Quantum Hall physics in photonic systems

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SPICE workshop, Mainz
June 2017

Outline of this talk

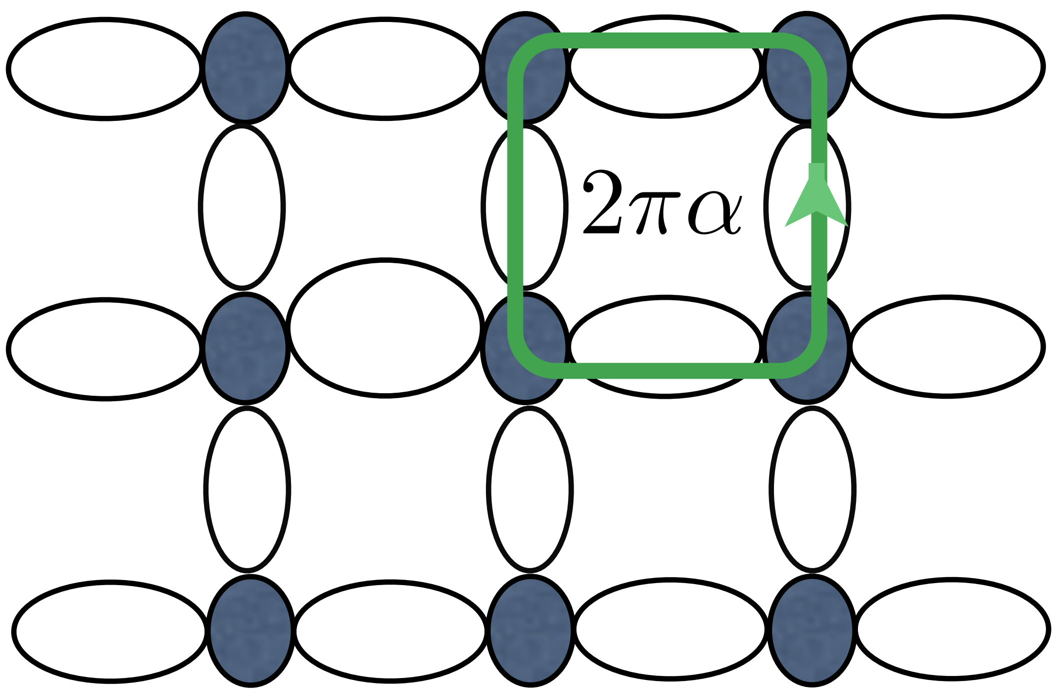
- Review of topological ring resonators
  - Measuring topological invariants
- Quantum directions
    - Topological photonic crystals
- Photons and electronic quantum Hall states

Synthetic Magnetic Field

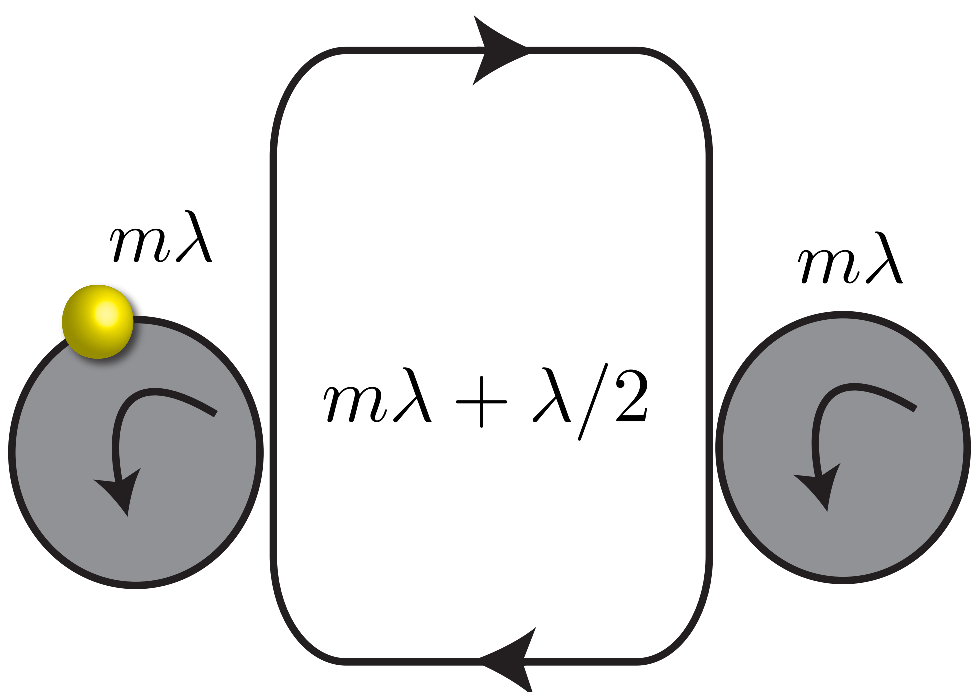
In analogy to electrons on a magnetic lattice:

$$H_0 = -J \sum_{x,y} \hat{a}^\dagger_{x+1,y}\hat{a}_{x,y}e^{-i2\pi\alpha y} + \hat{a}^\dagger_{x,y}\hat{a}_{x+1,y}e^{i2\pi\alpha y} + \hat{a}^\dagger_{x,y+1}\hat{a}_{x,y} + \hat{a}^\dagger_{x,y}\hat{a}_{x,y+1}$$

- Tight-binding form
- Magnetic phase



Two resonator case:

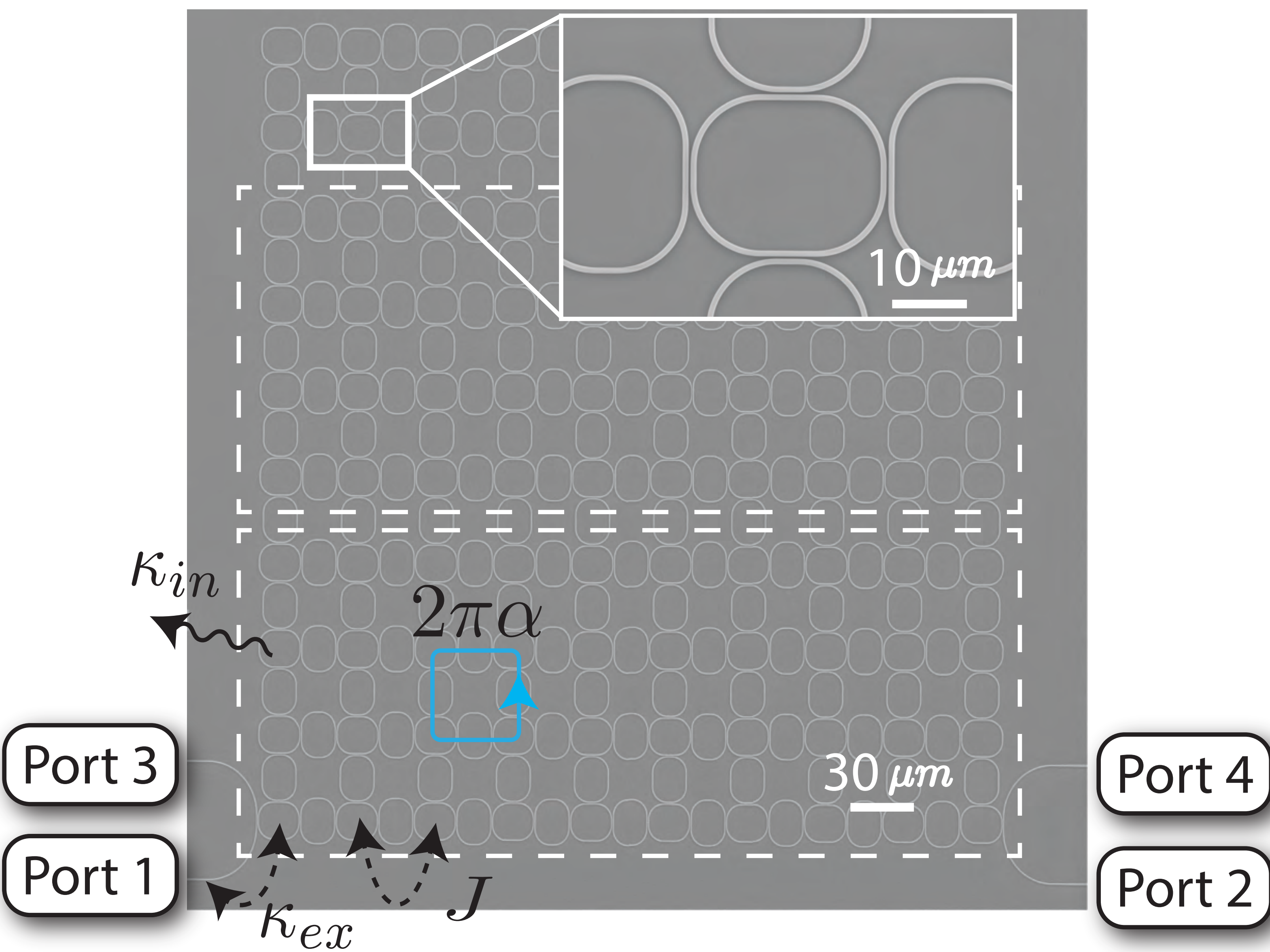


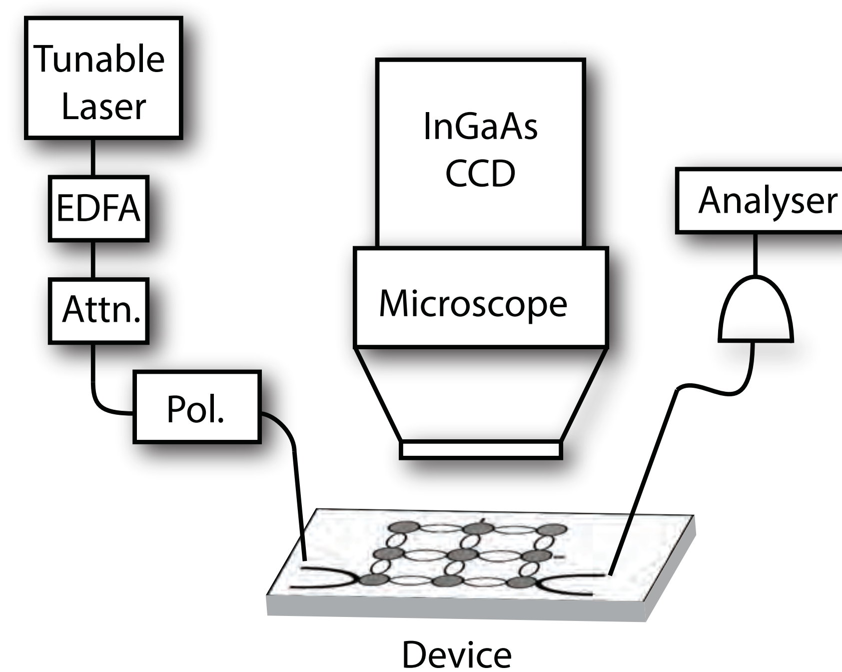
$$H_{eff} = -\kappa\hat{a}^\dagger_{x+1}\hat{a}_x e^{-2\pi i\alpha} - \kappa\hat{a}^\dagger_x\hat{a}_{x+1}e^{2\pi i\alpha}$$

Nat. Phys. 7, 907 (2011)
see also Microwave : Haldane PRL (2008), Soljacic Nat. (2009)
Koch PRA (2010) Carusotto PRA (2011)

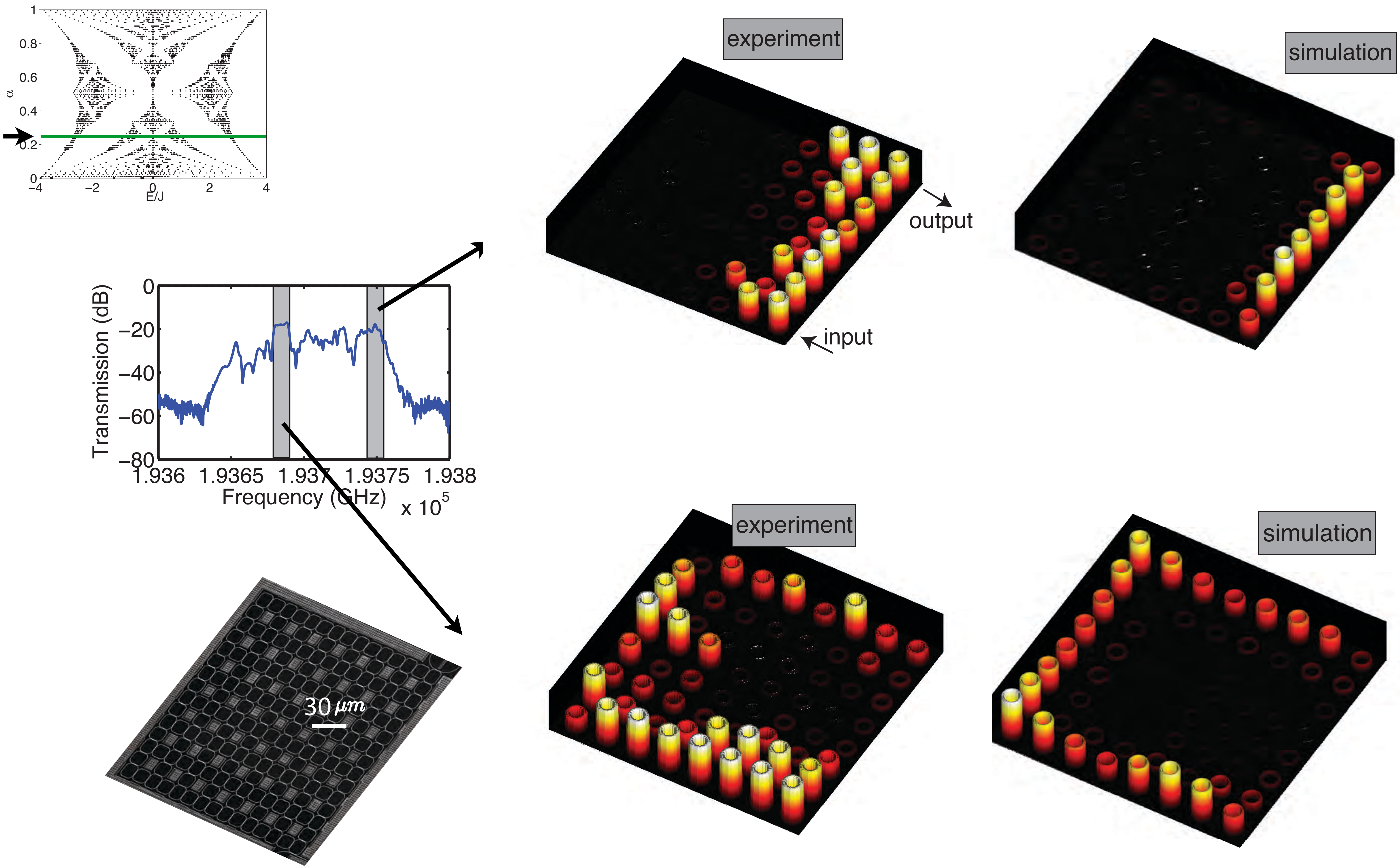
Experimental realization of the gauge field

Silicon-on-Insulator technology



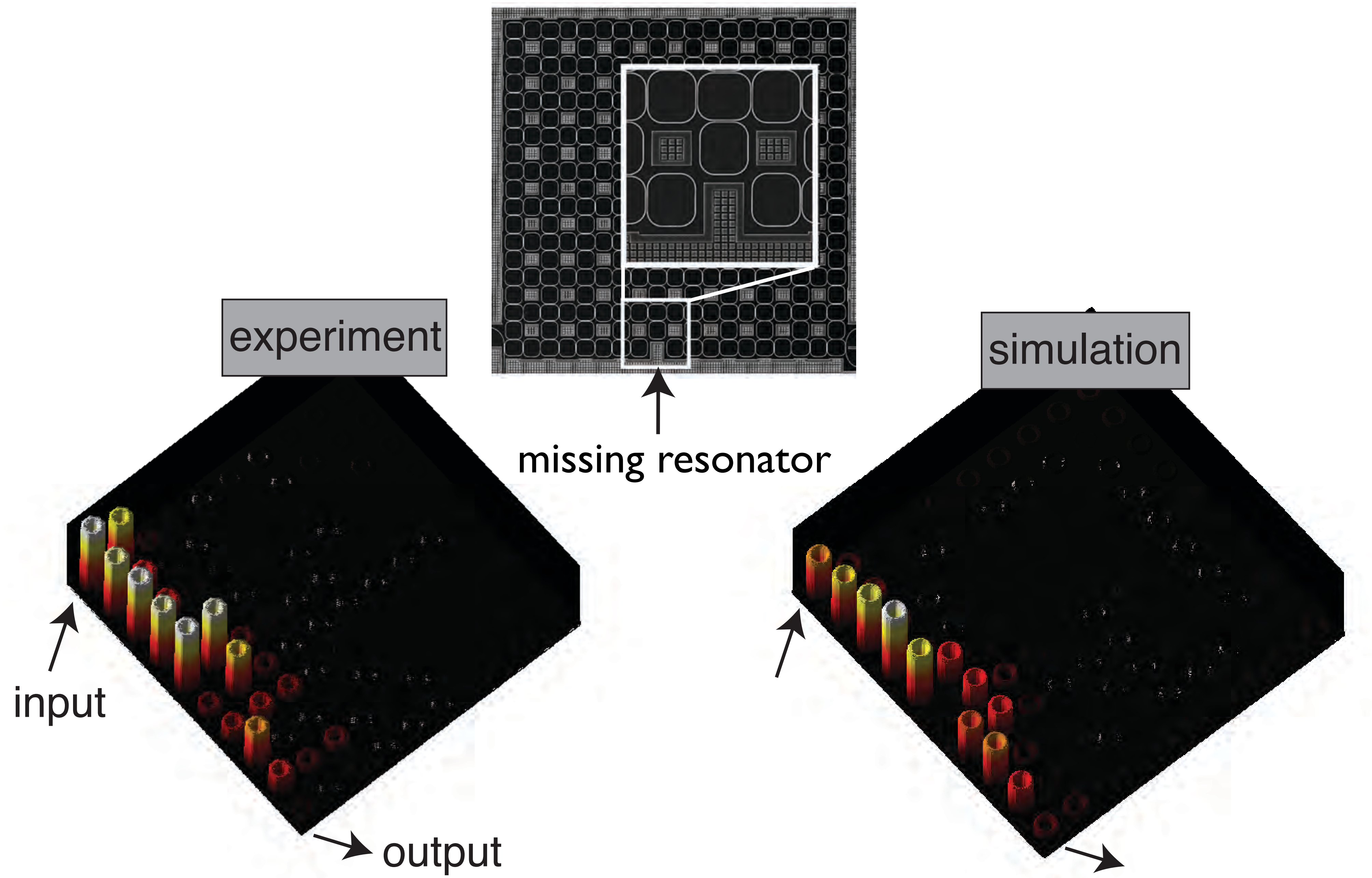


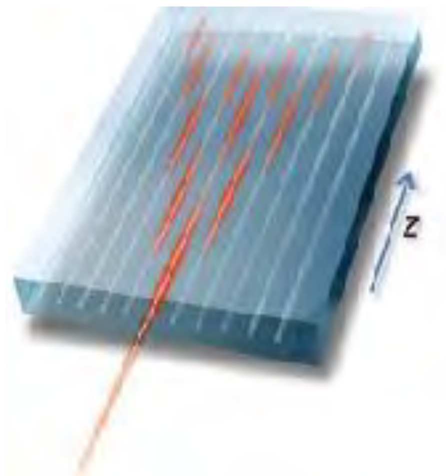
Observation of topological edge states



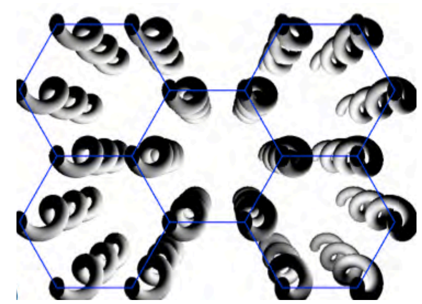
Nature Photonics 7, 1001 (2013)
see also Rechtsman et al. Nature (2013)

Robustness against an introduced disorder

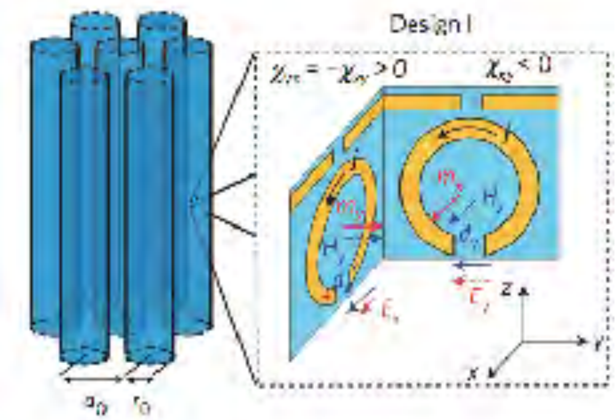




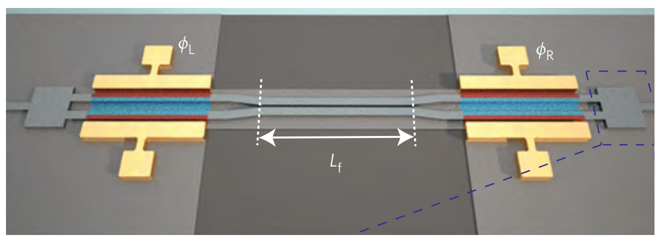
Kraus, Zilberberg PRL (2012)



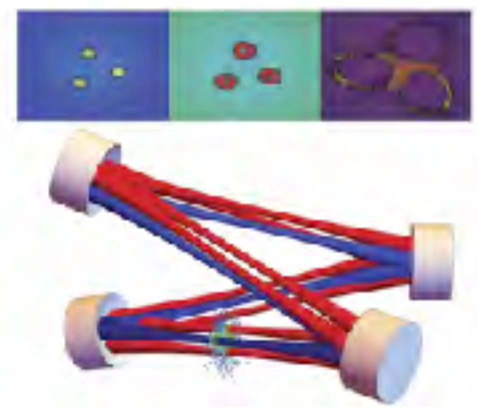
Rechtsman, Segev Nature (2013)



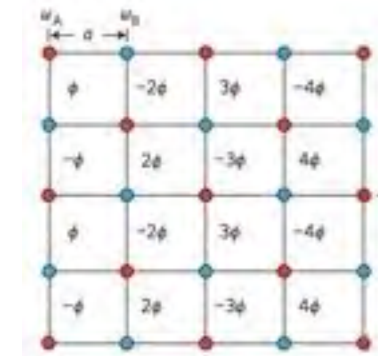
A. Khanikaev, G. Shvets Nature Material (2012)



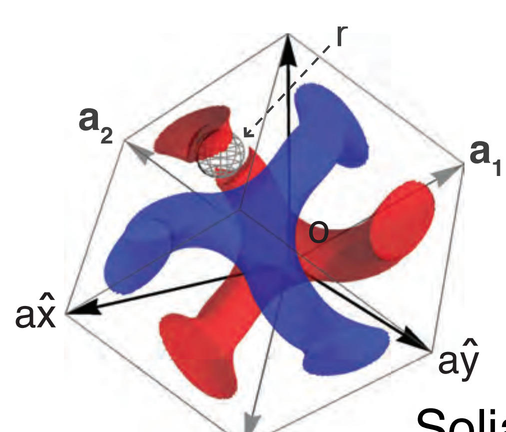
Lipson et al. Nat. Photon. (2014)



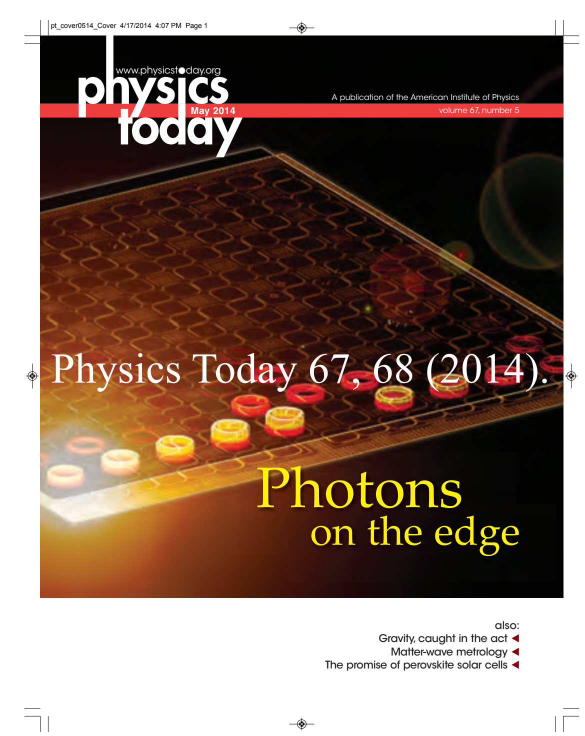
Simon's group Nature (2016)



Fan's group - Nature Photonics (2012)



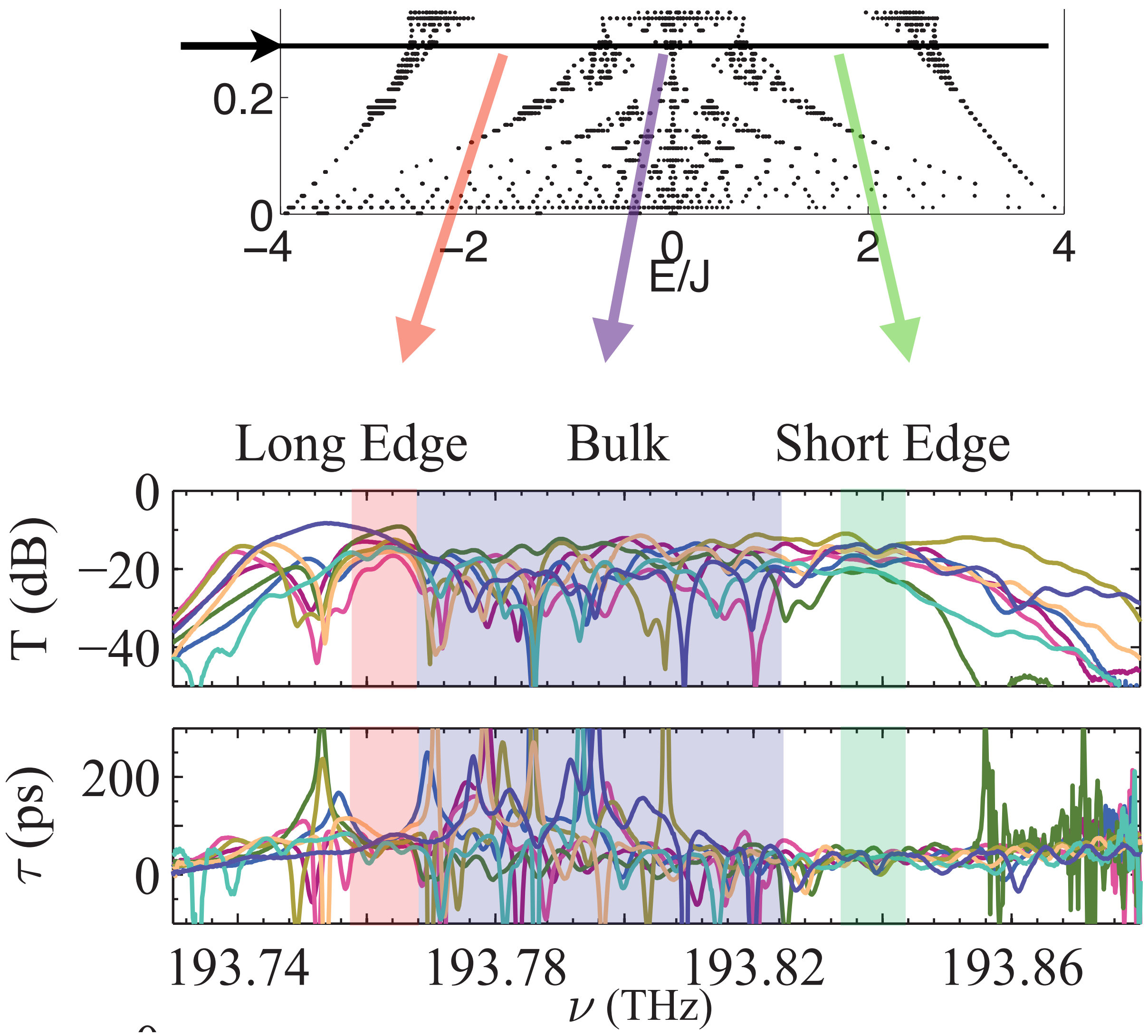
Soljacic's group (2015)



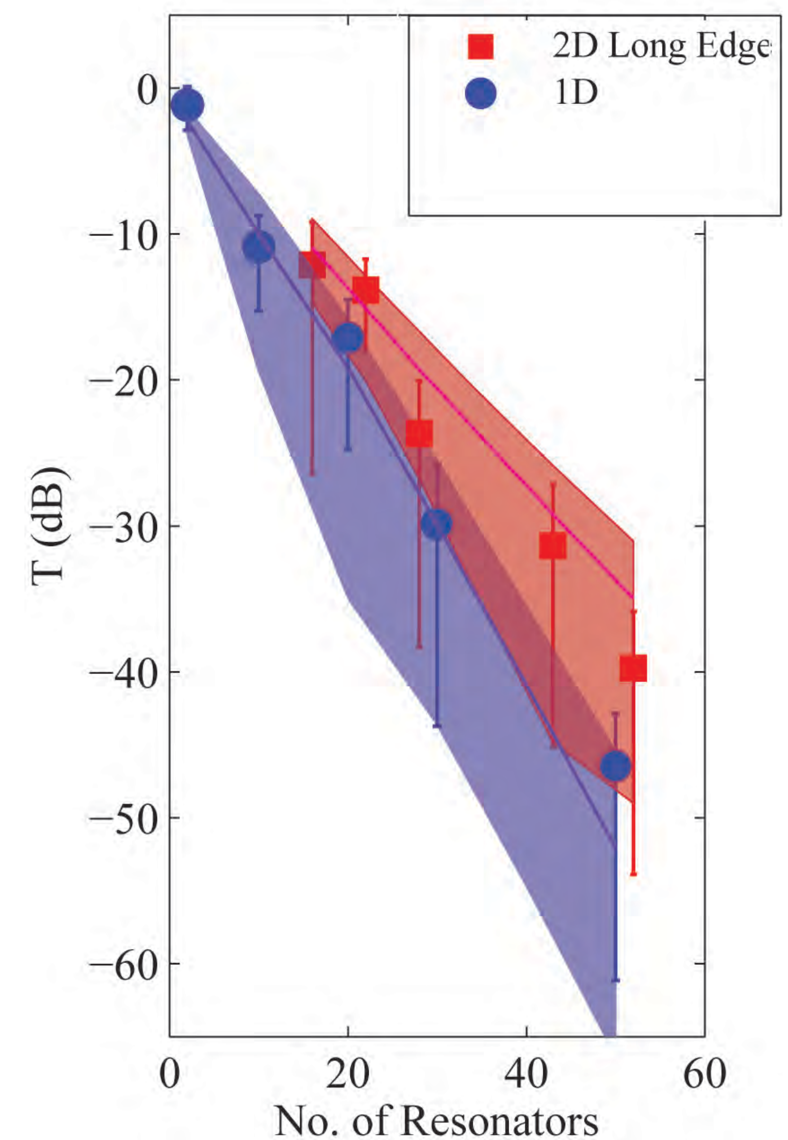
Physics Today 67, 68 (2014).

M. H. "Synthetic gauge fields with photon" Int. J. Mod. Phys. B 28, 1441002 (2014).
L Lu, JD Joannopoulos, M Soljačić - Nature Photonics, 2015

Transport statistics



15x15 arrays
Different colors: different samples



S. Mittal et al.
Phys. Rev. Lett. 113, 087403 (2014)

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    - Measuring topological invariants
- Quantum directions
    - Topological photonic crystals
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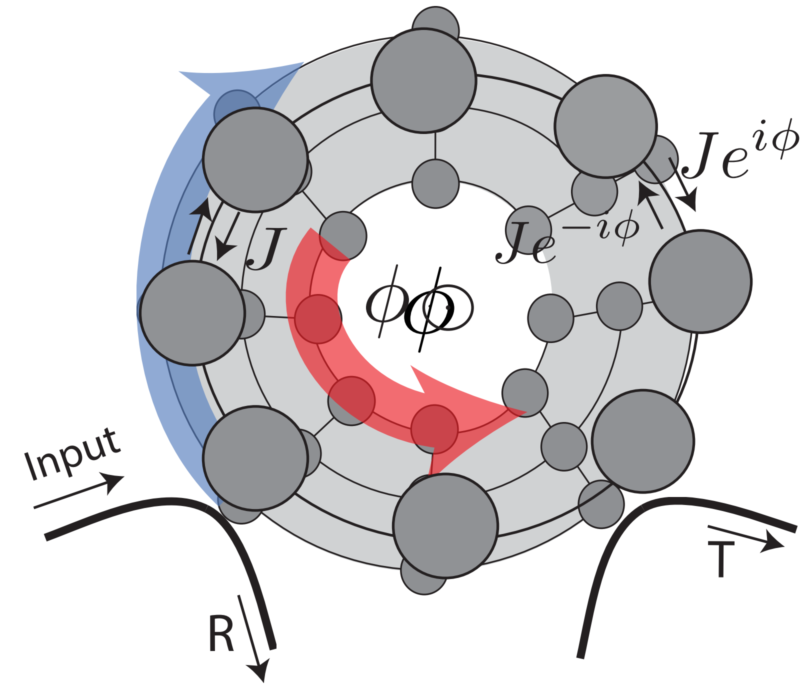
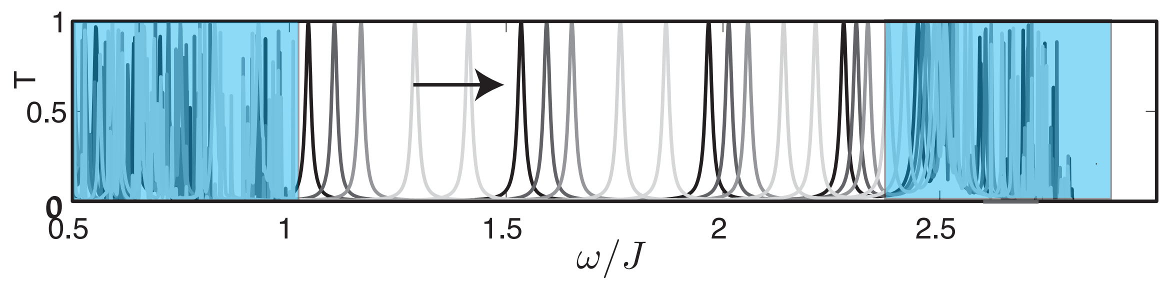
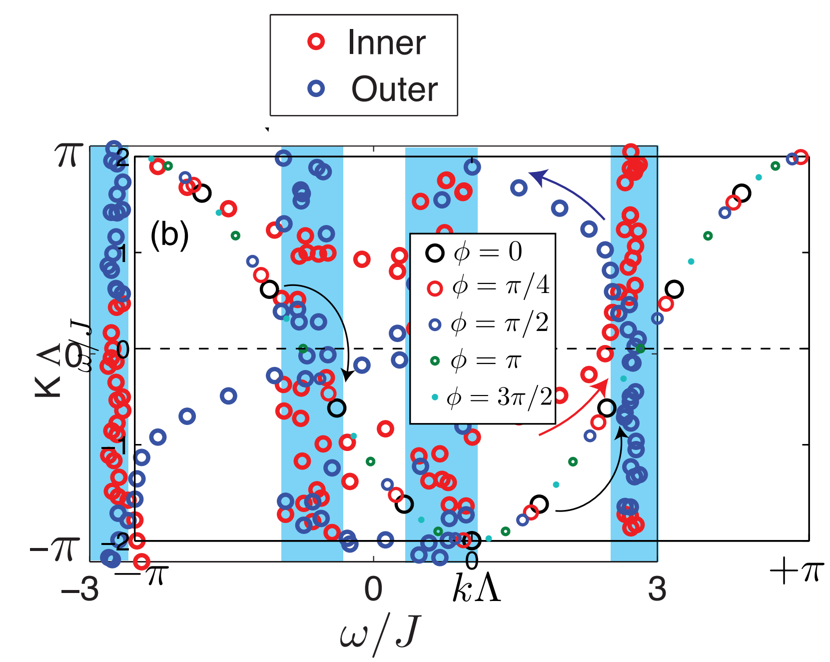
Topological invariants in photons

- What is the manifestation of this integer conductance in a photonic system?

Laughlin's argument

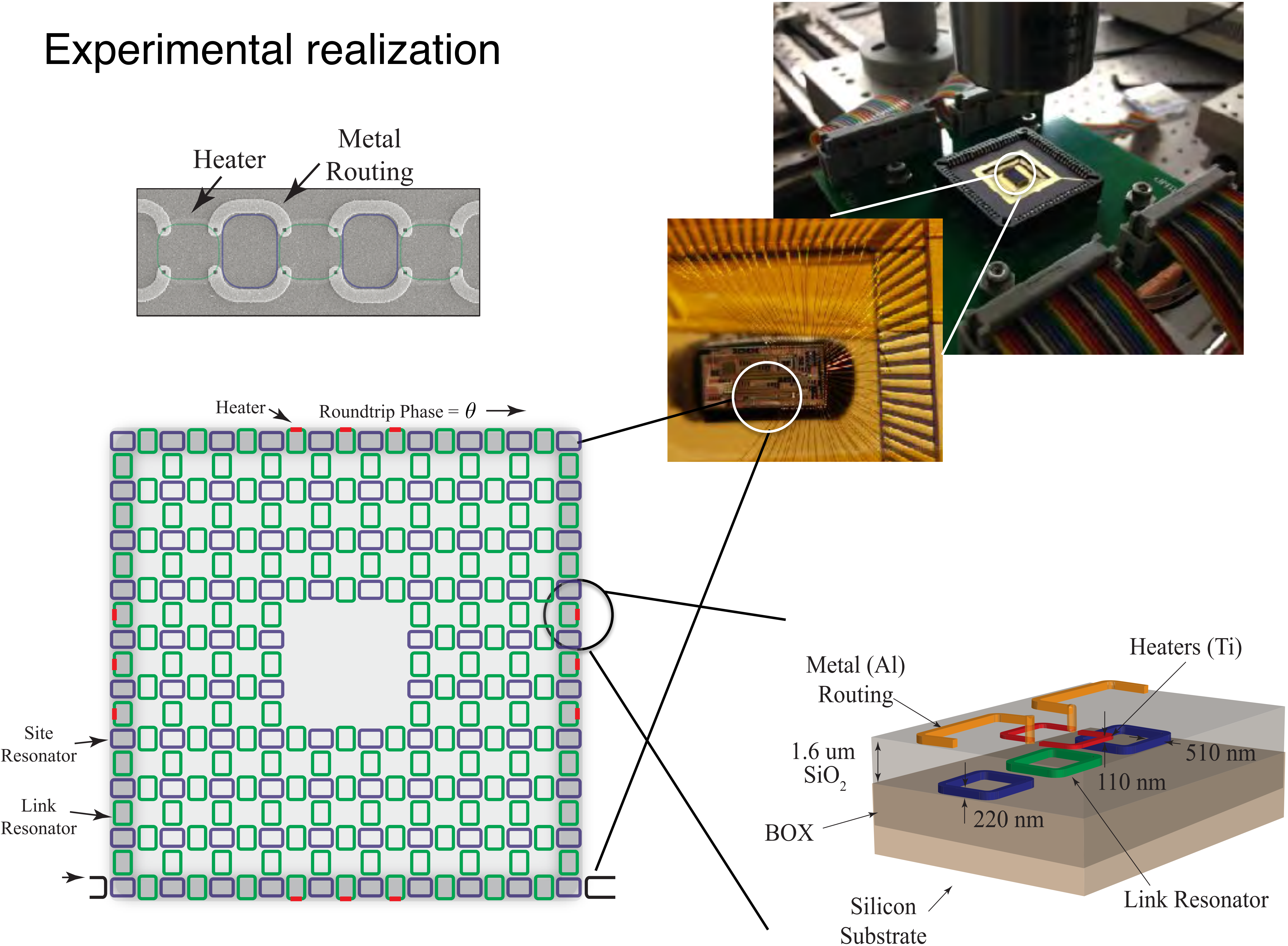






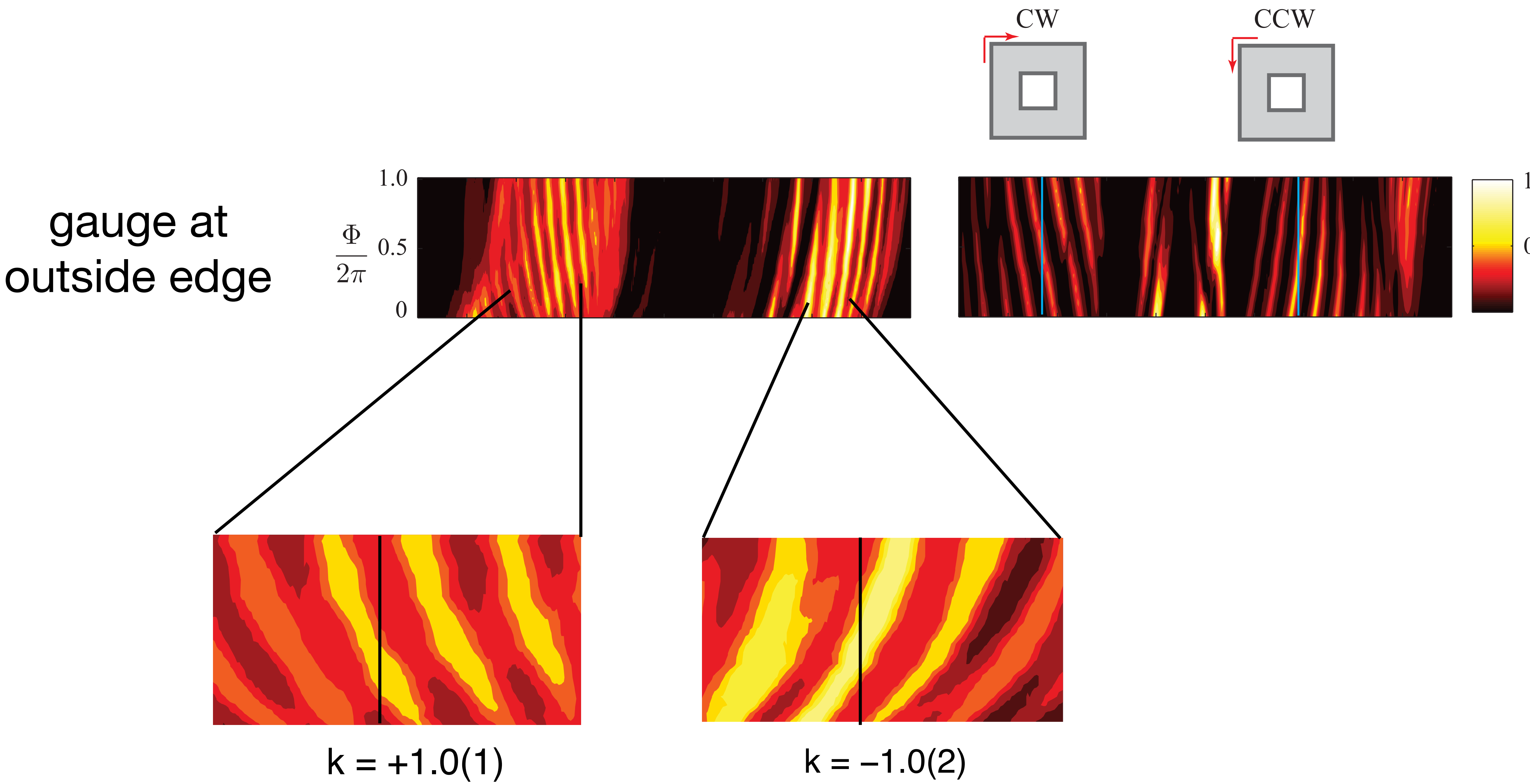
MH, PRL 112, 210405 (2014)
see also: Ozawa et al. PRL 2014, Bardyn et al., Y. Chong

Experimental realization



Measured

Simulated



S. Mittal, S. Ganeshan, J. Fan, A. Vaezi, MH Nature Photonics 10, 180 (2016)

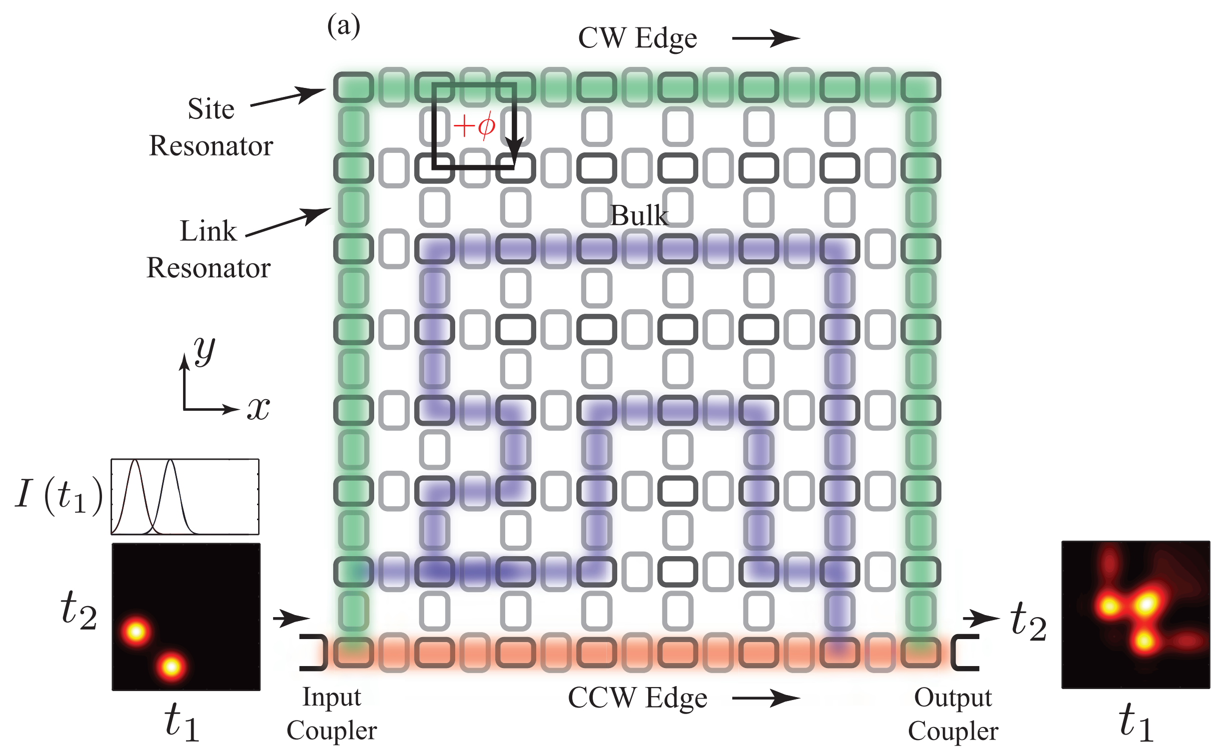
Quantum directions

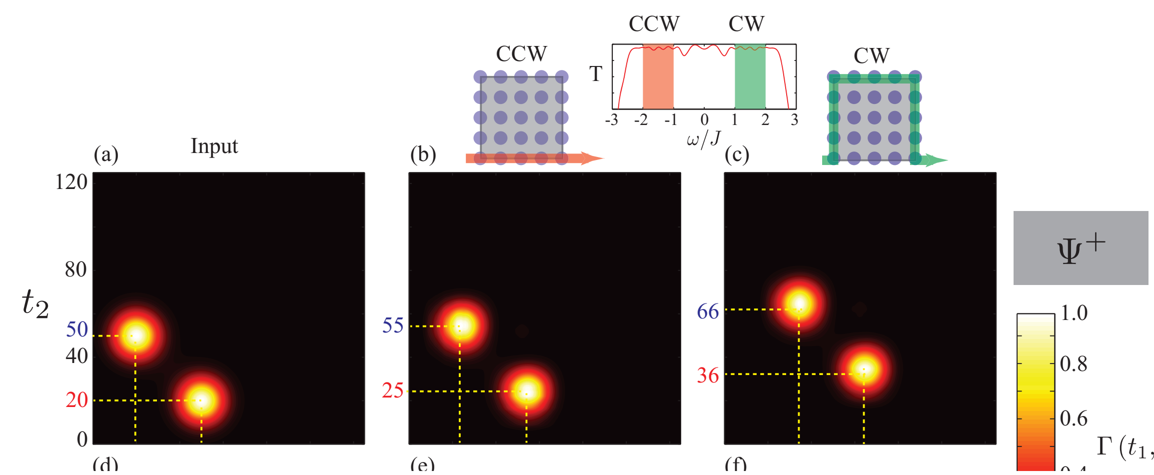
Linear/weakly nonlinear

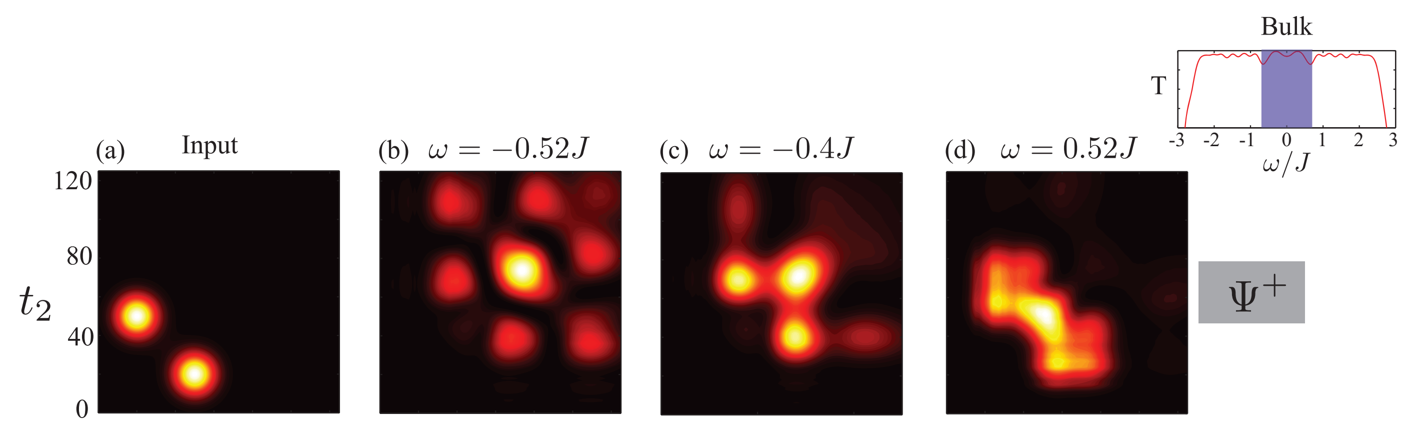
Strong photon-emitter interaction

Quantum transport of non-classical light

Quantum transport in topological photonics systems







$$|2\rangle = \int dx_1 dx_2 \psi(x_1, x_2; t)\hat{a}^\dagger(x_1)\hat{a}^\dagger(x_2)|0\rangle$$

Theory: S. Mittal, V. Vikram Orre, and M. H., Optics Expres 24, 15632 (2016)
see also Rechtsman et al. arXiv:1605.02053

Quantum directions

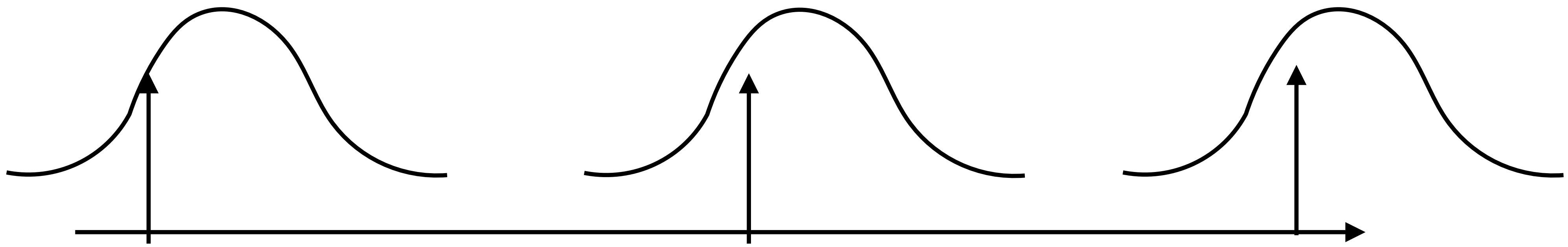
Linear/weakly nonlinear

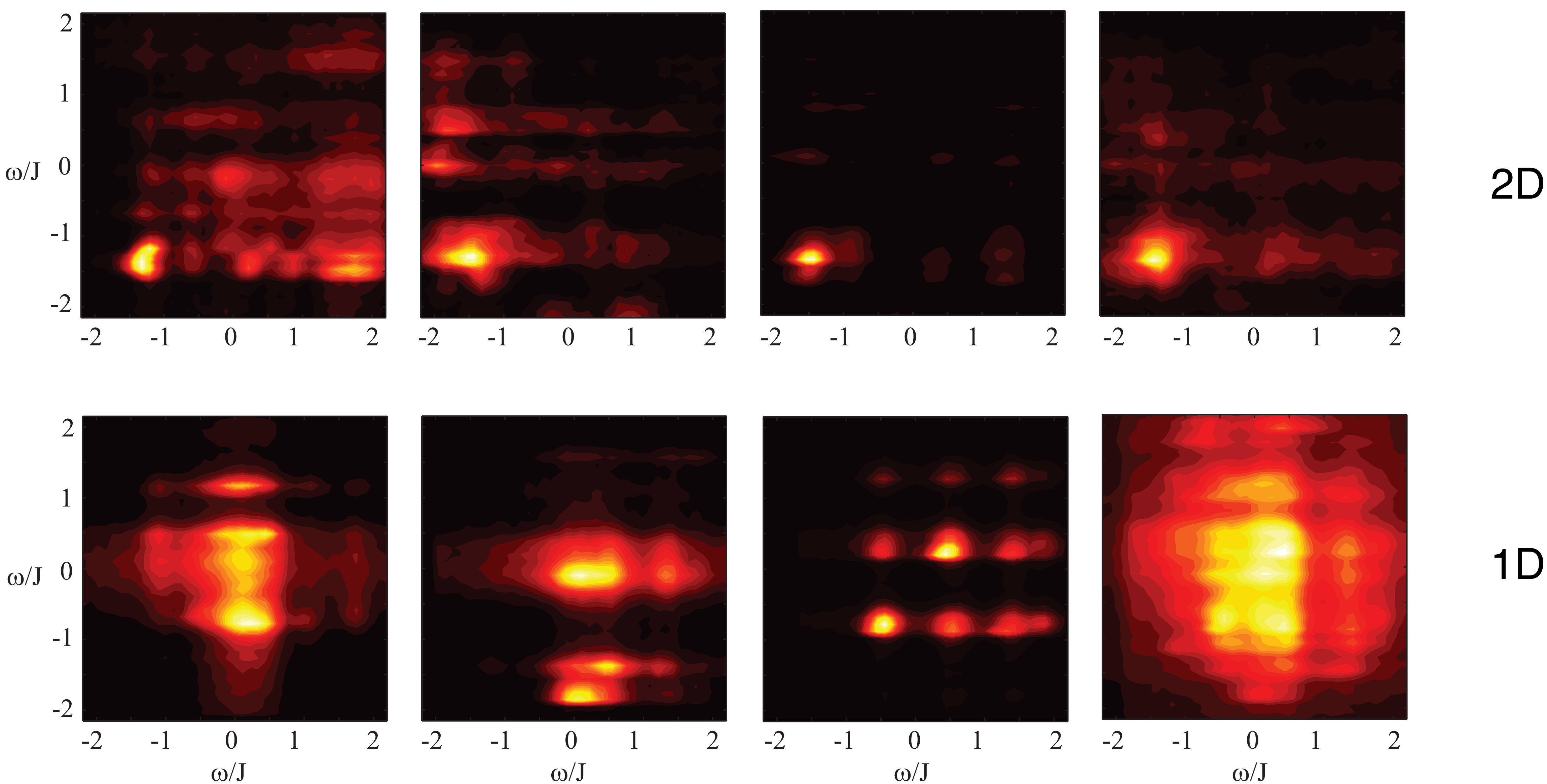
Strong photon-emitter interaction

Quantum transport of non-classical light

Topologically robust generation and amplification of photons

Topologically robust generation of photons





Quantum directions

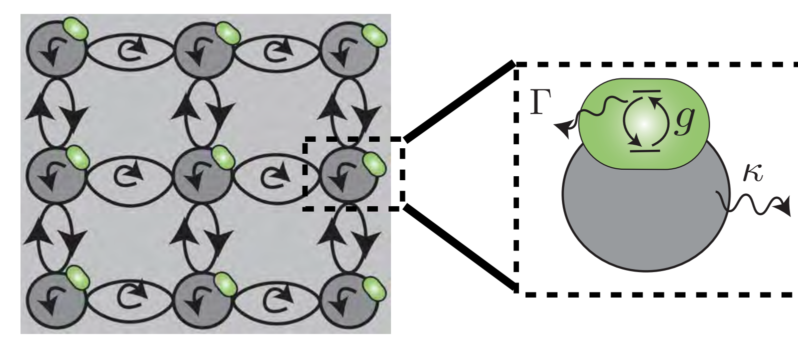
Linear/weakly nonlinear

Quantum transport of non-classical light

Topologically robust generation of photons

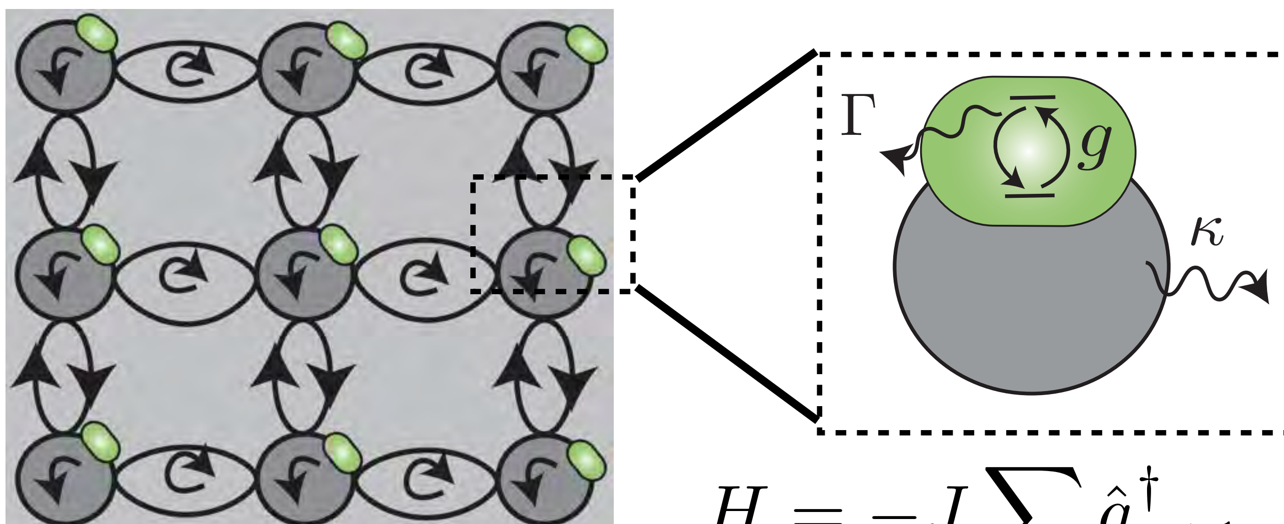
Strong photon-emitter interaction

Fractional Quantum Hall states



Fractional Quantum Hall state of light

Gauge field + interaction (k-body) → Fractional Quantum Hall states



$$H = -J \sum_{x,y} \hat{a}^{\dagger}_{x+1,y}\hat{a}_{x,y}e^{i2\pi\alpha y} + \hat{a}^{\dagger}_{x,y+1}\hat{a}_{x,y} + h.c.$$
$$+U\hat{n}_{x,y}(\hat{n}_{x,y}-1)$$

$U >> J$: photon blockade regime

Atomic case: MH, Sorensen, Demler, Lukin (2007)
Exp: Spielman, Ketterle, Dalibard, Bloch,....

Fractional Quantum Hall state of light

$$H = -J \sum_{x,y} \hat{a}^{\dagger}_{x+1,y} \hat{a}_{x,y} e^{i2\pi\alpha y} + \hat{a}^{\dagger}_{x,y+1} \hat{a}_{x,y} + h.c.$$
$$+U \hat{n}_{x,y} (\hat{n}_{x,y} - 1)$$

$U >> J$: photon blockade regime

Starting with a fixed number of photons,
we can prepare a Laughlin state at $\nu = \frac{N_{ph}}{N_{mag}} = \frac{1}{2}$

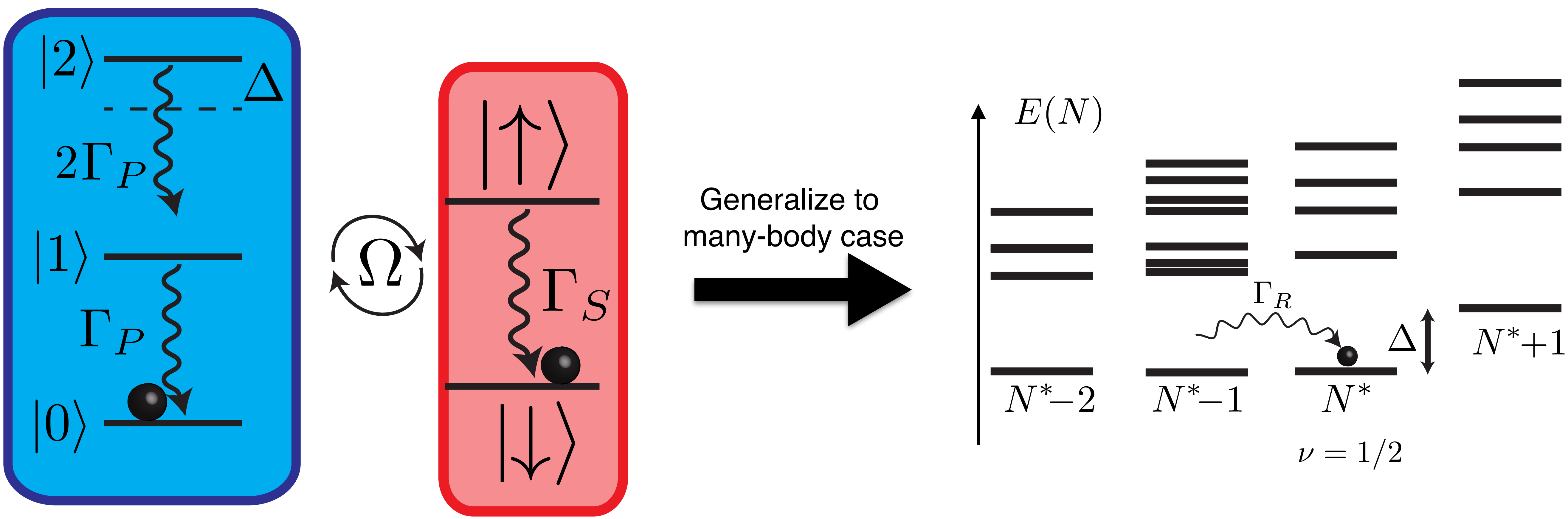
$$\Psi_m(z_1, z_2, ..., z_N) \propto \prod_{j<k}^{N_e} (z_j - z_k)^m \prod_{j=1}^{N_e} e^{-|z_j|^2/4}$$

How to make fixed photon number states
and also combat loss?

Use incompressibility (blockade) to prepare many-body states of photons

$$E(N) - E(N-1) \neq E(N+1) - E(N)$$

How to prepare a cavity in the single photon state:

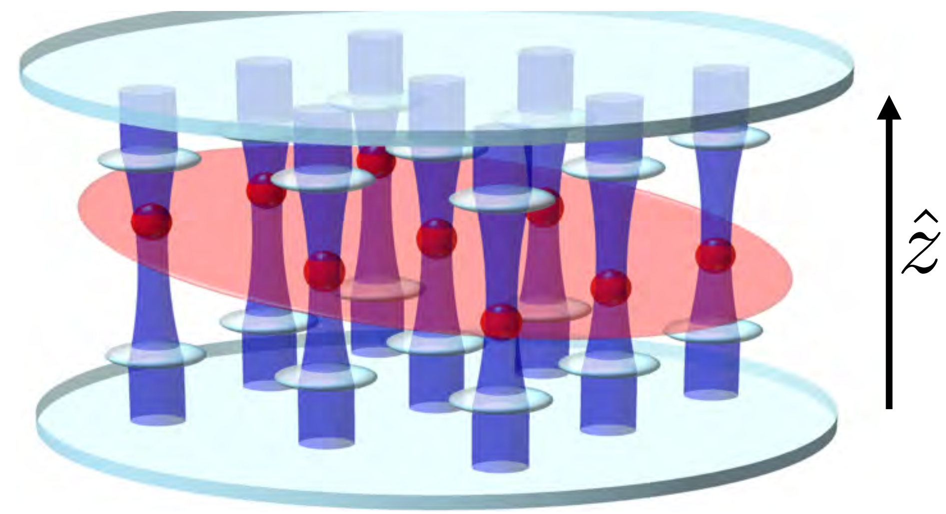


$$\Omega \cos(2\omega_0 t) \left[a_P^\dagger \sigma_S^+ + a_P \sigma_S^- \right]$$

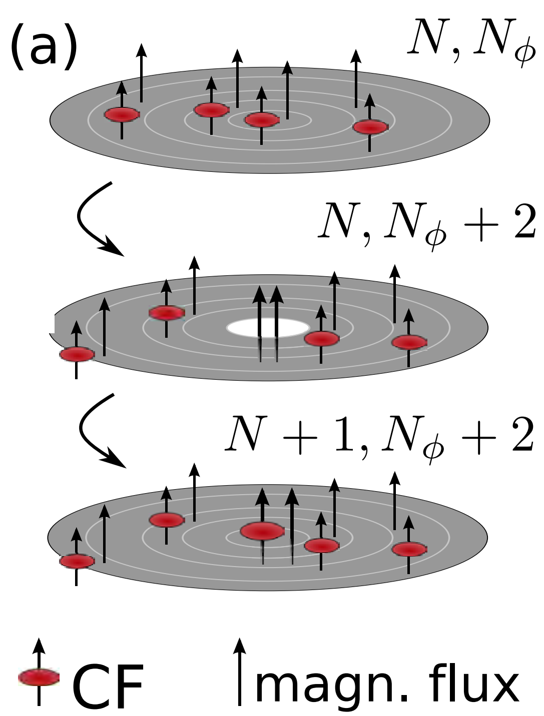
$$\Delta \gg \Gamma_S \sim \Omega \gg \Gamma_P$$

E. Kapit, MH and S. Simon PRX 2014
see also Lebreuilly Carusotto 2015, Ma
et al. 2017

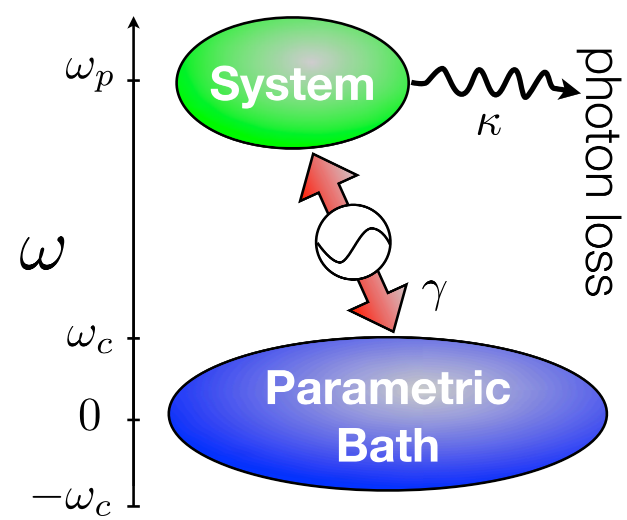
Other methods to prepare FQH states of light



Maghrebi, Yao, MH, Pohl, Firstenberg, Gorshkov PRA (2014).



Grusdt, Letscher, MH, Fleischhauer PRL (2014)



MH Adhikari Taylor PRB (2015)

see also: Angelakis et al. PRL (2008), Carusotto, Umucalilar PRL (2012) Greentree et al. PRL (2012)

Three-body interaction and Pfaffian states

Greiter, Wen, Wilczek Phys. Rev. Lett (1991)
The parent Hamiltonian for Pfaffian state
has three-body short range interaction

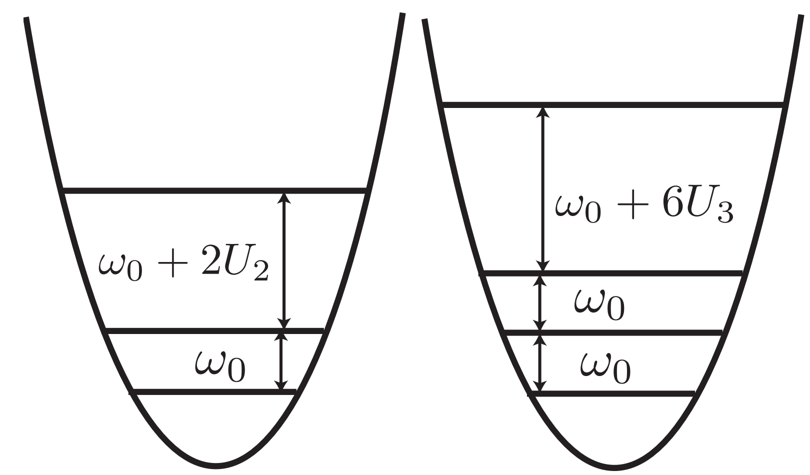
$$V = \sum \delta^{(2)}(z_i - z_j)\delta^{(2)}(z_i - z_k)$$

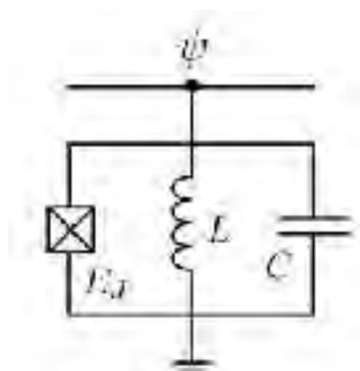
For bosons:

$$\nu = N/N_\phi = 1$$

The lattice version of their model:

$$H = -J\sum_{x,y} \hat{a}^\dagger_{x+1,y}\hat{a}_{x,y}e^{-i2\pi\alpha y} + \hat{a}^\dagger_{x,y}\hat{a}_{x+1,y}e^{+i2\pi\alpha y}$$
$$+\hat{a}^\dagger_{x,y+1}\hat{a}_{x,y} + \hat{a}^\dagger_{x,y}\hat{a}_{x,y+1} + U_3\hat{a}^{\dagger 3}_{x,y}\hat{a}^3_{x,y}$$





MH, P. Adhikari, J. Taylor
PRB (2014)

Artificial magnetic field: Koch et al (2010), Kamal (2011) Kapit (2013)
Zakka-Bajjani (2011)
atoms: Cooper et al PRL (2001), Mazza et al PRA (2010)

Quantum directions

Linear/weakly nonlinear

Quantum transport of non-classical light

Topologically robust generation of photons

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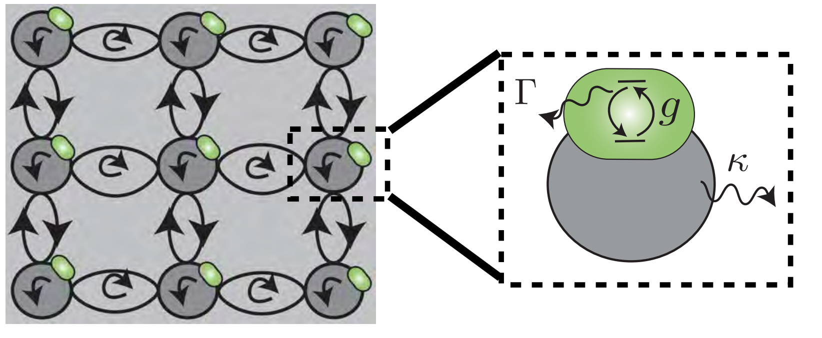
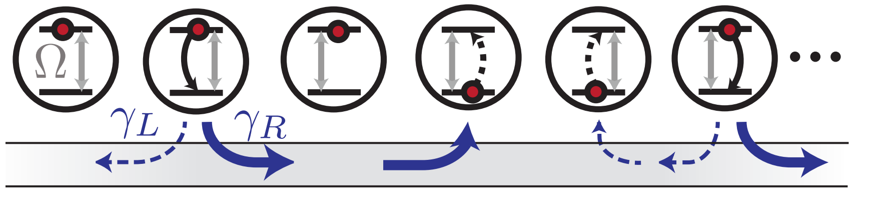
Fractional Quantum Hall states



Chiral Quantum Optics



Review: P. Lodahl et al. Nature (2017)

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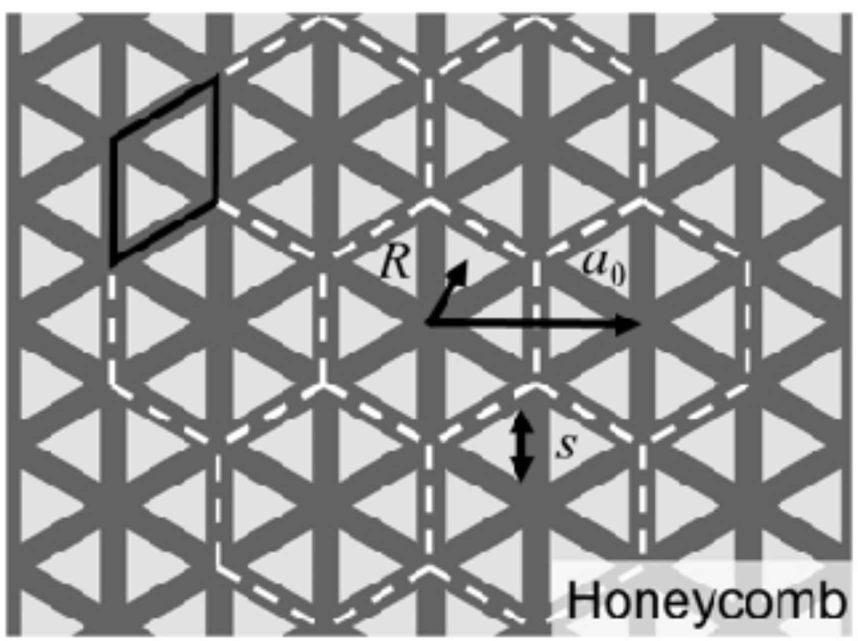
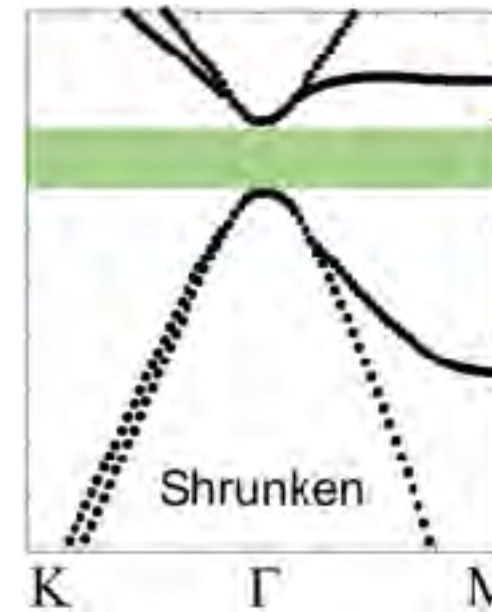
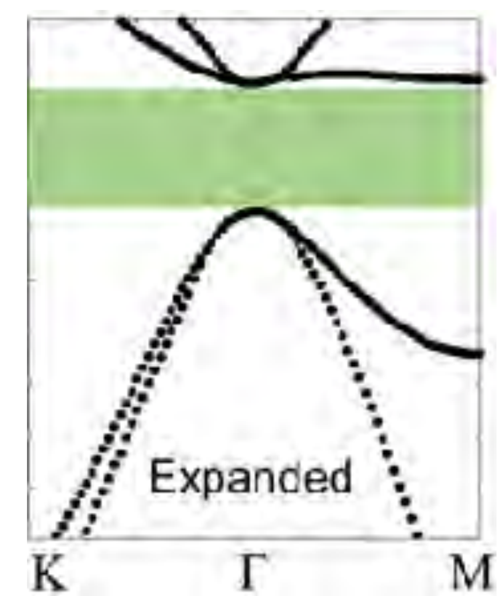
Topological photonic crystals

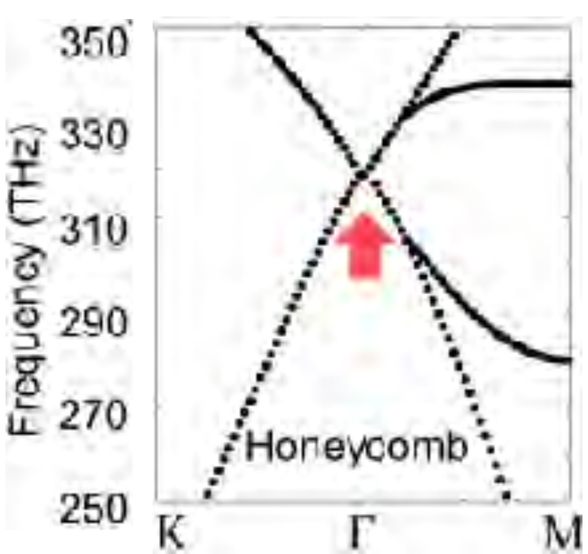
- Synthesize spin-orbit in photonic crystals
- Find a compatible structure with solid-state emitters in optical domain

Challenges:
★ Full bandgap in the bulk
★ E&M should be confined in prep. direction to the slab





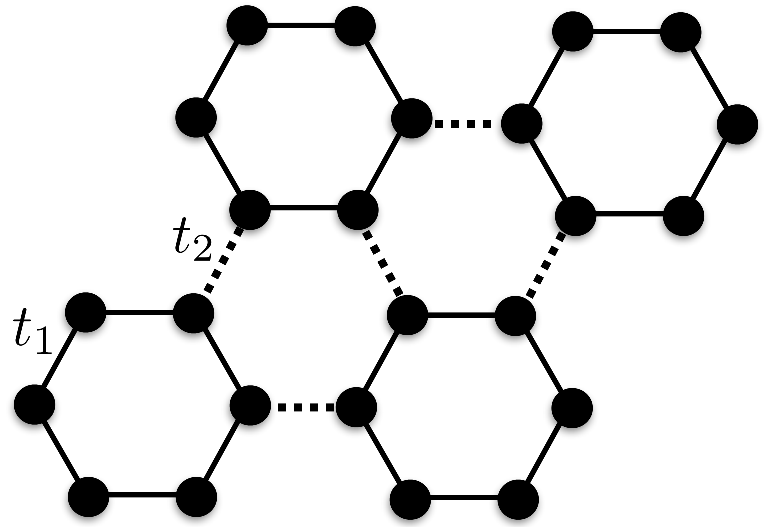




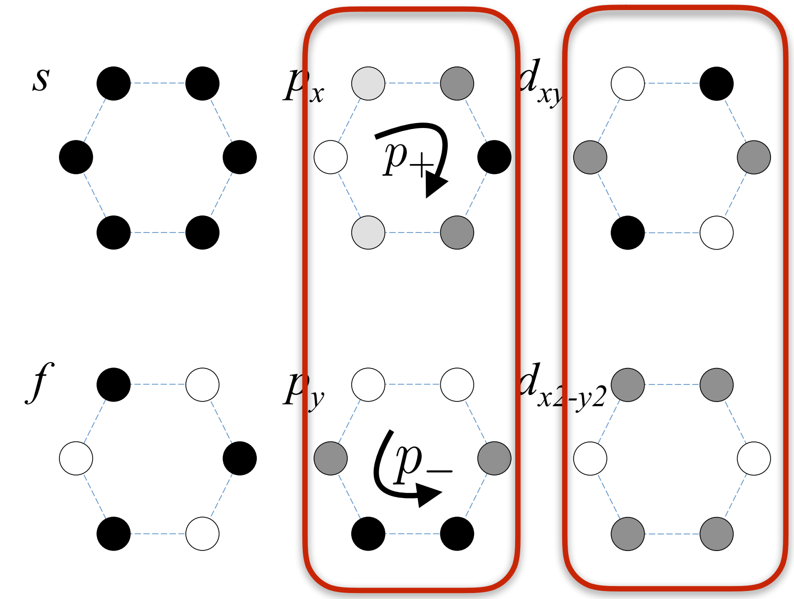
S. Barik, H. Miyake, W. DeGottardi, E. Waks, M.H. NJP (2016)

previous works: Rechtsman/Segev Nat. Photon (2012)
Shvets/Khanikaev PRL (2014), Wu/Hu PRL (2015)

Tight-binding approximation



$$t_1 \neq 0, t_2 = 0$$



✓ Obtain band inversion, requirement for non-trivial topology

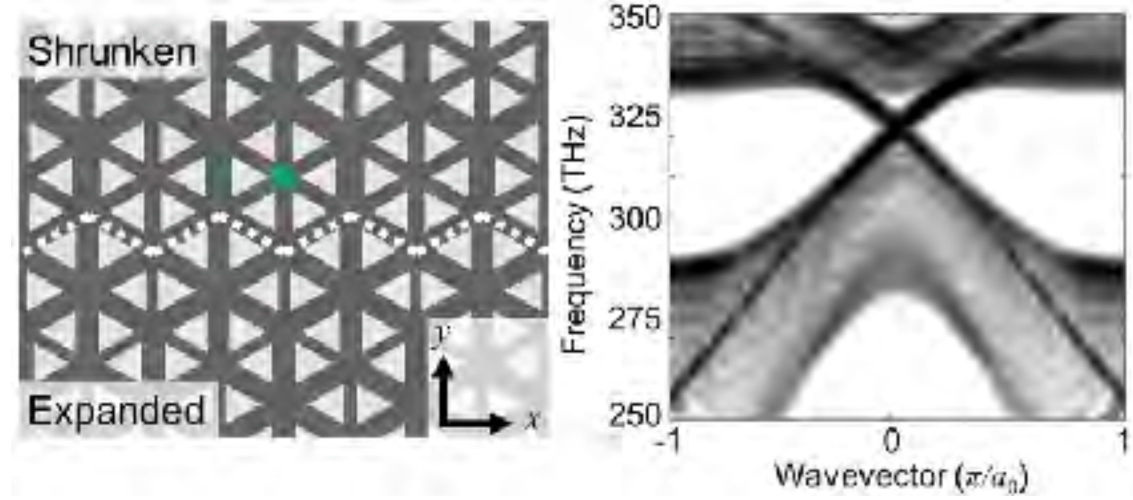
$$\mathcal{H}_+ = \frac{\sqrt{3}}{2} t_2 a \left(-k_x \sigma_x + k_y \sigma_y\right) + \left[t_2 - t_1 + \mathcal{O}(k_x^2 + k_y^2)\right] \sigma_z \qquad (|p_+\rangle, |d_+\rangle)$$

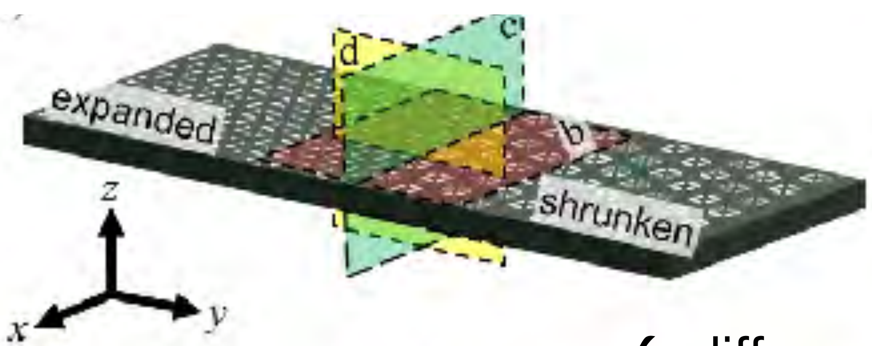
$$\mathcal{H}_- = \frac{\sqrt{3}}{2} t_2 a \left(k_x \sigma_x + k_y \sigma_y\right) + \left[t_2 - t_1 + \mathcal{O}(k_x^2 + k_y^2)\right] \sigma_z \qquad (|p_-\rangle, |d_-\rangle)$$

S. Barik, H. Miyake, W. DeGottardi, E. Waks, M.H. NJP (2016)

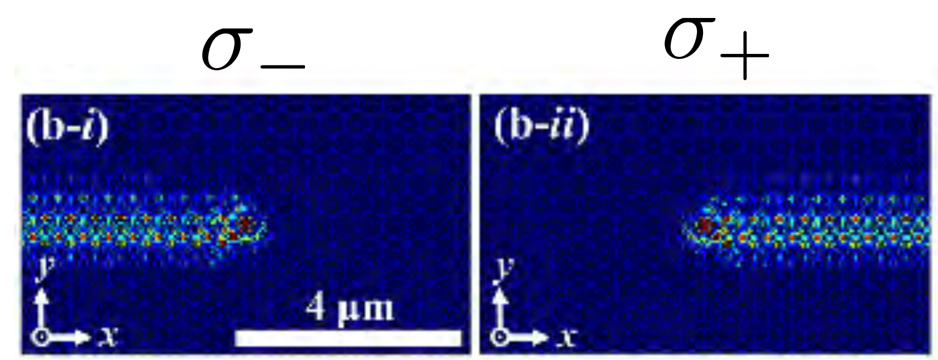
helical/chiral topological edge states

✓ Interface between two distinct band structure
✓ Topological edge state appear in the bulk gap
✓ 2D version/topological version of Lodahl/Rauschenbeutel

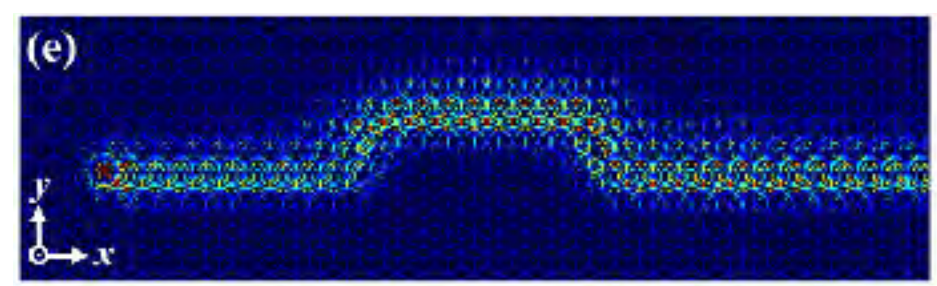




✓ different polarization propagate
in different directions

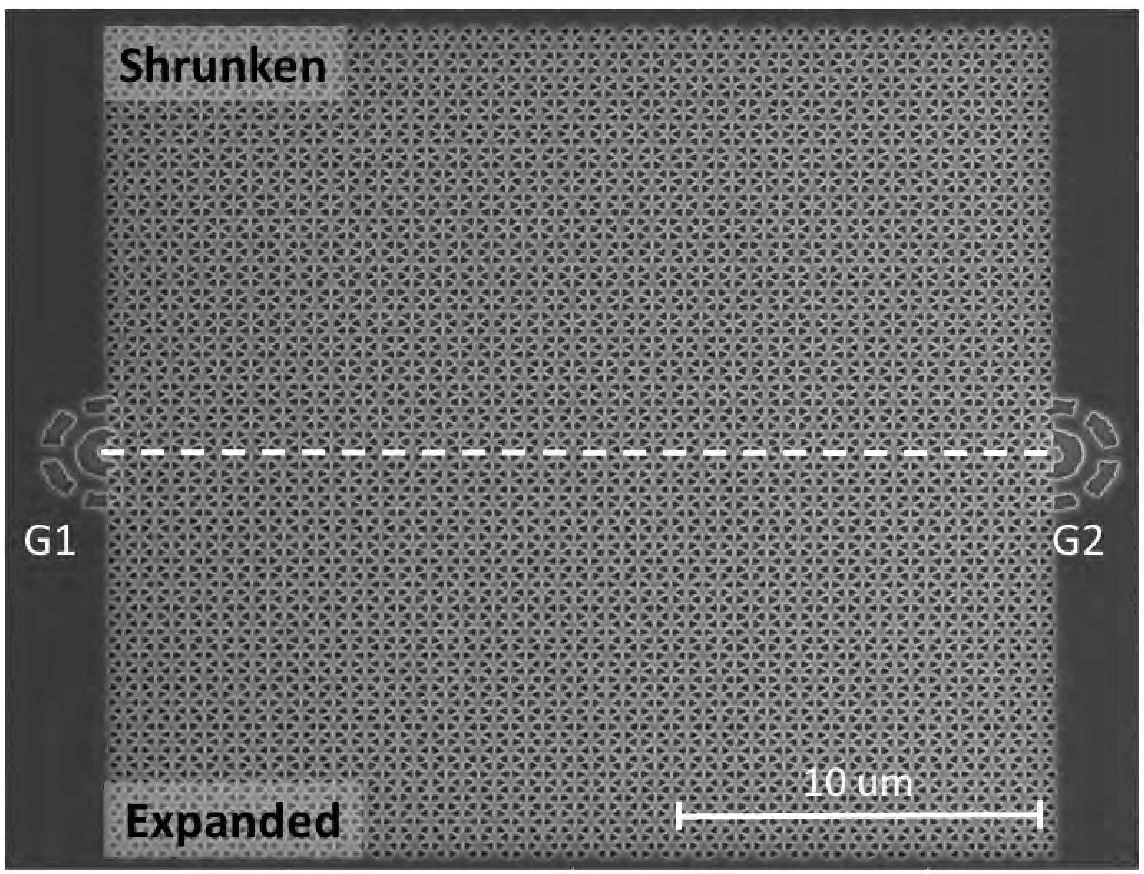


✓ robustness against deformation of edge

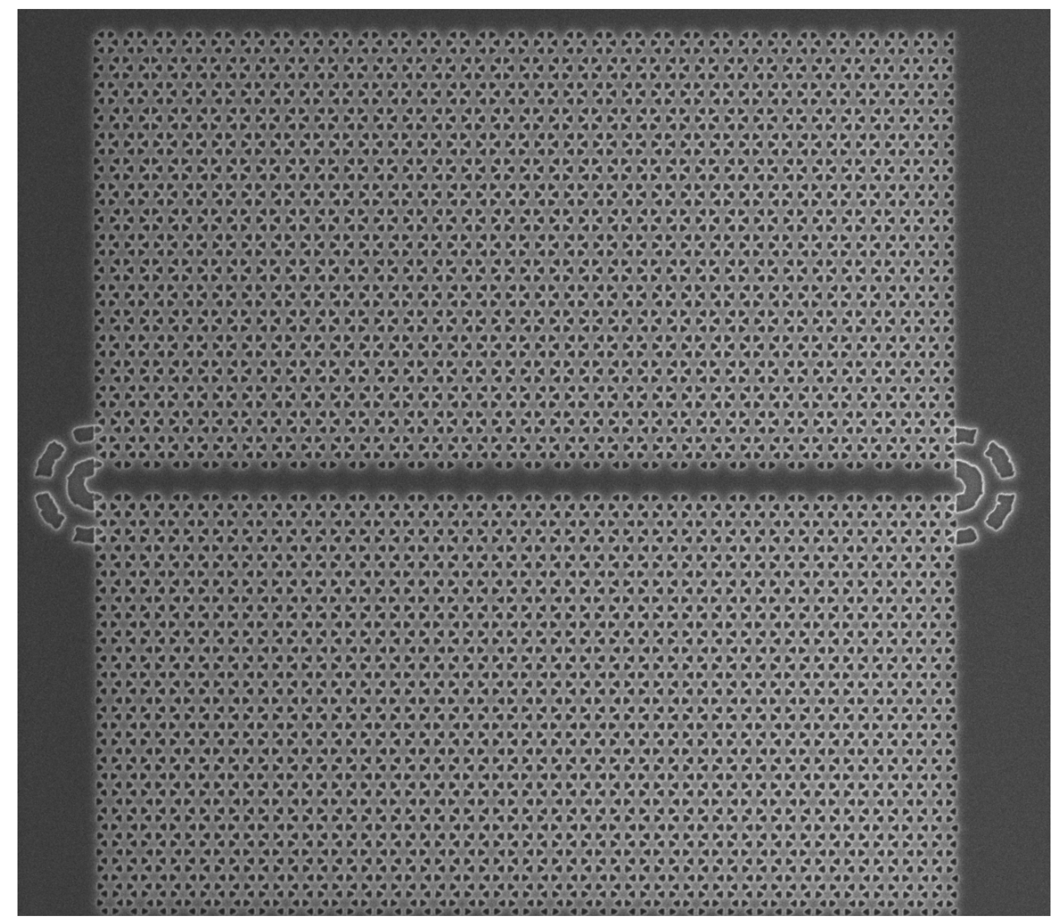


S. Barik, H. Miyake, W. DeGottardi, E. Waks, M.H. NJP (2016)

Topological Photonic Crystal



Ordinary waveguide

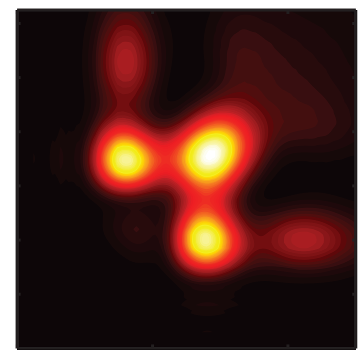


Measuring topological invariants



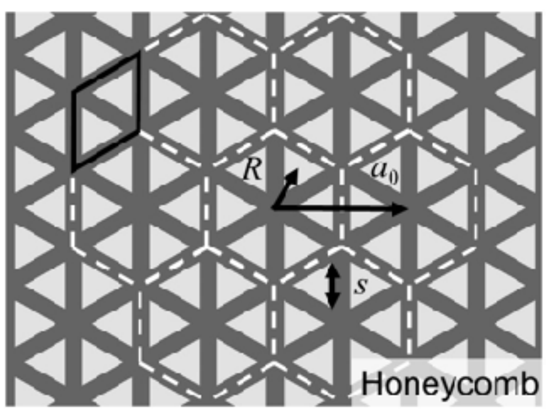

S. Mittal, S. Ganeshan, J. Fan, A. Vaezi, MH Nature Photonics 10, 180 (2016)

topological quantum optics

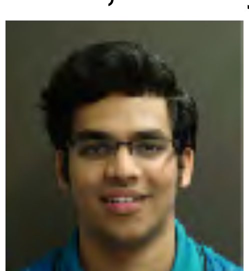


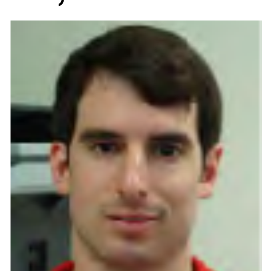

S. Mittal, Vikram Orre, and M. H., OP. EXP. 24, 15632 (2016)

Topological photonic crystals

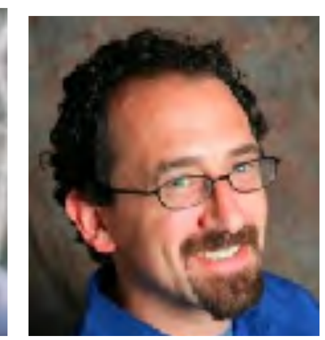


S. Barik, H. Miyake, W. DeGottardi, E. Waks, M.H. NJP (2016)



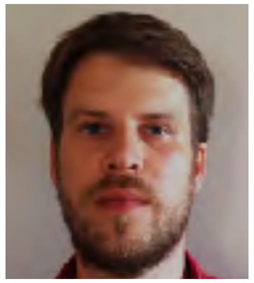
E. Kapit, MH and S. Simon PRX 2014

- Review of ring resonator
  - Measuring topological invariants
- Quantum directions
  - Topological photonic crystals
- Photons and electronic quantum Hall states

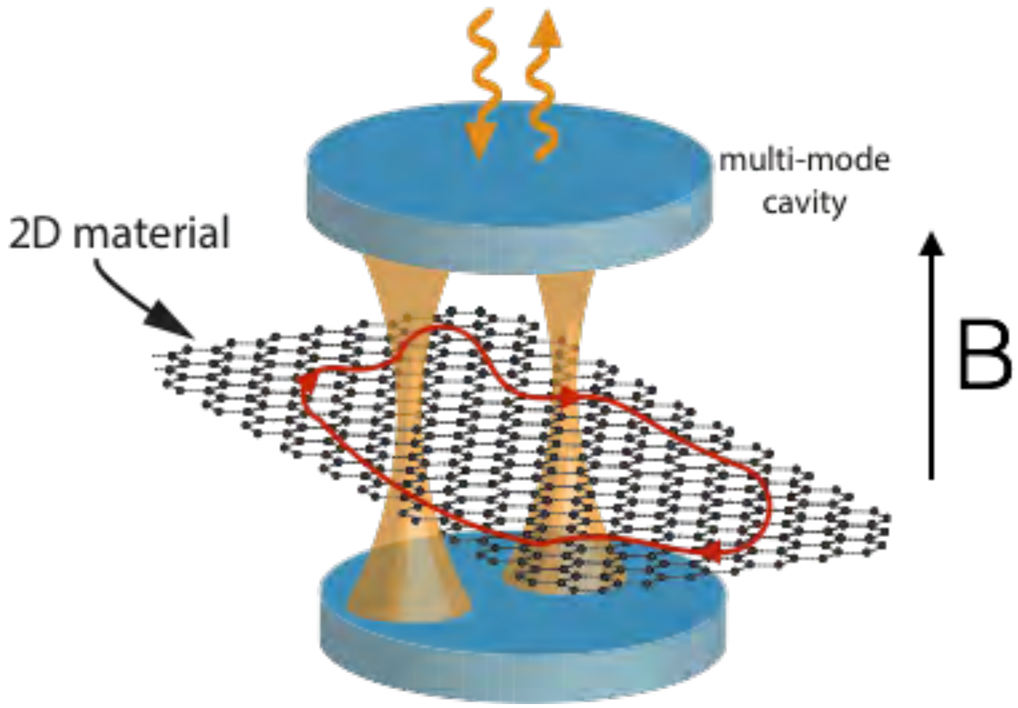
M. Gulllans

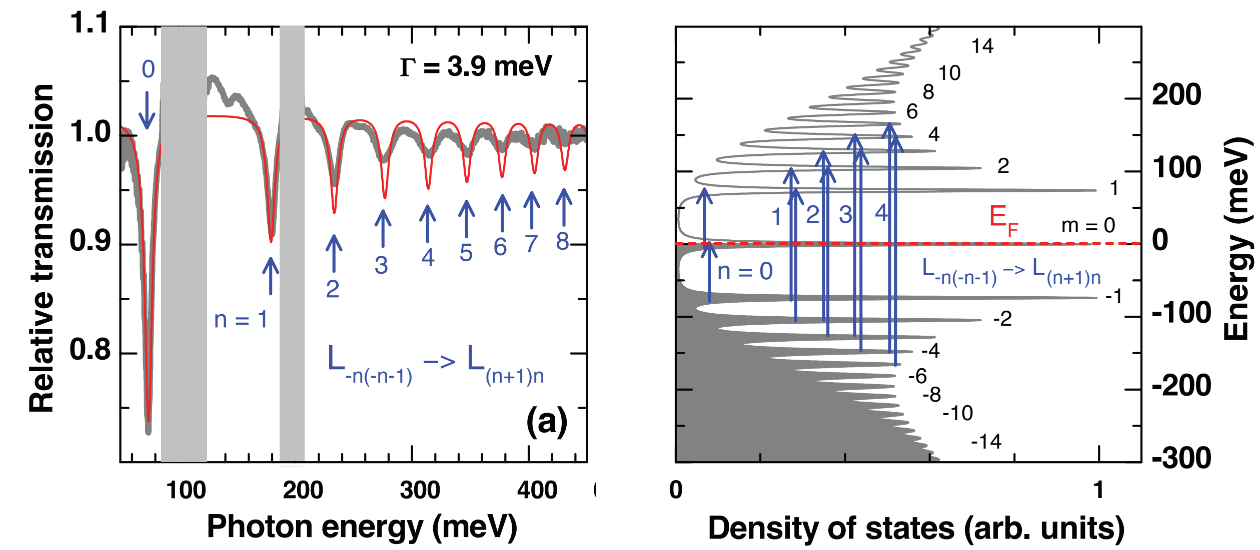
A. Gazaryan



T. Grass

Use light to detect/manipulate electronic topological states





Orlita, Potemski et al.

graphene

$$B = 4T$$

$$H_{\mathrm{quad}} \propto (p + eA)^2 \rightarrow \hbar\omega_c a^\dagger a$$

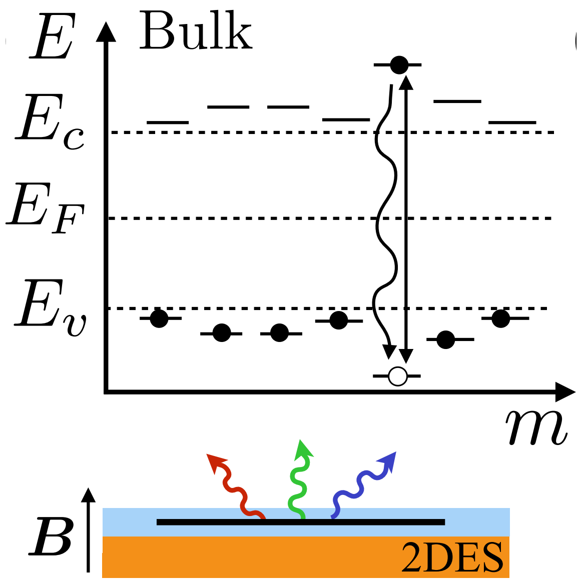
$$H_{\mathrm{lin}} \propto \begin{pmatrix} 0 & v_f(p_x - ip_y + eA_x - ieA_y) \\ v_f(p_x + ip_y + eA_x + ieA_y) & 0 \end{pmatrix} \rightarrow \frac{v_f}{l_b} \begin{pmatrix} 0 & a \\ a^\dagger & 0 \end{pmatrix}$$

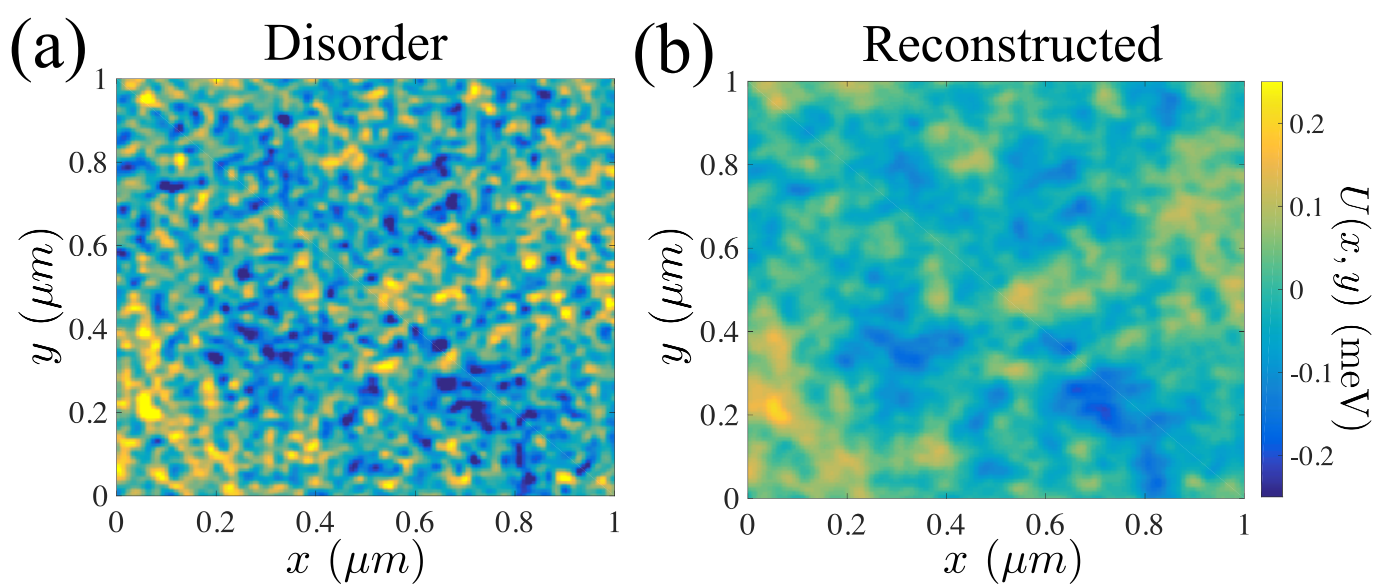
M. Gullans, J. Taylor, A. Imamoglu,
P. Ghaemi, and MH arXiv:1701.03464

GaAs works by Pinczuk,….
Recently in cavity: Imamoglu Science (2016)
Dicke-superradiance: Ciuti, Fazio, McDonald ..

Mapping disorder landscape

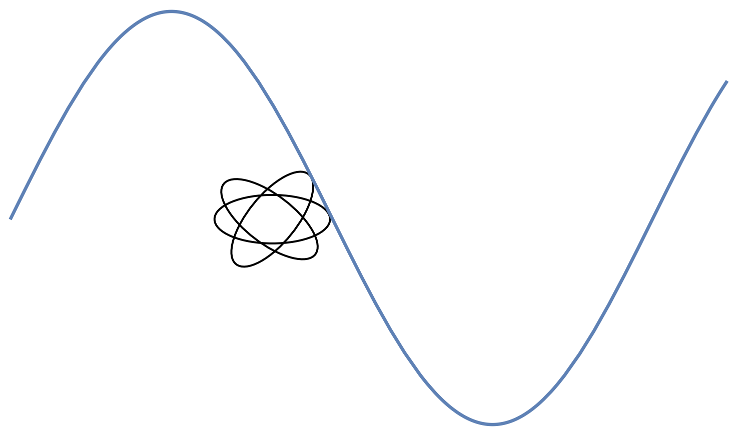
$$H_{\text{dis}} = u_0(\boldsymbol{r})I + \boldsymbol{u}(\boldsymbol{r}) \cdot \boldsymbol{\tau}$$



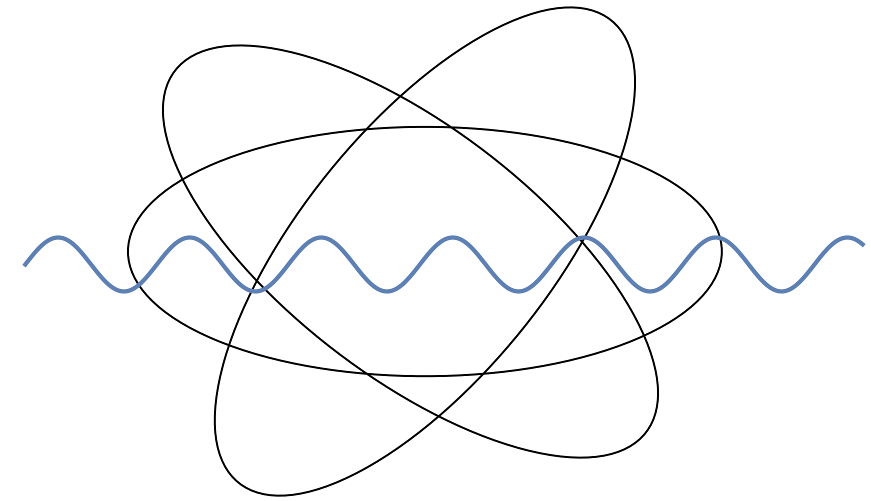


$$H_{\text{int}} = (-1)^s \frac{ev}{\sqrt{2}c}[\tau_+ A_+^*(x,y) + \tau_- A_-^*(x,y)]e^{-i\omega t} + h.c.$$

Most cases:
dipole approximation



Multipole emission



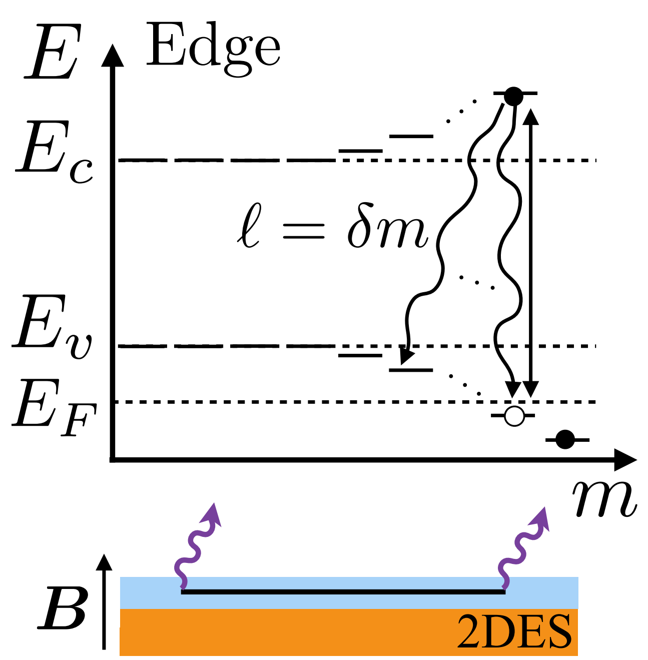
Extended states of electrons,
e.g. Quantum Hall, Rydberg excitations

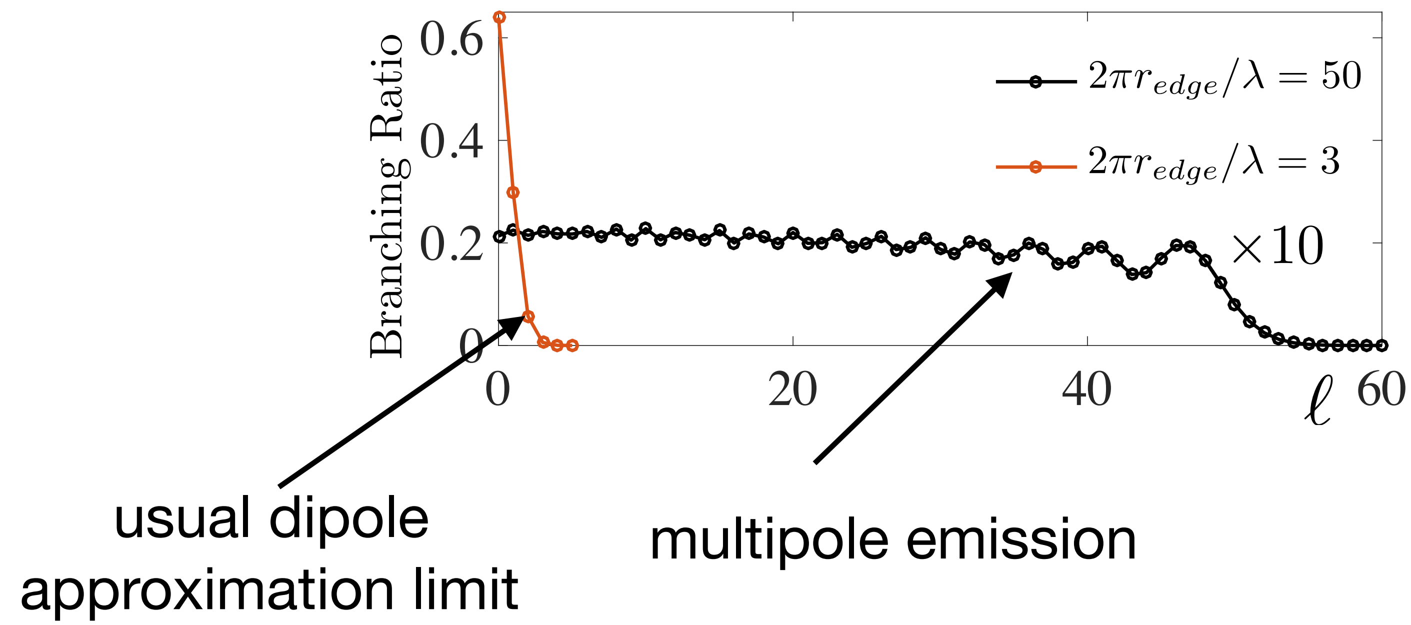
$$(re^{-i\theta})^{m'} \qquad\qquad (re^{i\theta})^{m}$$

$$ev_f\langle 1, m'|\tau_+\mathbf{A}.\sigma|0, m\rangle \;\to\; \delta_{m',m+l}$$

$$A \propto e^{ikz+il\theta}J_l(k_\perp r)$$

higher orbital angular
momentum emission

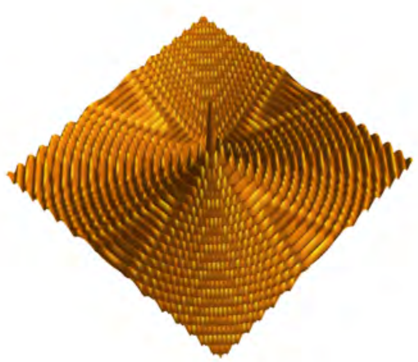




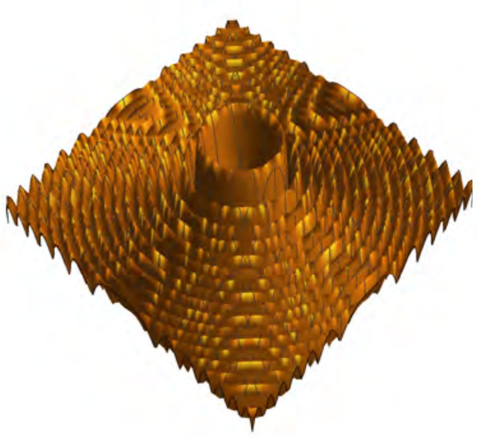
Solutions of Maxwell's equations are
given by Bessel functions:

$$k_\perp r_{vortex} = l$$

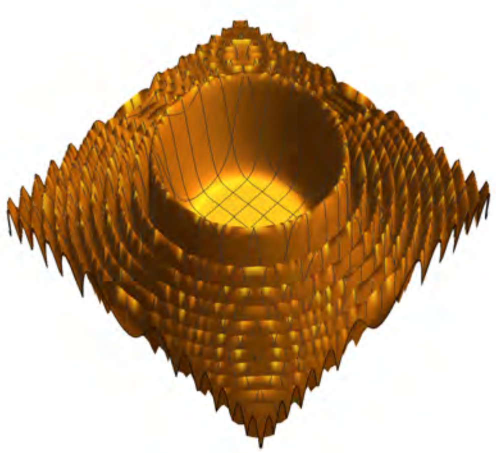
$$k_\perp = \sqrt{(\omega/c)^2 - k_\parallel^2}$$



$l = 0$



$l = 10$



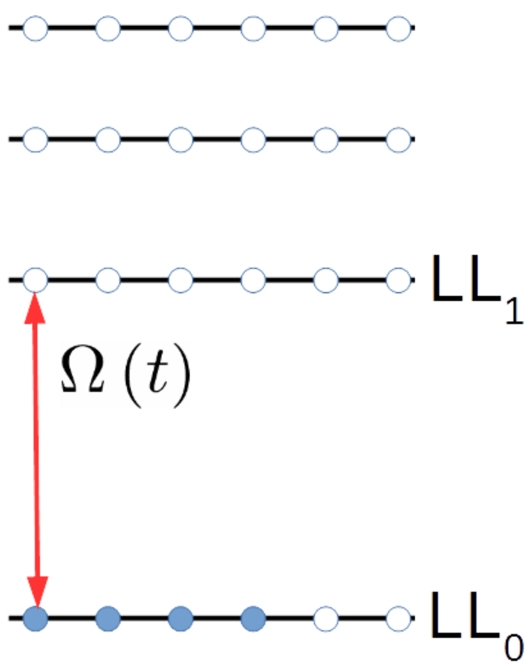
$l = 25$

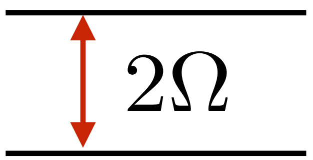
so the maximum OAM: $\frac{2\pi}{\lambda} r_{edge} = l_{max}$

Synthetic bilayer Graphene (?)

We use light to couple to LL and form a bilayer where:

(1) Different LL plays the role of layers
(2) Light plays the role of tunneling



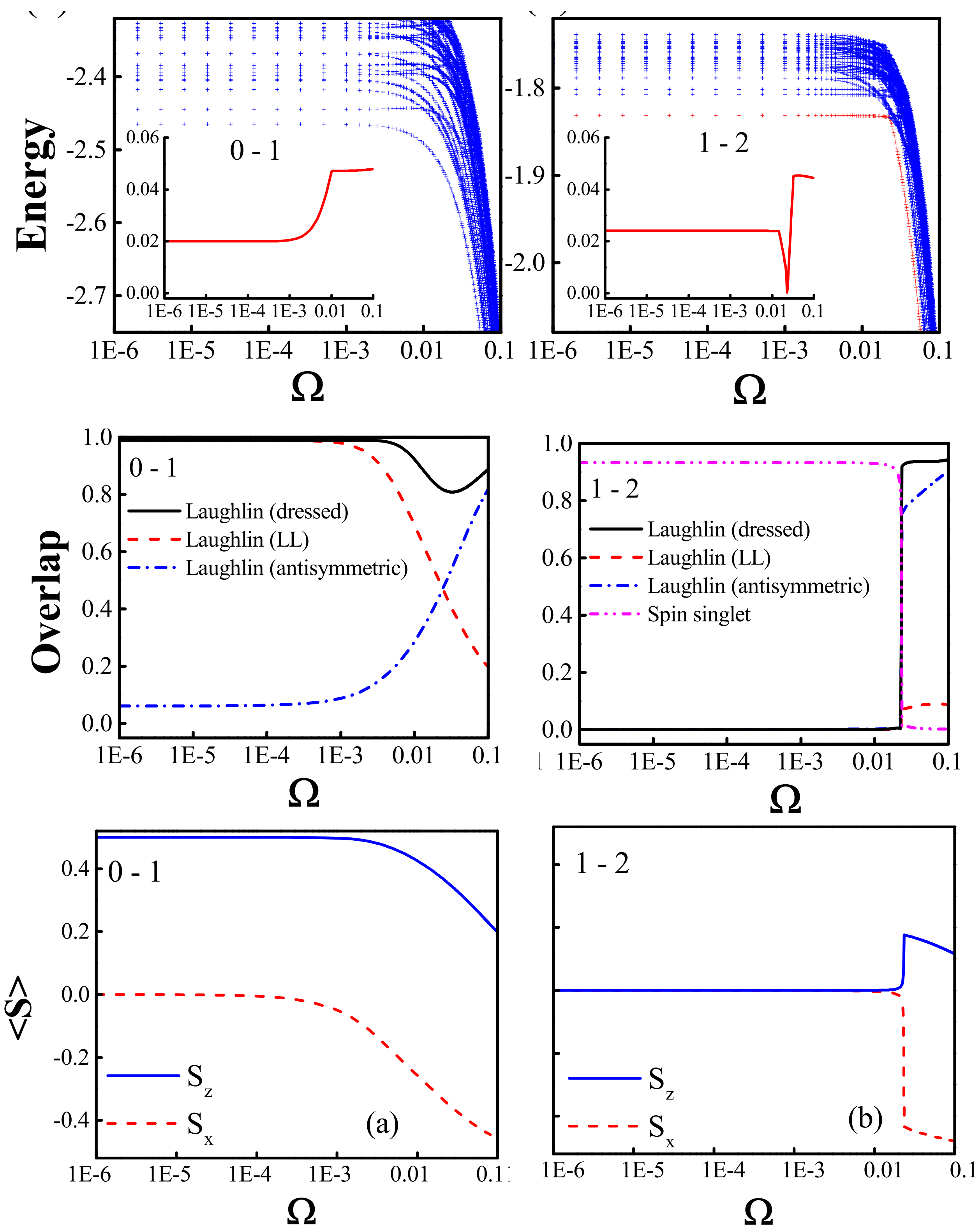


- What type of state one can engineering with light?

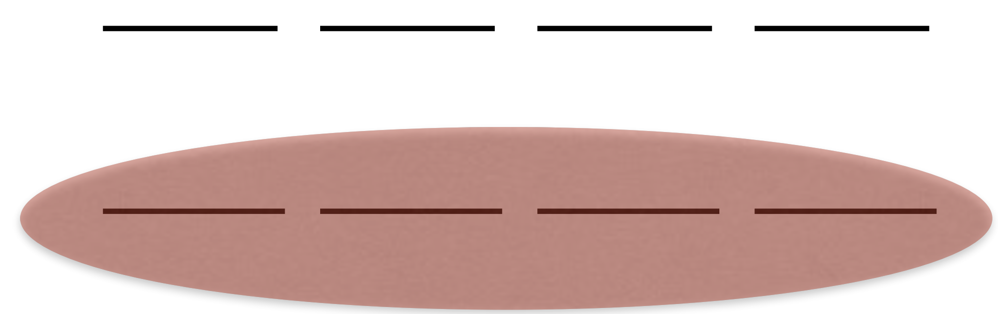
A. Ghazaryan, M. J. Gullans, P. Ghaemi, and M. H. arXiv:1612.08748

- Filling factor is $\nu = 2/3$

For bilayer: McDonald Haldane PRB (1996)
Peterson, Barkeshli, Wen…



Dressed Laughlin $\quad \Omega \ll e^2/l_B$



$$z_i^m \longrightarrow \prod_{i<j} (z_i - z_j)^m$$

Outlook:

Thermalization in the driven system

H. Dehghani, T. Oka, and A. Mitra, PRB(2014)
K. I. Seetharam, C.-E. Bardyn, N. H. Lindner, M. S. Rudner, and G. Refael, PRX (2015)

Engineering interaction

Constructing twist defects?

- Sunil Mittal
- Vikram Orre
- Mahmud Khan
- Hwanmun Kim
- Bin Cao
- Chris Flower
- Alireza Seif
- Sabyasachi Barik
- Wade DeGottardi
- Hiro Miyake
- T. Grass
- Guanyu Zhu

publications: hafezi.umd.edu

JQI

- A. Restelli
- E. Goldschmidt (ARL)
- J. Fan
- M. Gullans
- T. Huber
- Aziz Karahasin
- J. Taylor
- A. Migdall
- G. Solomon
- E. Waks

- S. Ganeshan (Stony Brook)
- P. Ghaemi, A. Ghazaryan (CUNY)
- A. Vaezi (Stanford)
- R. Salem (PicoLuz/Thorlabs)
- A. Imamoglu (ETHZ)