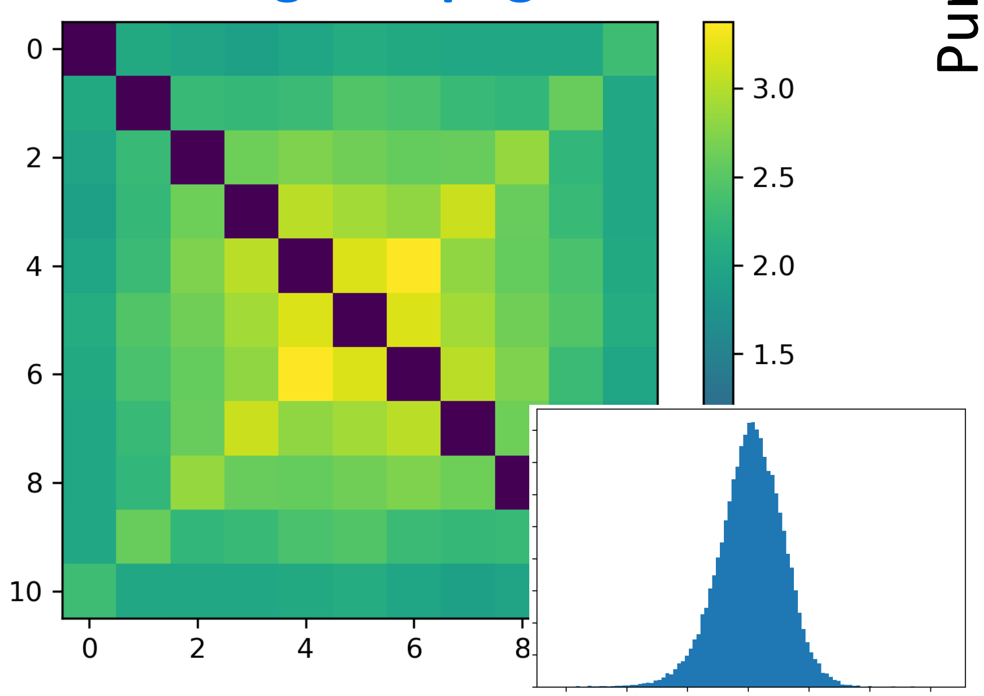


Chaotic “Effective” Hamiltonian

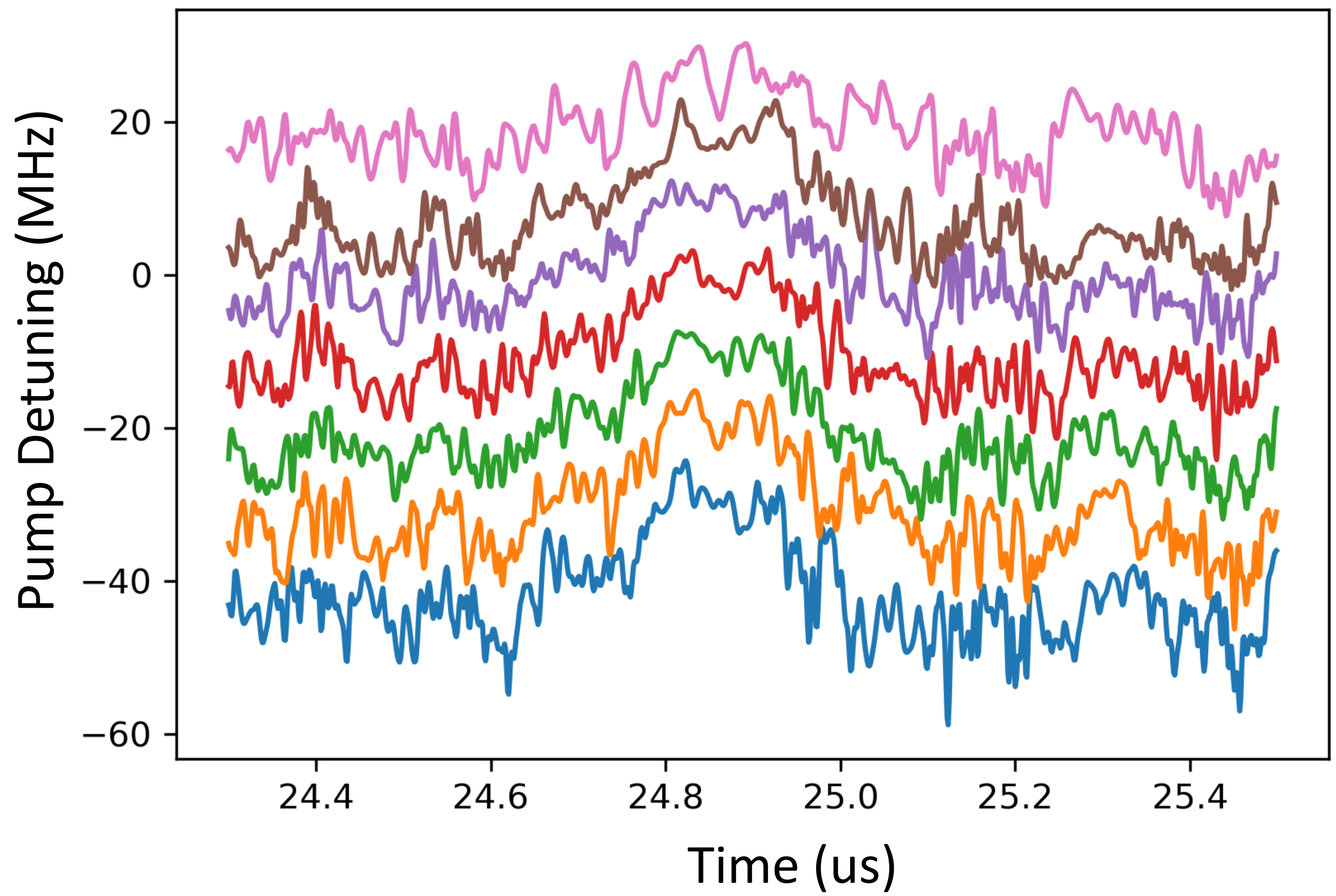
Sample Propagator



Average Propagator



Eigenenergies



Conclusion and Outlook

- Circuit QED lattices
  - Artificial photonic materials
  - Interacting photons
- Hyperbolic lattices
  - Unusual band structures
  - On-chip fabrication
- Flat-band lattices
  - 0, -2
  - Optimal gaps
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  - Limit Cycles
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Kollár *et al*. arXiv:1802.09549 (2018)
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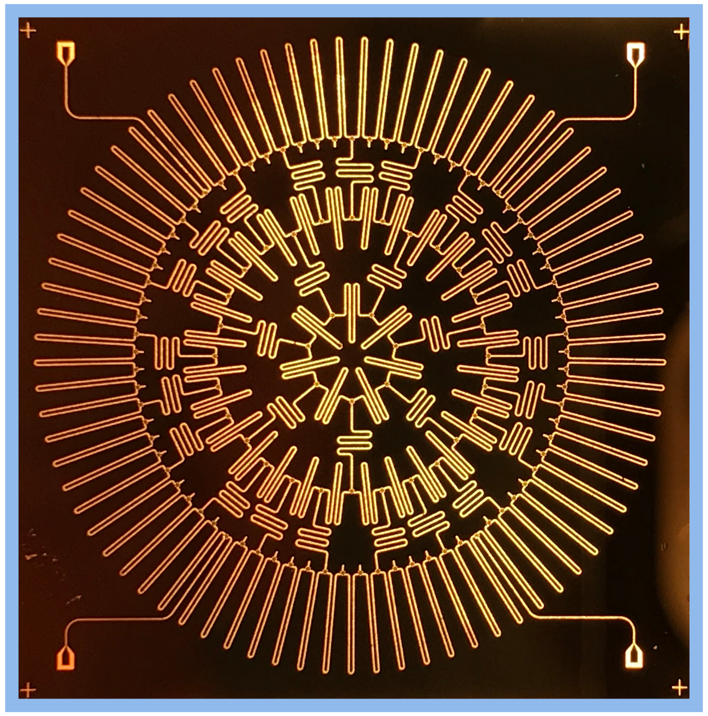

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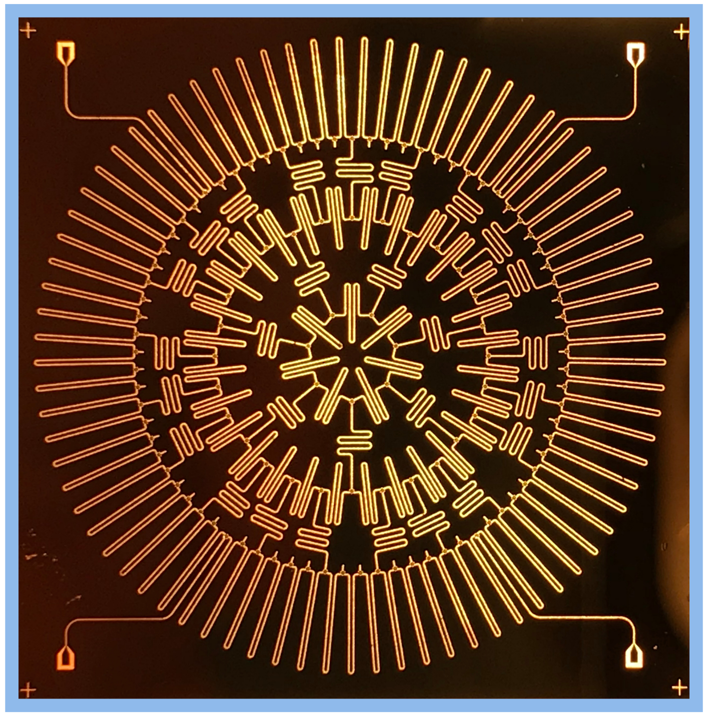

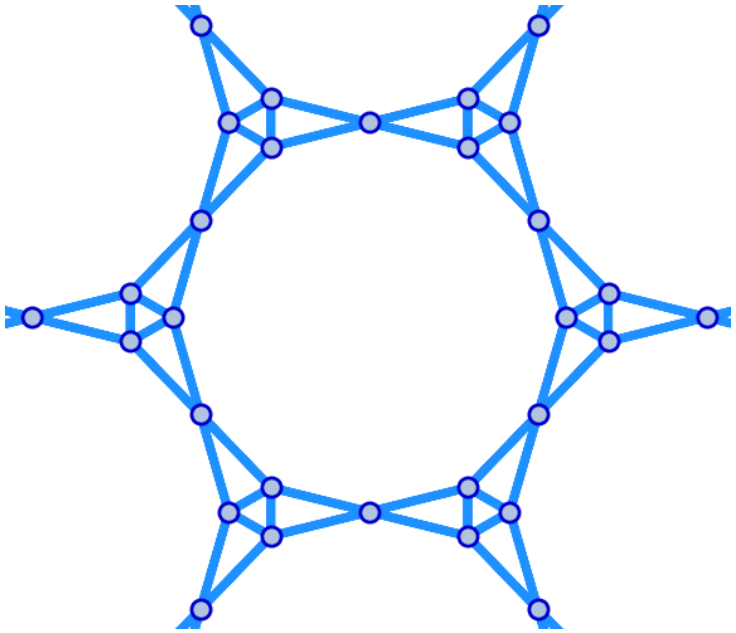

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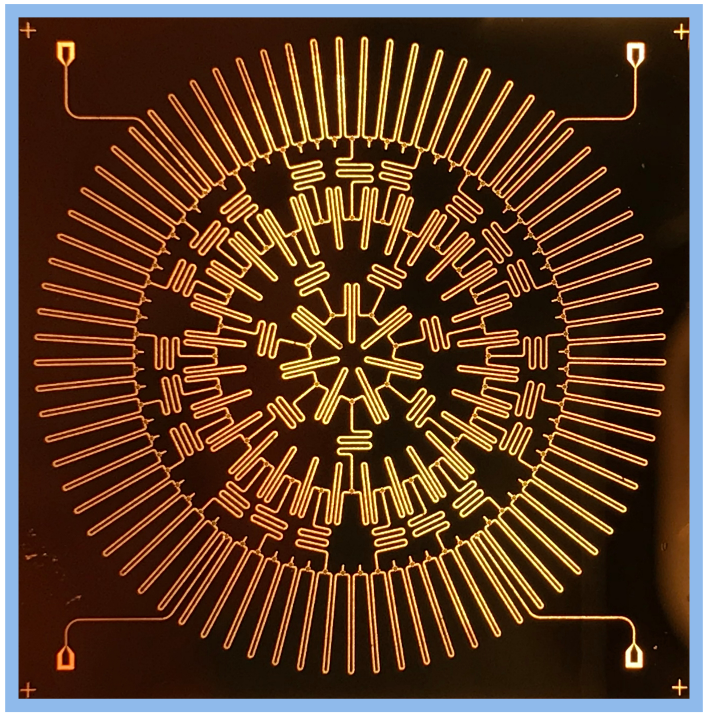

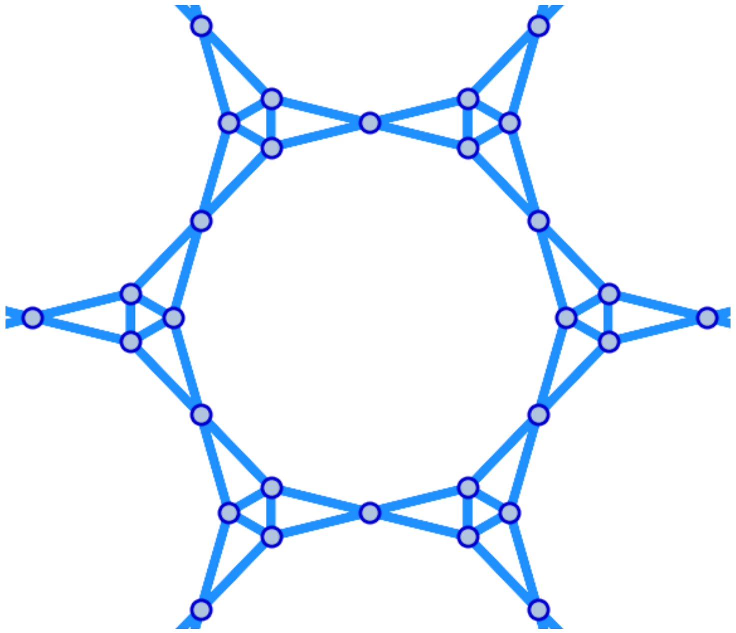

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Lattice Simulators in Circuit QED

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EE, Princeton

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Math, Princeton

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EE, Princeton

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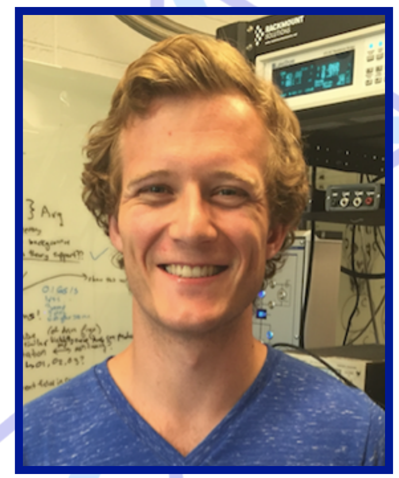

HOUCK LAB

KITP, April 9th, 2019