Driven quantum Hall models in photonic systems

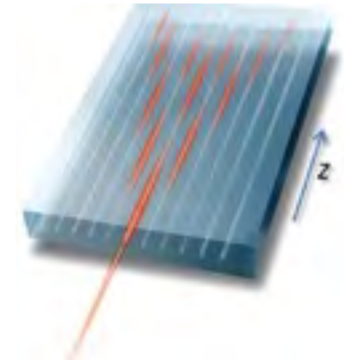
Mohammad Hafezi

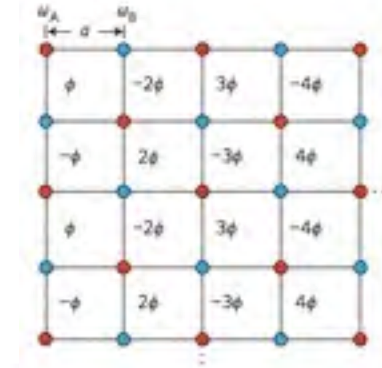
KITP, Synthetic Quantum Matter,
Sept 2016

Outline of this talk

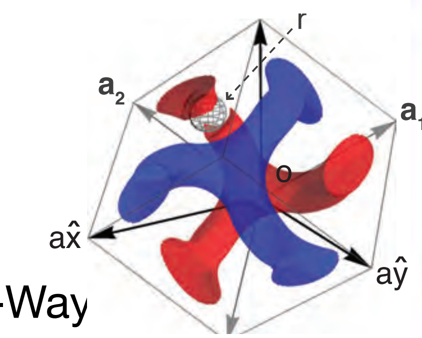
- Review of recent experiments on ring-resonators
  S. Mittal, S. Ganeshan, J. Fan, A. Vaezi, MH Nature Photonics 10, 180 (2016)
- Quantum transport of two-photons
  (non-classical input)
  S. Mittal, V. Orre, and MH, Optics Express 24, 15632 (2016)
- Topological photonic crystals
  (towards strong photon-photon interaction)
  S. Barik, H. Miyake, W. DeGottardi, E. Waks and M.H. arXiv:1605.08822 (2016)
- Effect of disorder on FQH of photons

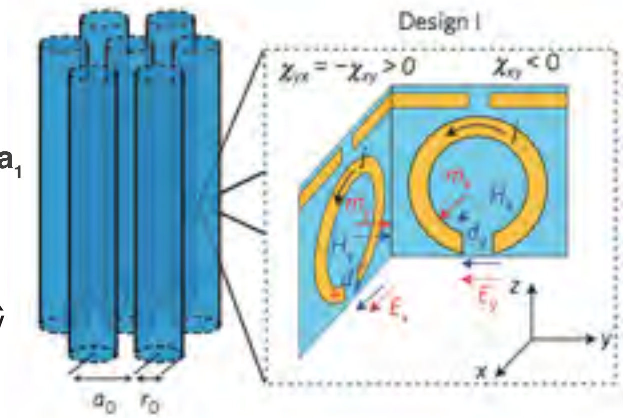
Recent publications exploring topological properties of light



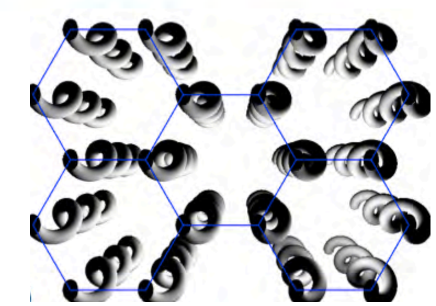


- Topological States and Adiabatic Pumping in Quasicrystals
  YE Kraus, Y Lahini, Z Ringel, M Verbin, O Zilberberg - Physical Review Letters, 2012
- Weyl points and line nodes in gapless gyroid photonic crystals
  L. Lu, L. Fu, J. Joannopoulos and M. Soljacic Nature Photonics **7**, 294–299 (2013)
- Realizing effective magnetic field for photons by controlling the phase of dynamic modulation
  K Fang, Z Yu, S Fan - Nature Photonics (2012)
- Strain-induced pseudomagnetic field and Landau levels in photonic structures
  M Rechtsman, et al. - Nature Photonics (2012)



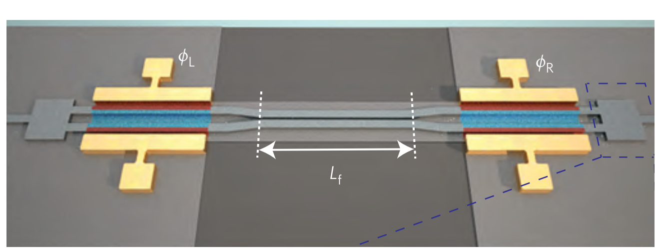


- Photonic Analogue of Two-dimensional Topological Insulators and Helical One-Way Transport in Bi-Anisotropic Metamaterial
  A. Khanikaev, S. Mousavi, W. Tse, M. Kargarian, A. MacDonald, G. Shvets, Nature Material (2012)
- Photonic Floquet Topological Insulators
  MC Rechtsman, et al. - Nature (2013)

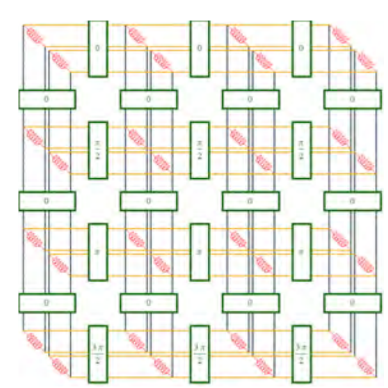


- Optical Resonator Analog of a Two-Dimensional Topological Insulator, G. Jiang, Y. Chong Physical Review Letters (2013)
- Photonic topological insulator with broken time-reversal symmetry C. Hea, X. Suna, X. Liua,b, M. Lua, Y. Chenc, L. Fengd and Y. Chen PNAS (2016)

...



Lipson Nat. Photon. (2014)



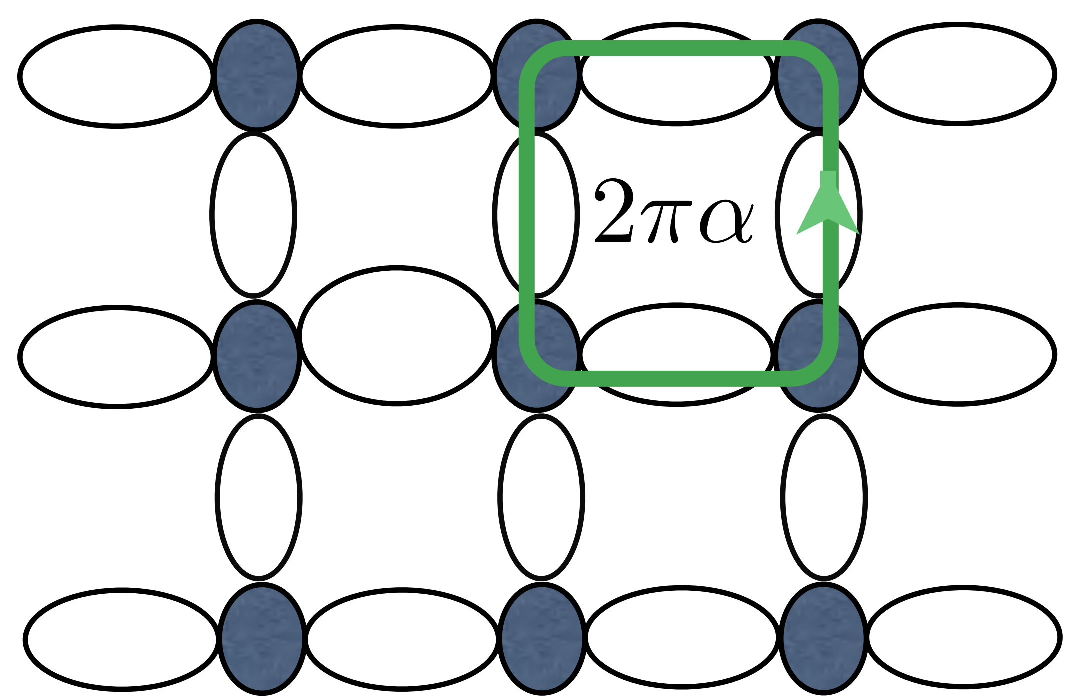
Schuster
Simon
PRX (2014)

L Lu, JD Joannopoulos, M Soljačić - Nature Photonics (2014)
M Hafezi, J. Taylor Physics Today (2014)

Synthetic Magnetic Field

Magneto-optical effects are weak

we need to synthesize magnetic field



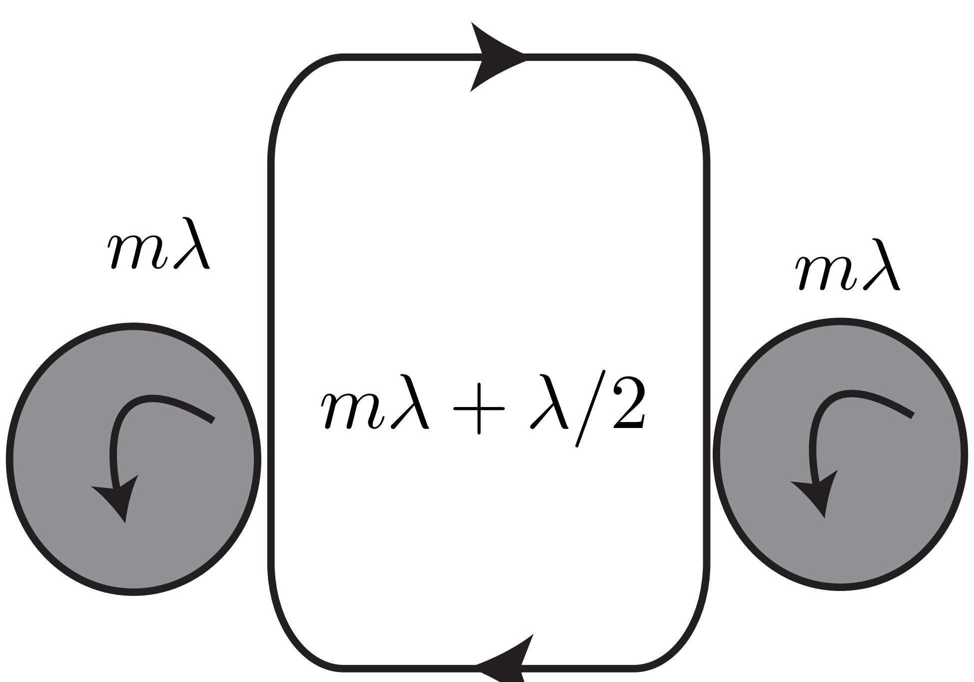
In analogy to electrons on a magnetic lattice:

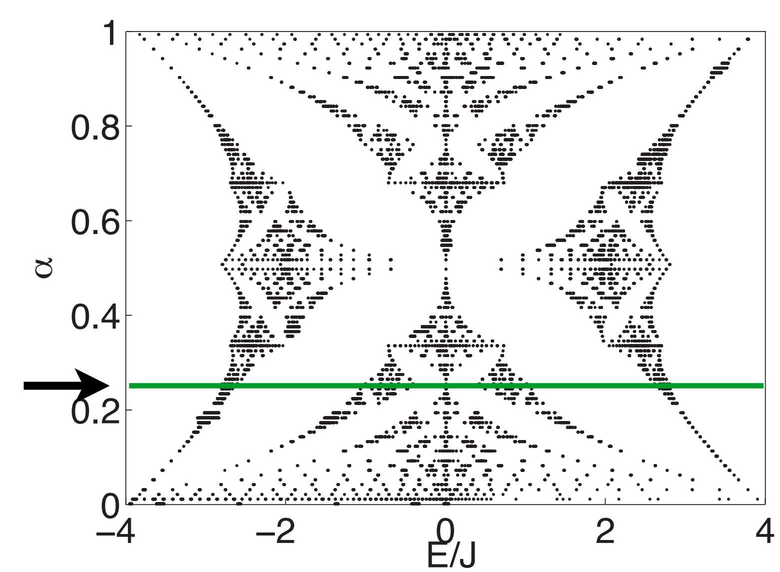
$$H_0 = -J \sum_{x,y} \hat{a}^\dagger_{x+1,y}\hat{a}_{x,y}e^{-i2\pi\alpha y} + \hat{a}^\dagger_{x,y}\hat{a}_{x+1,y}e^{i2\pi\alpha y} + \hat{a}^\dagger_{x,y+1}\hat{a}_{x,y} + \hat{a}^\dagger_{x,y}\hat{a}_{x,y+1}$$

- Tight-binding form
- Magnetic phase

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

Two resonator case:

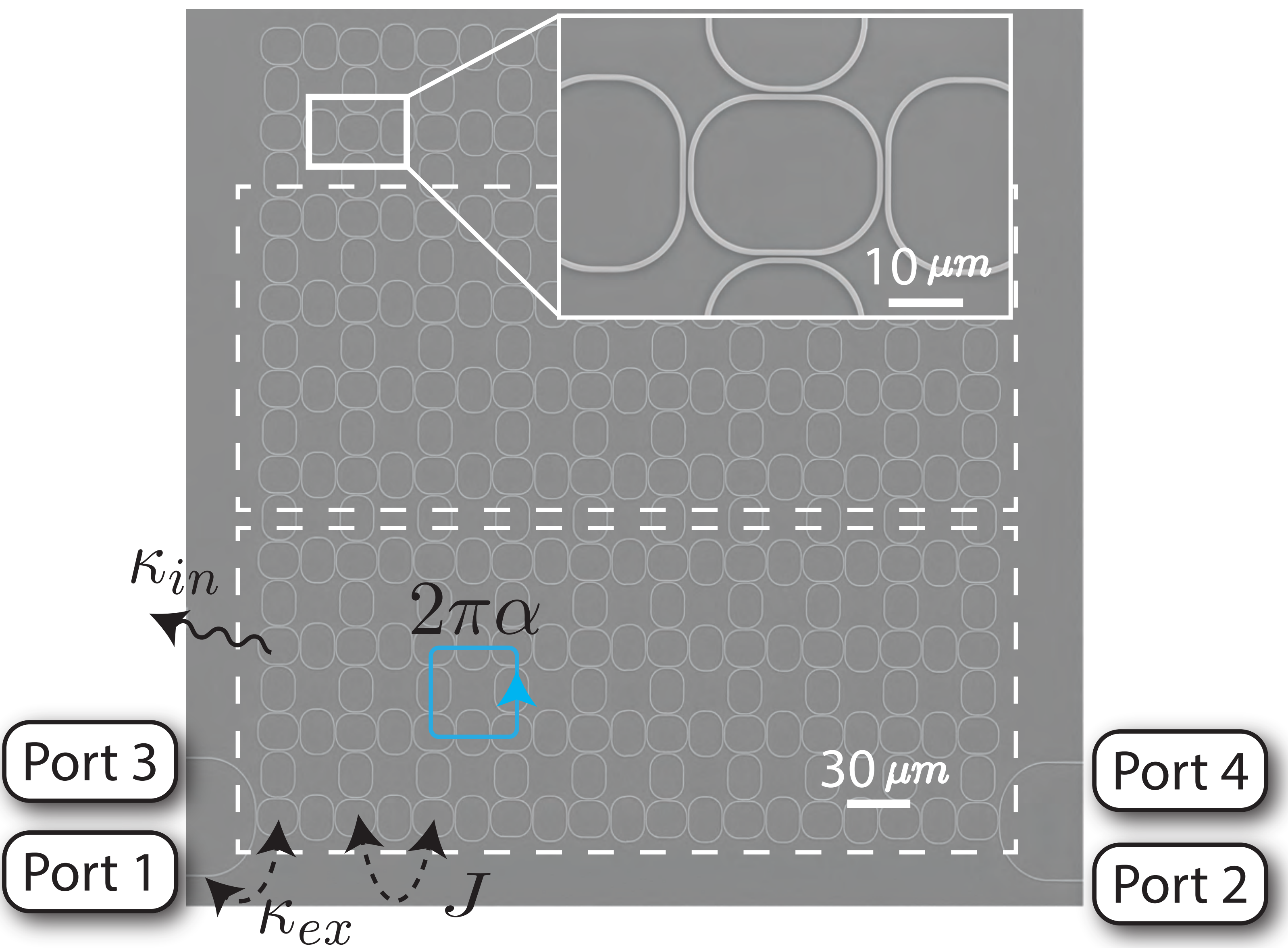


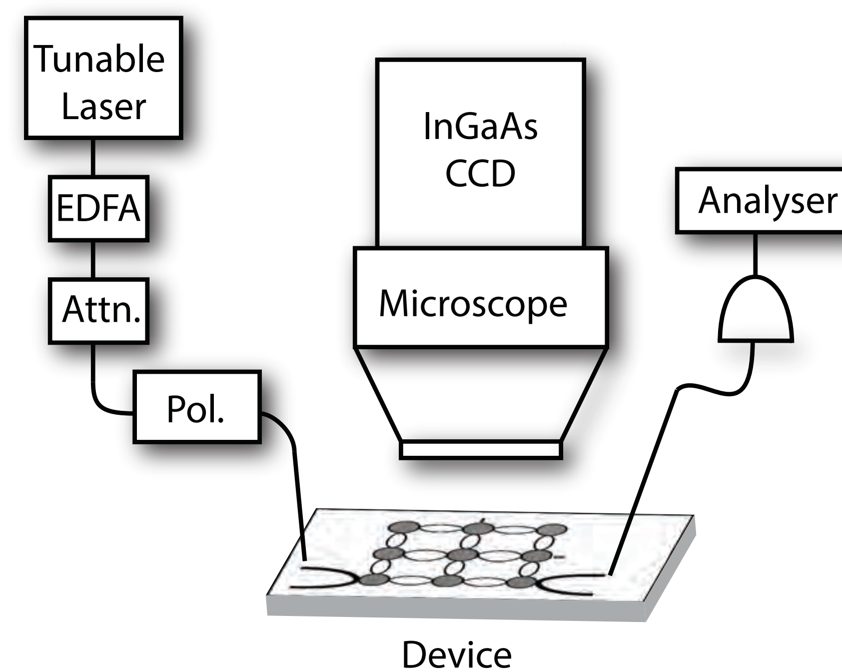


MH, Demler, Lukin, Taylor Nat. Phys. 7, 907 (2011)
see also Microwave : Haldane, Raghu PRL (2008), Soljacic's group Nature (2009) Carusotto's group PRA (2011)

Experimental realization of the gauge field

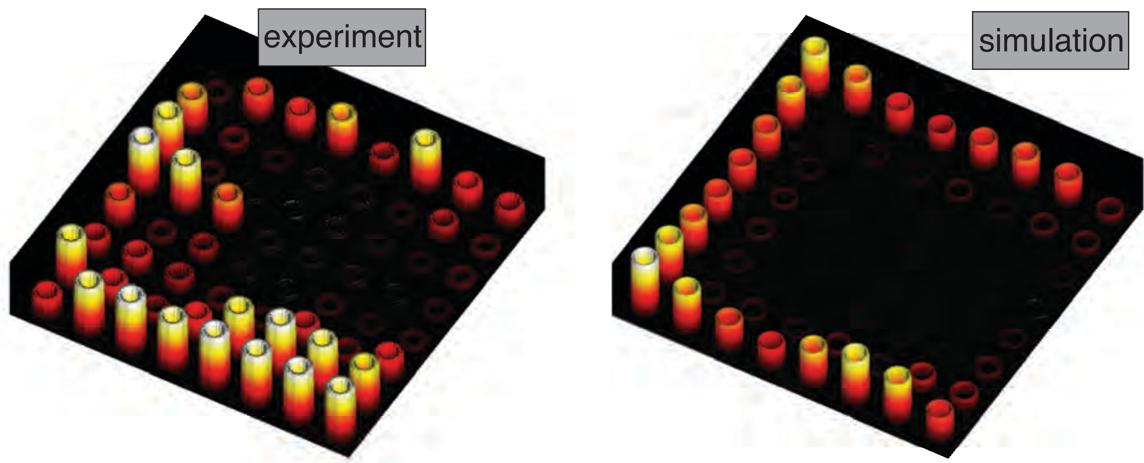
Silicon-on-Insulator technology

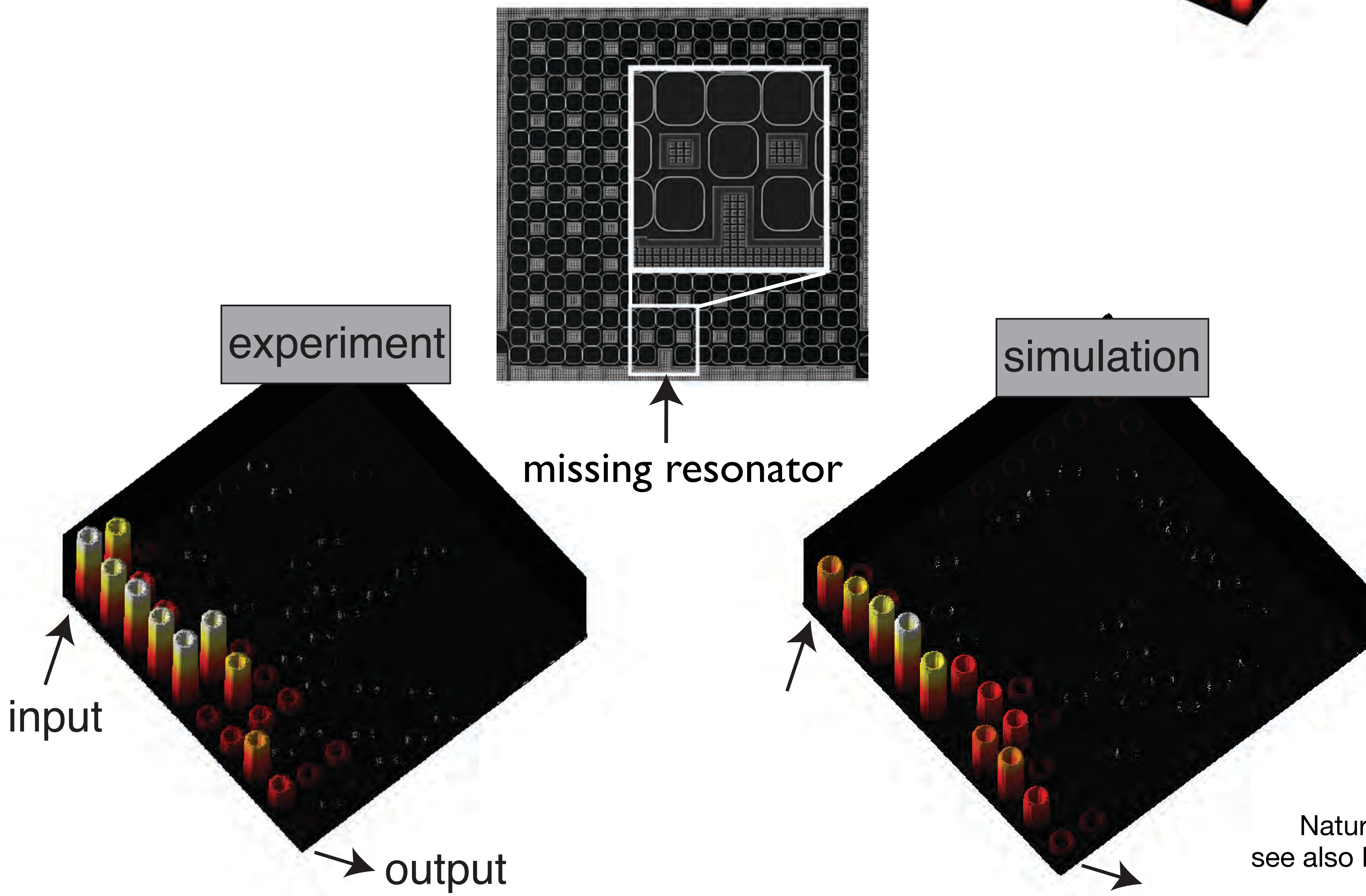




Robustness disorder

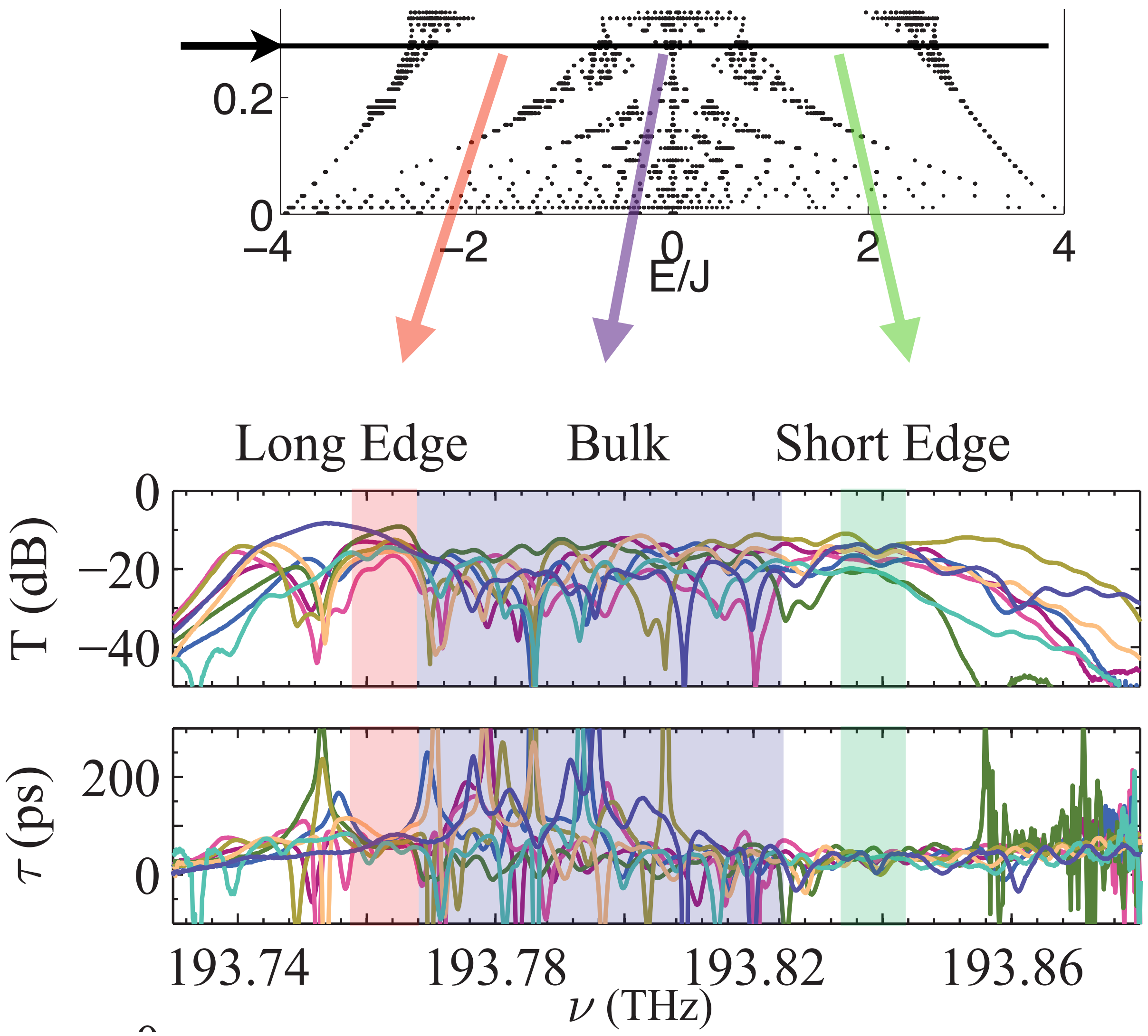
- ✓ Topological edge state when the system is excited in the bulk band gap
- ✓ Robustness against intrinsic and extrinsic disorders



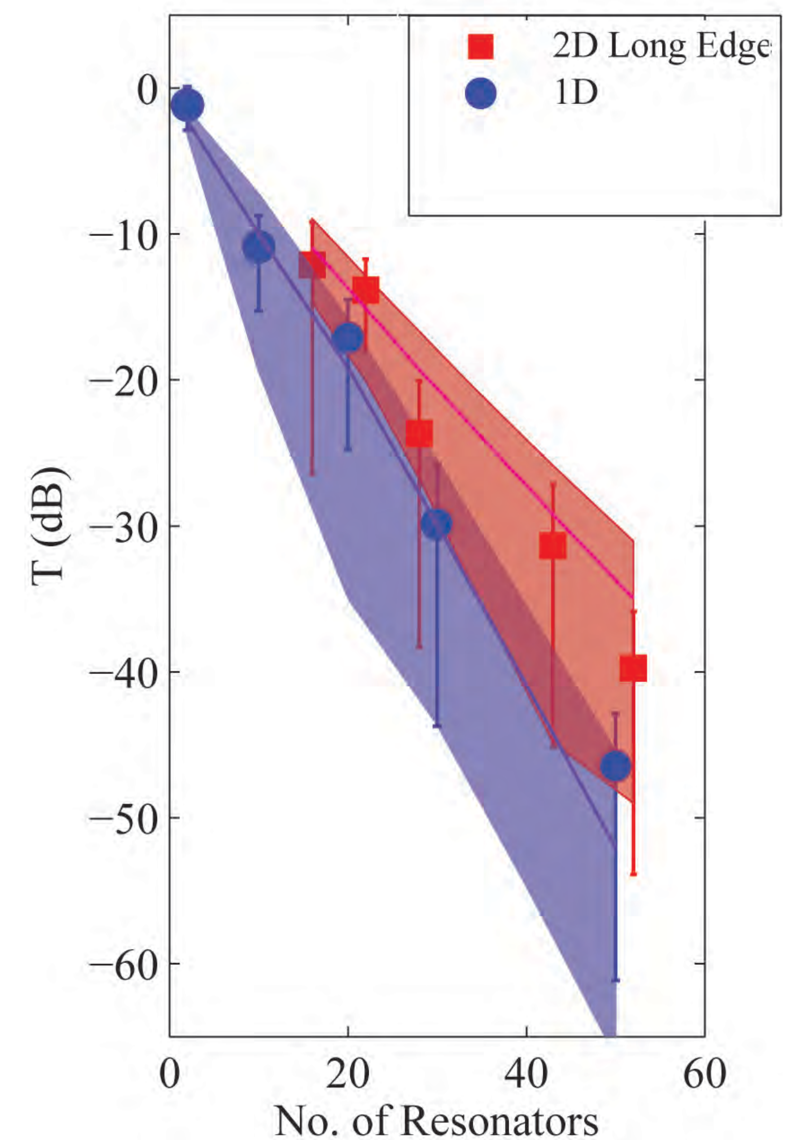


Nature Photonics 7, 1001 (2013)
see also Rechtsman et al. Nature (2013)

Transport statistics



15x15 arrays
Different colors: different samples



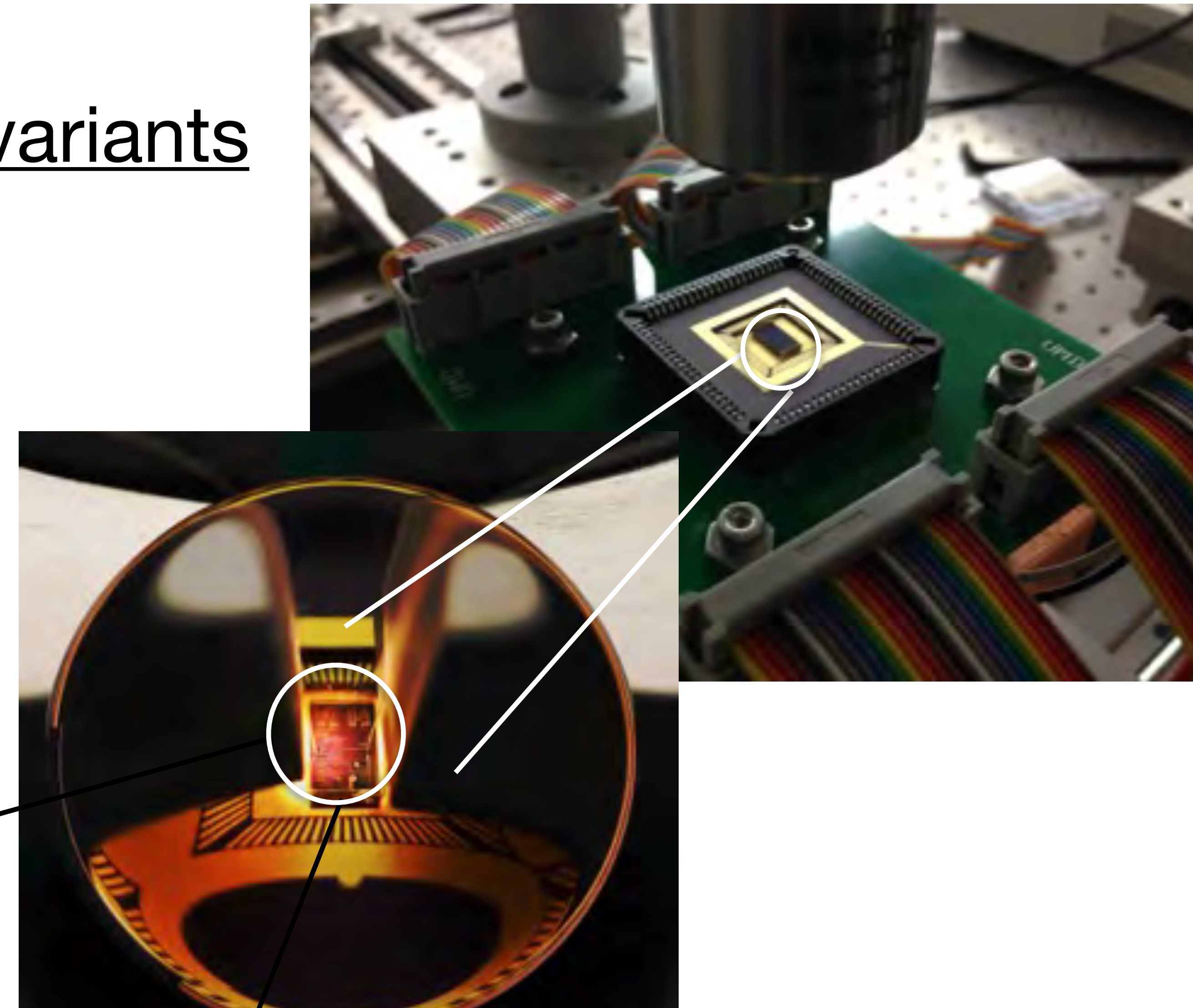
S. Mittal et al.
Phys. Rev. Lett. 113, 087403 (2014)

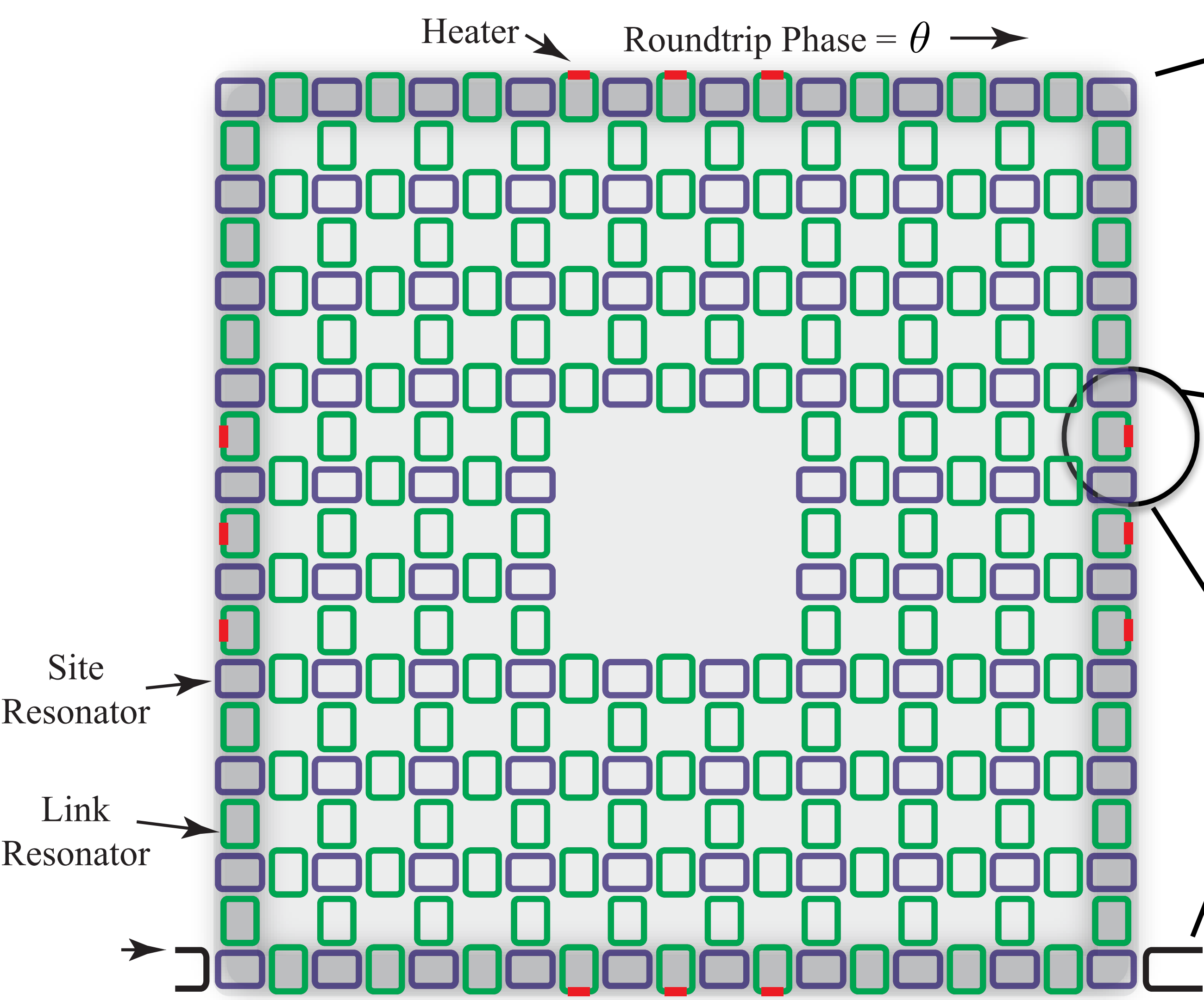
Measuring integer topological invariants

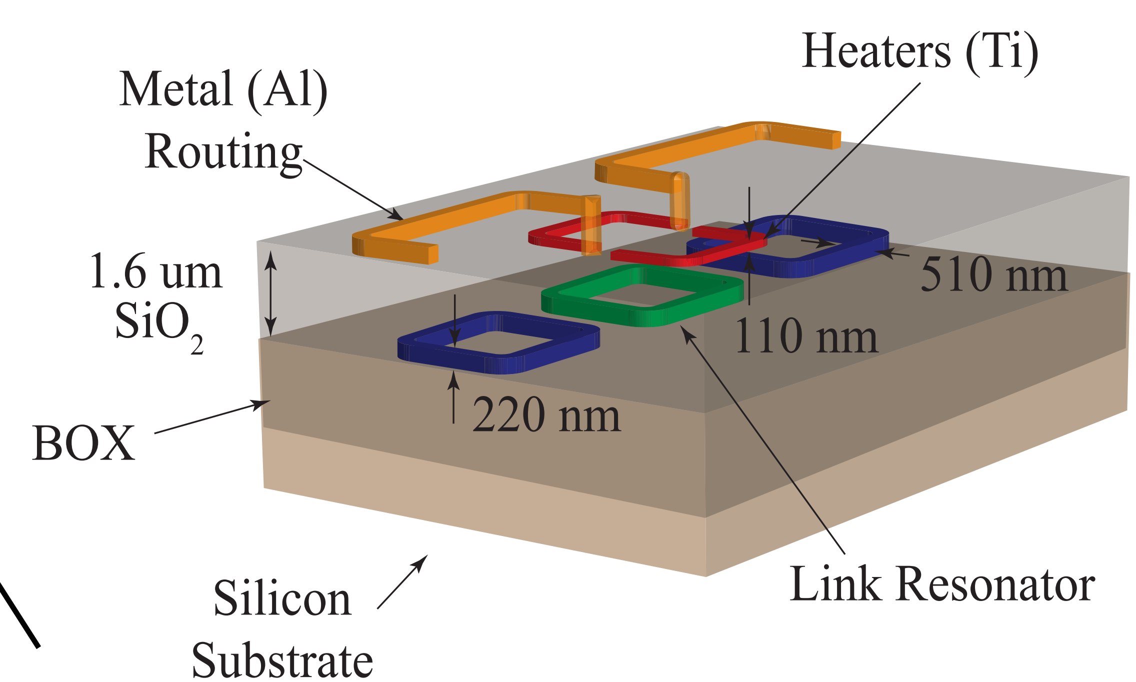
Bulk-edge correspondence

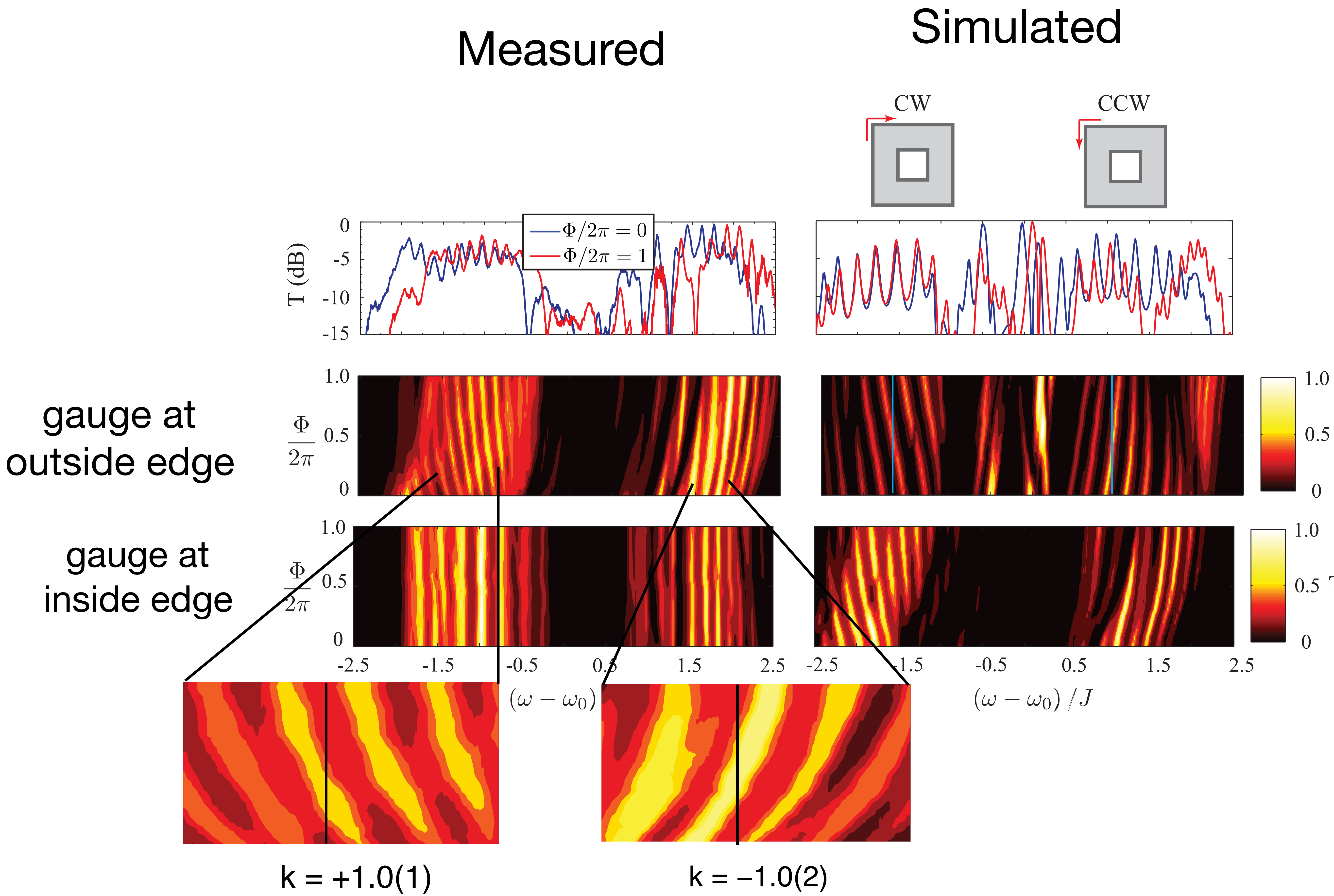
Laughlin-Halperin's argument applied to photonic system ✓

MH, PRL 112, 210405 (2014)









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

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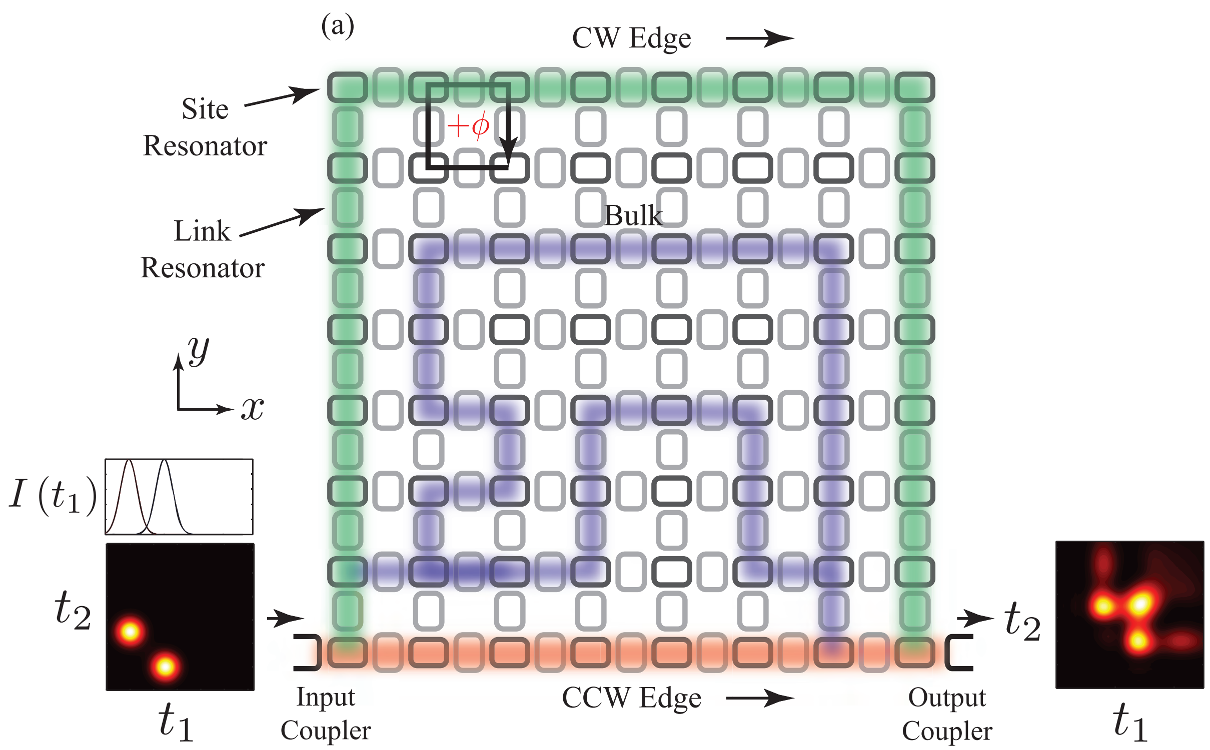
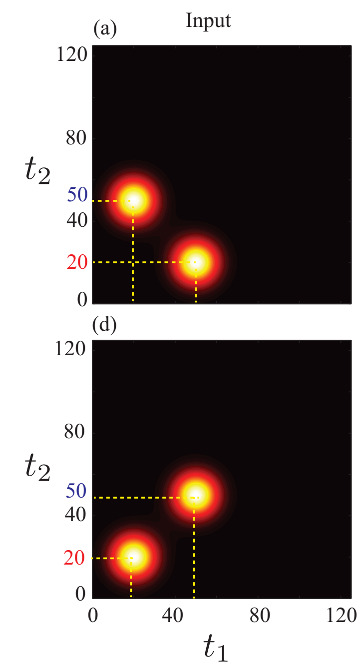
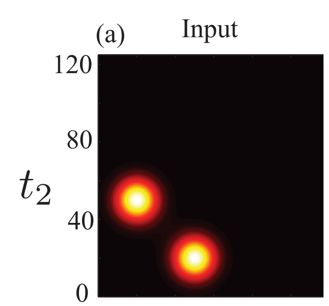
Quantum transport in topological photonics systems



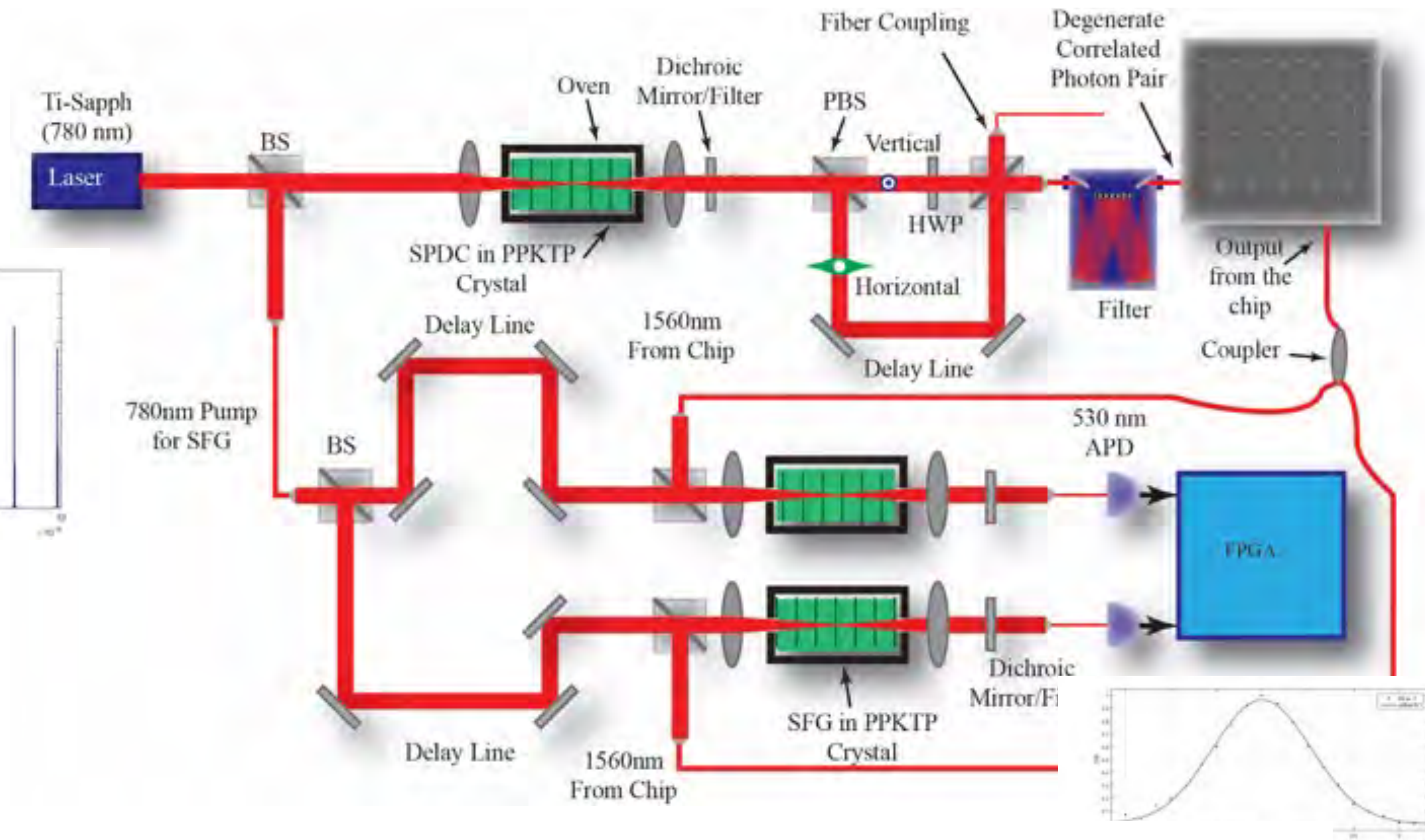


$$|2\rangle = \int dx_1 dx_2 \psi(x_1, x_2; t) \hat{a}^\dagger(x_1) \hat{a}^\dagger(x_2) |0\rangle$$

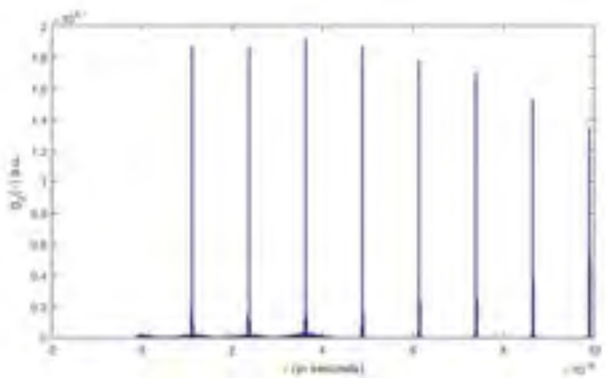


Theory: S. Mittal, V. Vikram Orre, and M. H., Optics Expres 24, 15632 (2016)
see also Rechtsman et al. arXiv:1605.02053

Experiment using SPDC



Time (ps)



$g_2(0) = 0.04$

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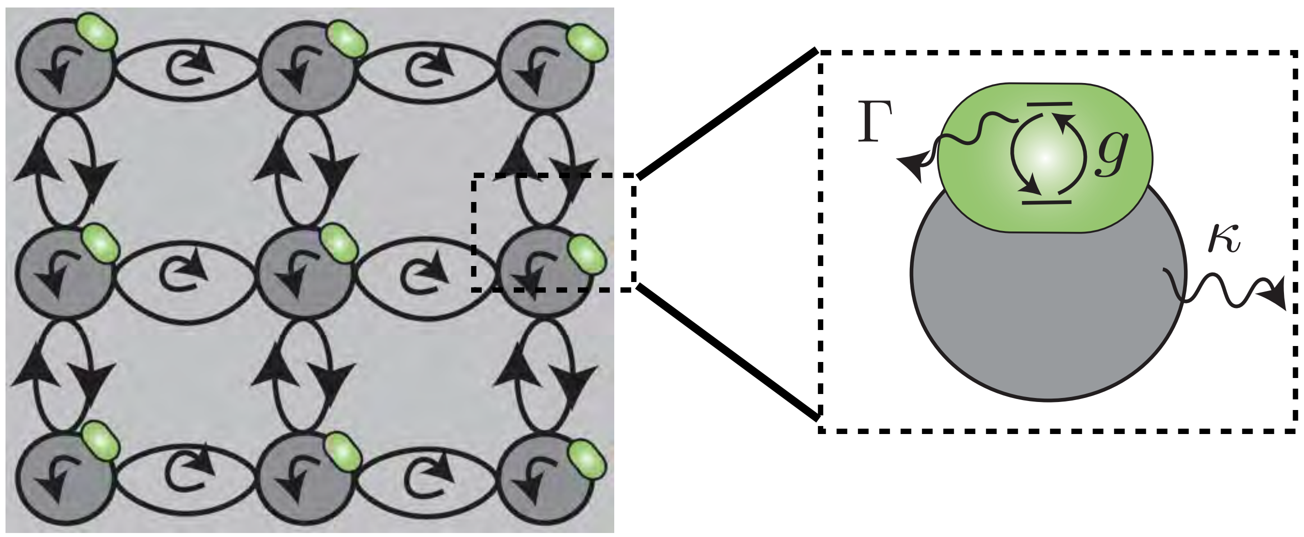
Fractional Quantum Hall state of light

Gauge field + interaction → Fractional Quantum Hall states

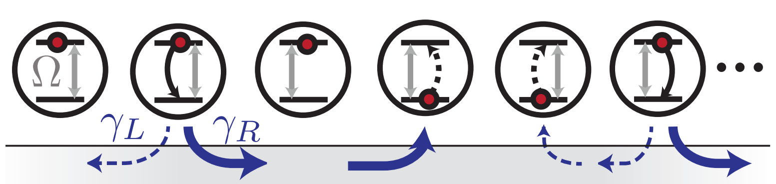


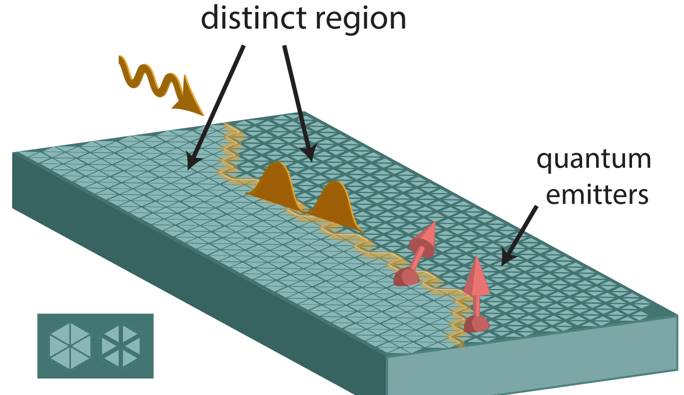
$$H = -J\sum_{x,y} \hat{a}^\dagger_{x+1,y}\hat{a}_{x,y}e^{i2\pi\alpha y} + \hat{a}^\dagger_{x,y+1}\hat{a}_{x,y} + h.c.$$
$$+U\hat{n}_{x,y}(\hat{n}_{x,y}-1)$$

$U >> J$: photon blockade regime

Angelakis PRL (2008), Carusotto PRL (2012) MH et al. NJP (2013)

Chiral coupling





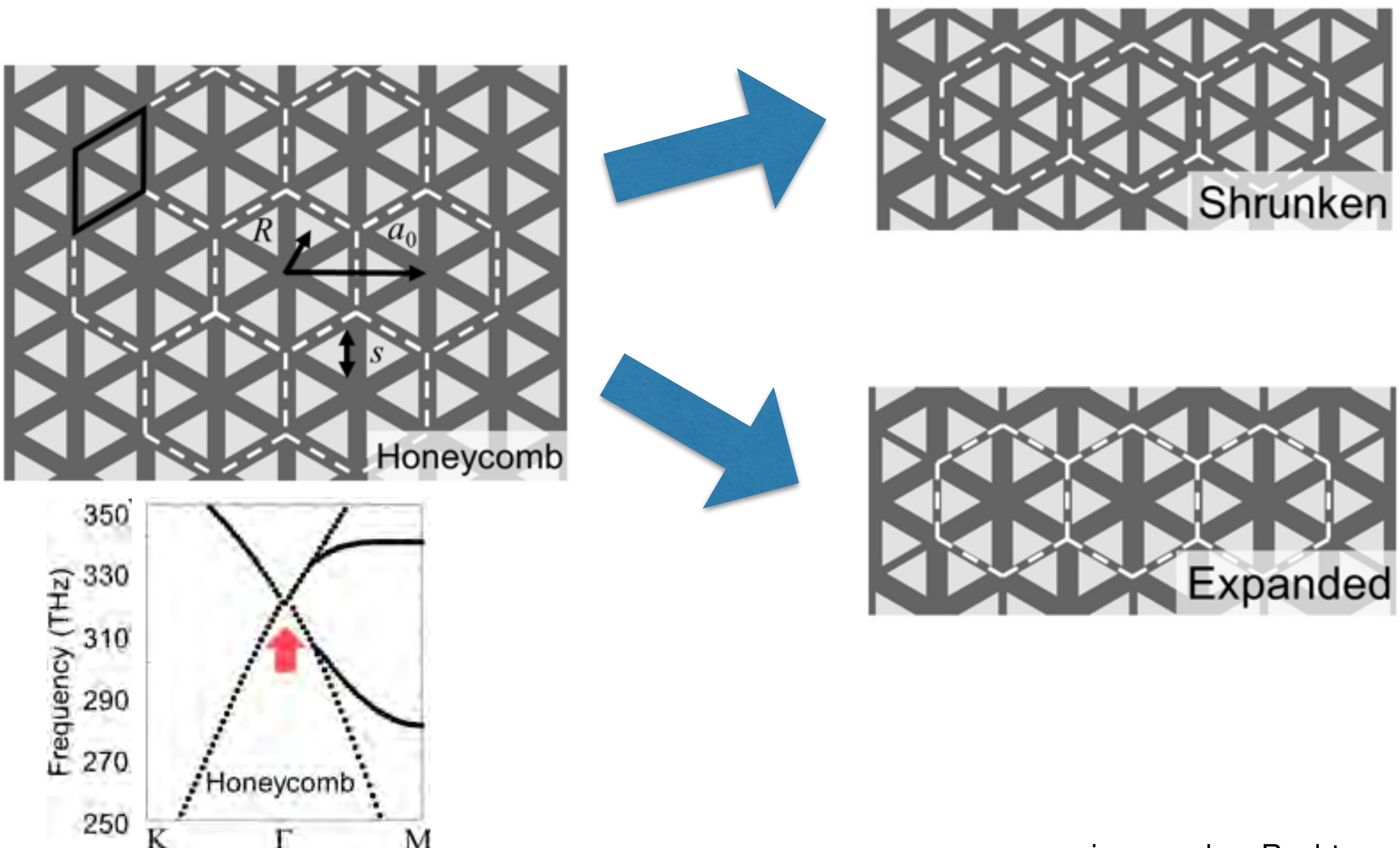
cf. P. Lodahl (Photonic crystal waveguides)
and A. Rauschenbeutel (nanofiber)

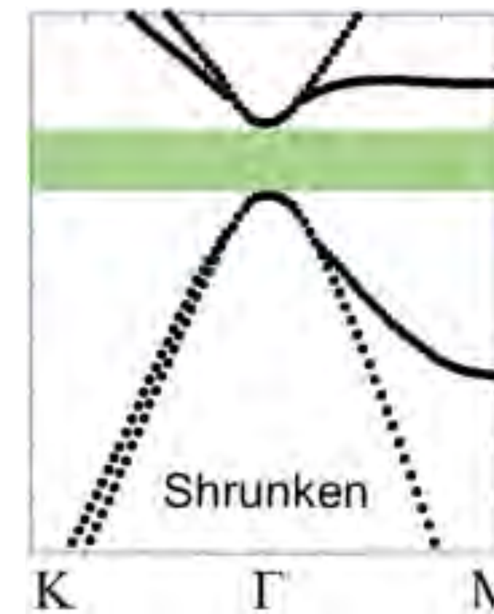
H. Pichler, T. Ramos, A. Daley, P. Zoller
PRA (2015)
earlier work on non-driven: Yudson,
Pletyukhov, Gritsev

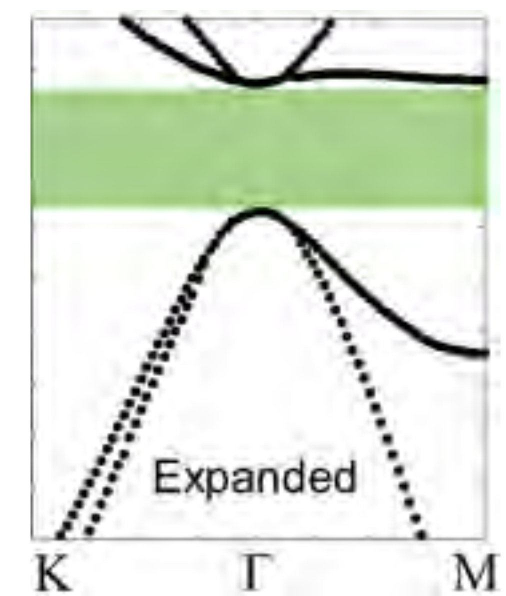
Topological photonic crystals

- 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



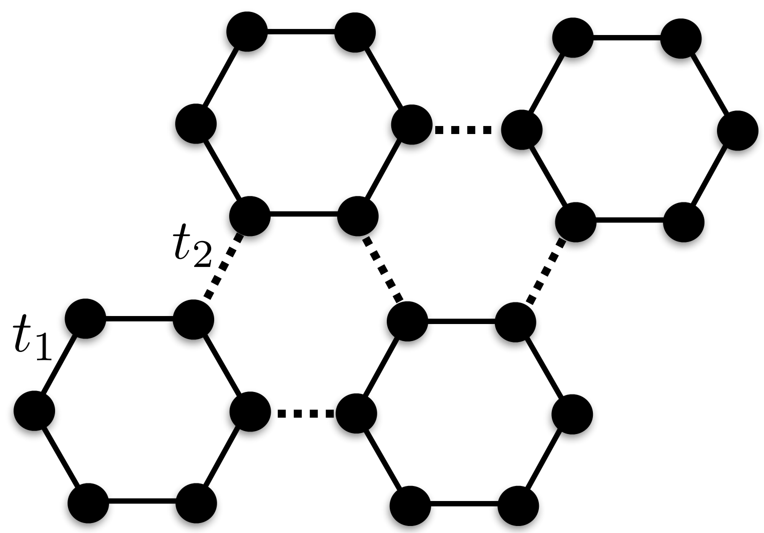




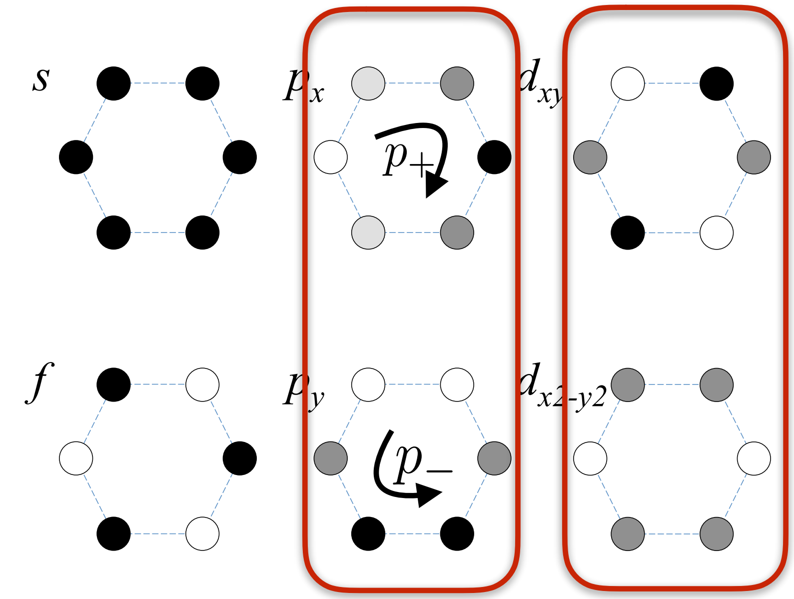
previous works: Rechtsman/Segev Nat. Photon (2012)
Shvets/Khanikaev PRL (2014), Wu/Hu PRL (2015)

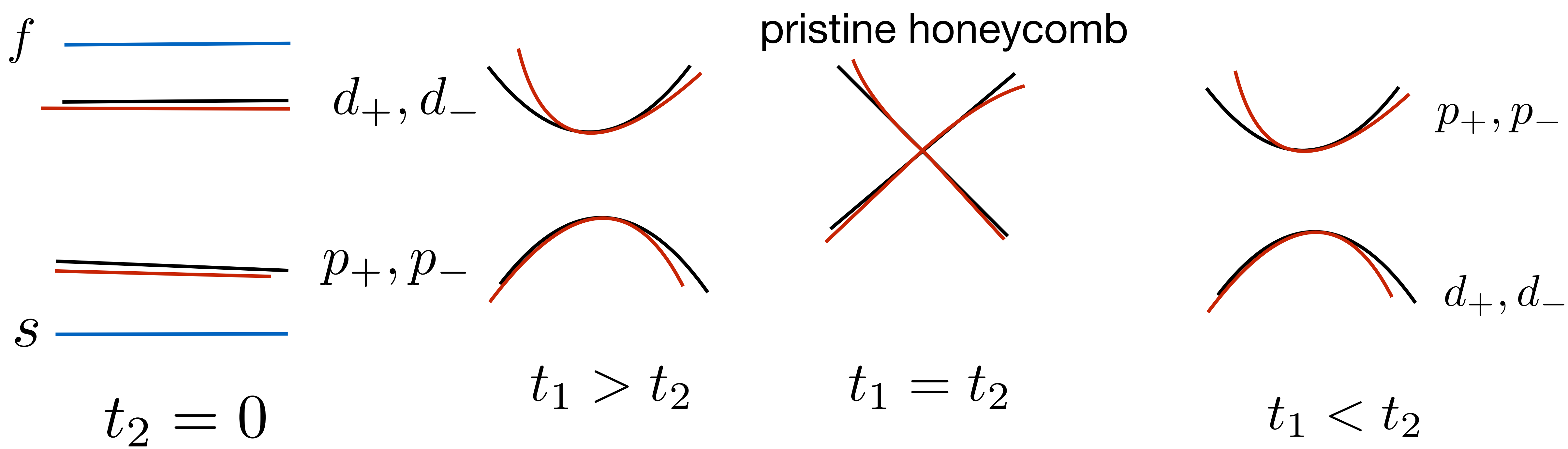
S. Barik, H. Miyake, W. DeGottardi, E. Waks, M.H. arXiv:1605.08822

Tight-binding approximation



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





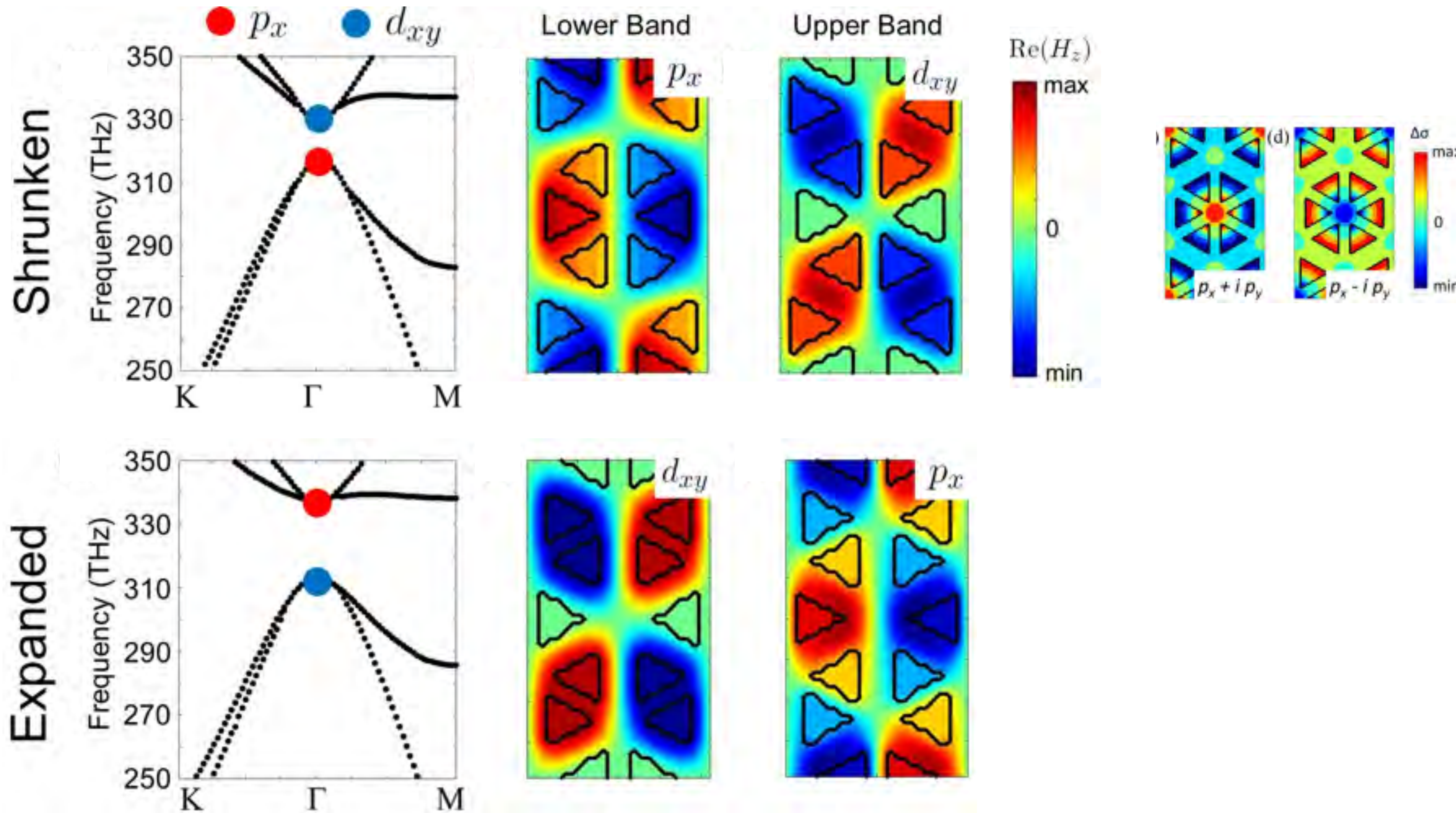
✓ Obtain band inversion, requirement for non-trivial topology

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

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

see also: Wu/Hu PRL (2015)

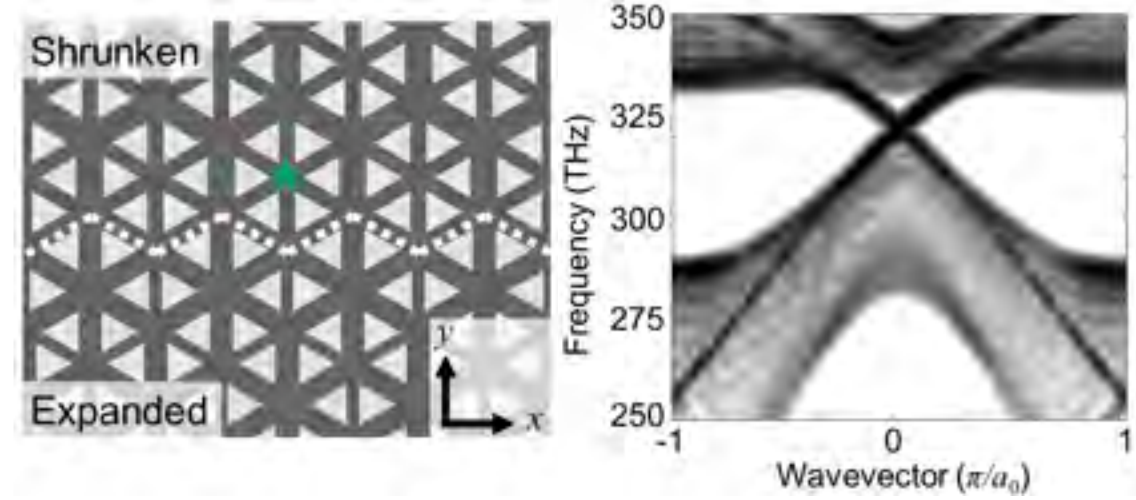
Band inversion: numerical simulation

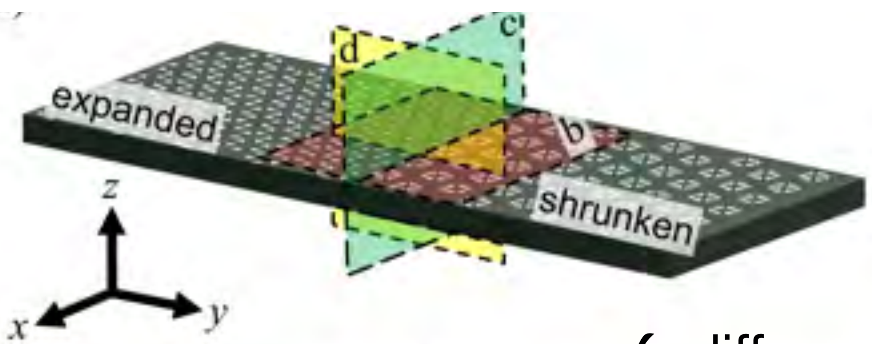


✓ Bulk/edge correspondence: We expect topological edge states to appear at the interface between expanded/shrunken system

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

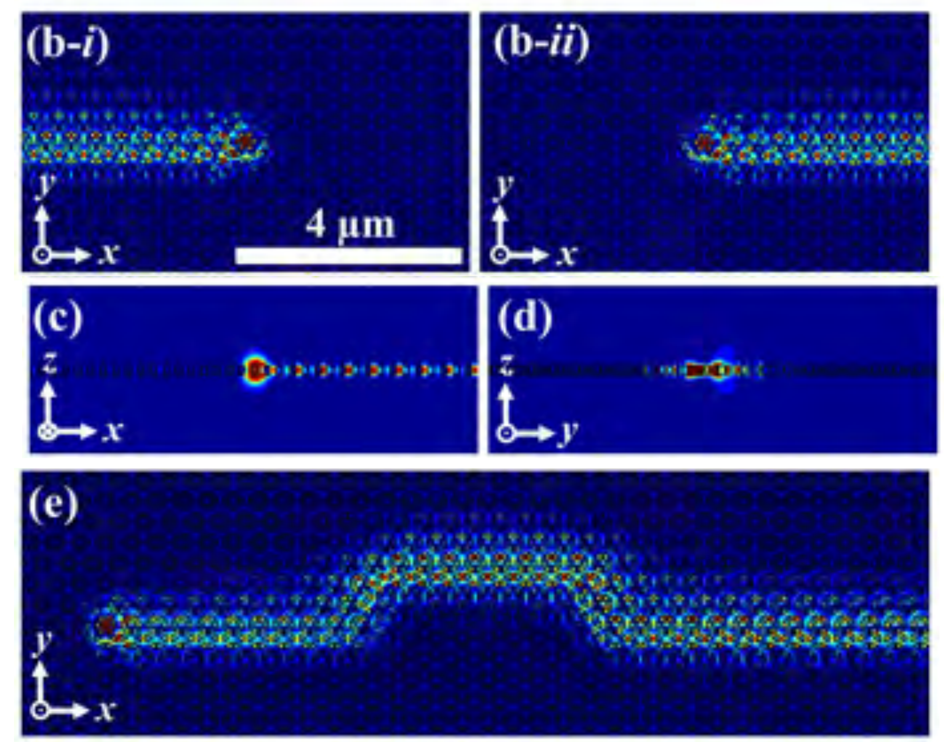




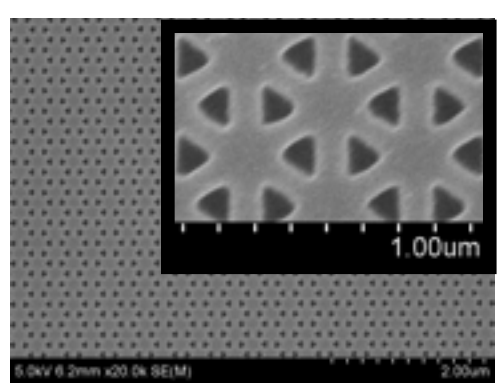
✓ different polarization propagate in different directions

✓ confinement in prep. direction

✓ robustness against deformation of edge



fabrication so far….



S. Barik, H. Miyake, W. DeGottardi, E. Waks, M.H. arXiv:1605.08822

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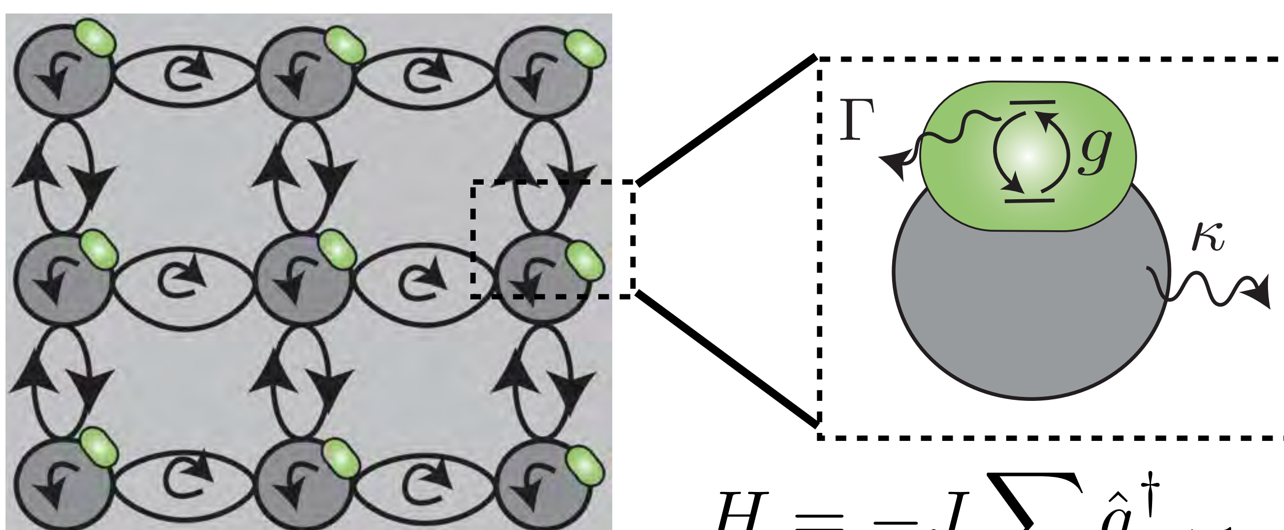
Fractional Quantum Hall state of light

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

Challenges:

- Weak interaction in the optical domain
- Photon loss
- lack of chemical potential
- lack of thermalization

Advantages:

- Synthetic gauge field
- k-body interaction
- length scale
- correlation function measurement

- MH, J. Taylor, M. Lukin NJP (2013)
- E. Kapit, MH and S. Simon PRX (2014)
- MH, Adhikari, Taylor PRB (2015)
- M. Schiro, M. Bordyuh, B. Oztop, and H. Tureci PRL (2012)
- F. Grusdt et al. PRL (2014)
- ….

- E. Kapit, S. Simon PRB (2013)
- MH, P. Adhikari, and J. Taylor PRB (2014)

(three-body interaction and Pfaffian states)

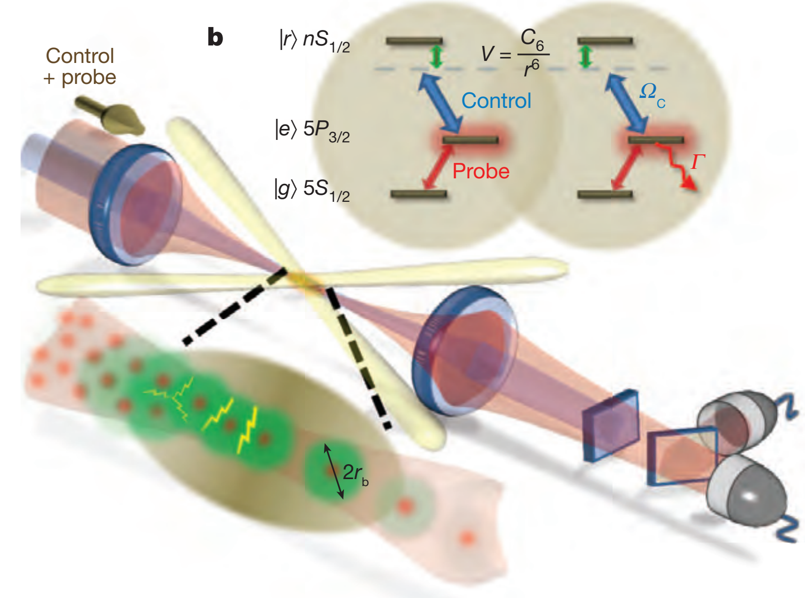
- R. Umucalılar, I. Carusotto PLA (2013)
- ……

Interaction between photons

Some challenges:

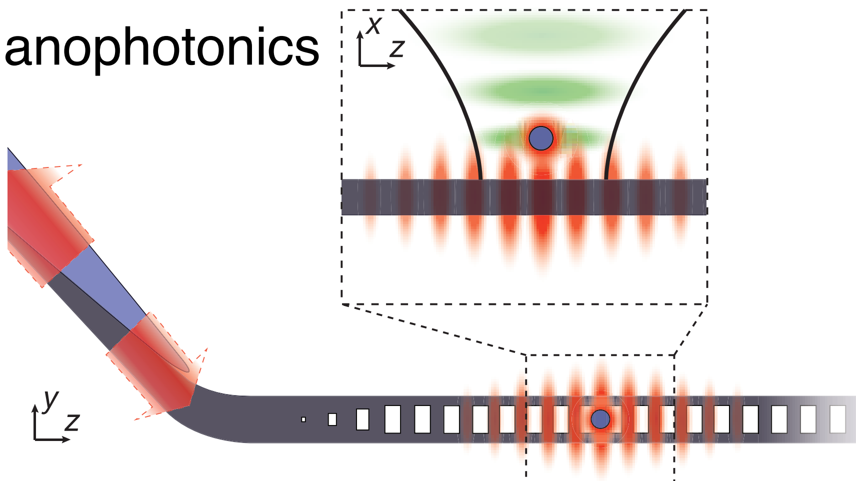
- Strong photon-photon interaction
- Scalable implementation of various Hamiltonians

Rydberg polaritons



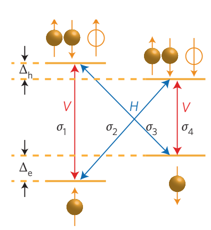
Peyronel et al. Nature (2012)
Harvard-MIT, Stuttgart, Chicago, ….

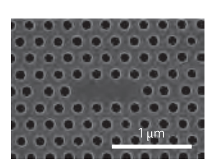
Nanophotonics

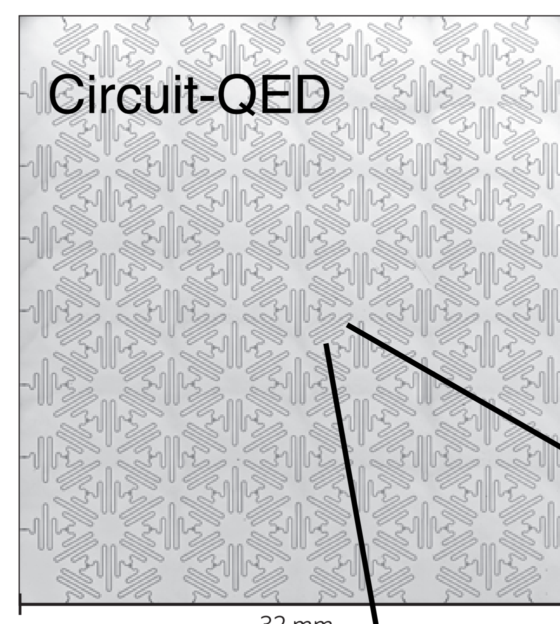


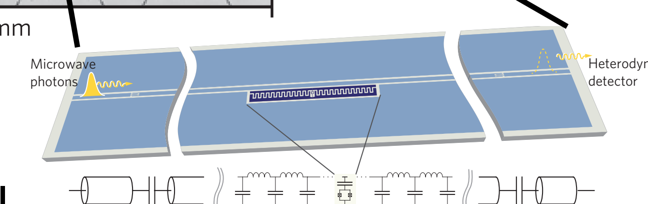
Tiecke, Thompson et al. Nature (2014)
Harvard, Caltech

solid states emitters:
Quantum dots, color centers in diamond

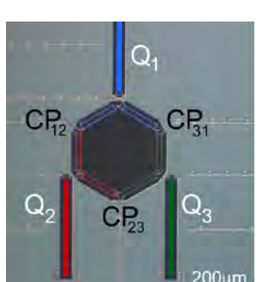








Houck, Tureci, Koch (2012)
Yale, Google, Princeton, JQI, Chicago, ….



Three sites and synthetic gauge field

arXiv:1606.00077

Fractional Quantum Hall state of light

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$$+U\hat{n}_{x,y}(\hat{n}_{x,y} - 1)$$

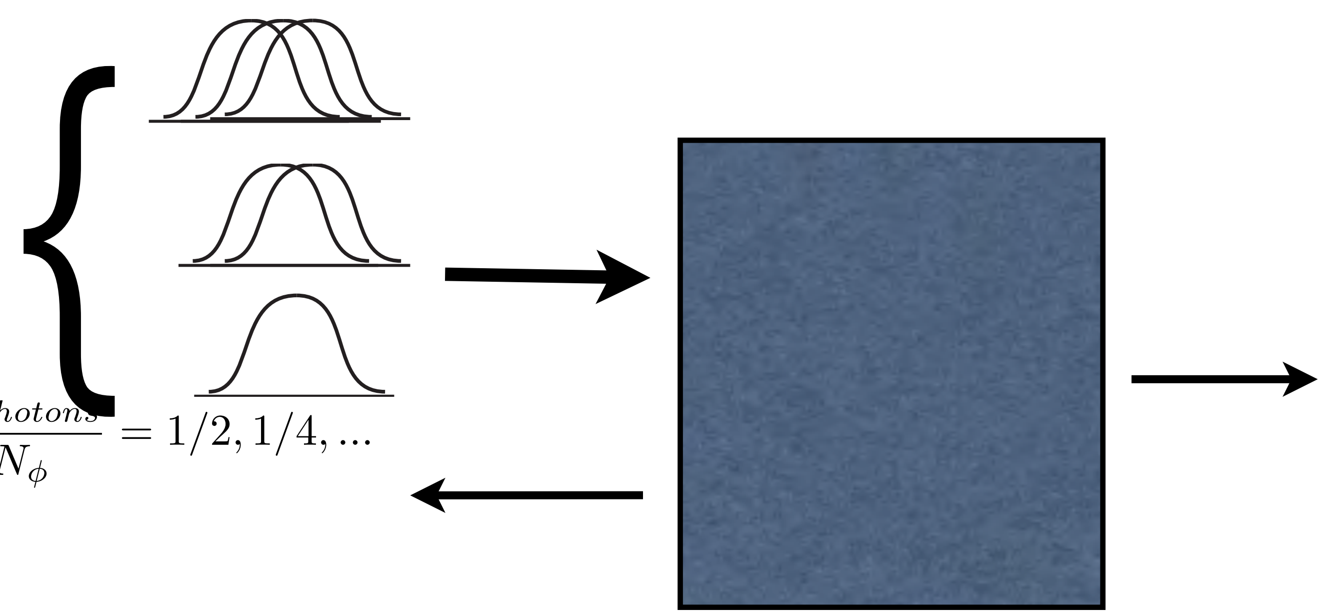
$U >> J$: photon blockade regime

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

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

Driven by a coherent state:

$$|\beta\rangle = e^{-\frac{|\beta^2|}{2}}\sum_{n=0}^{\infty}\frac{\beta^n}{\sqrt{n!}}|n\rangle$$



If the number of photons is such that $\nu = \frac{N_{photons}}{N_{\phi}} = 1/2, 1/4, ...$
then photons reorganize themselves
and form a "Laughlin state"

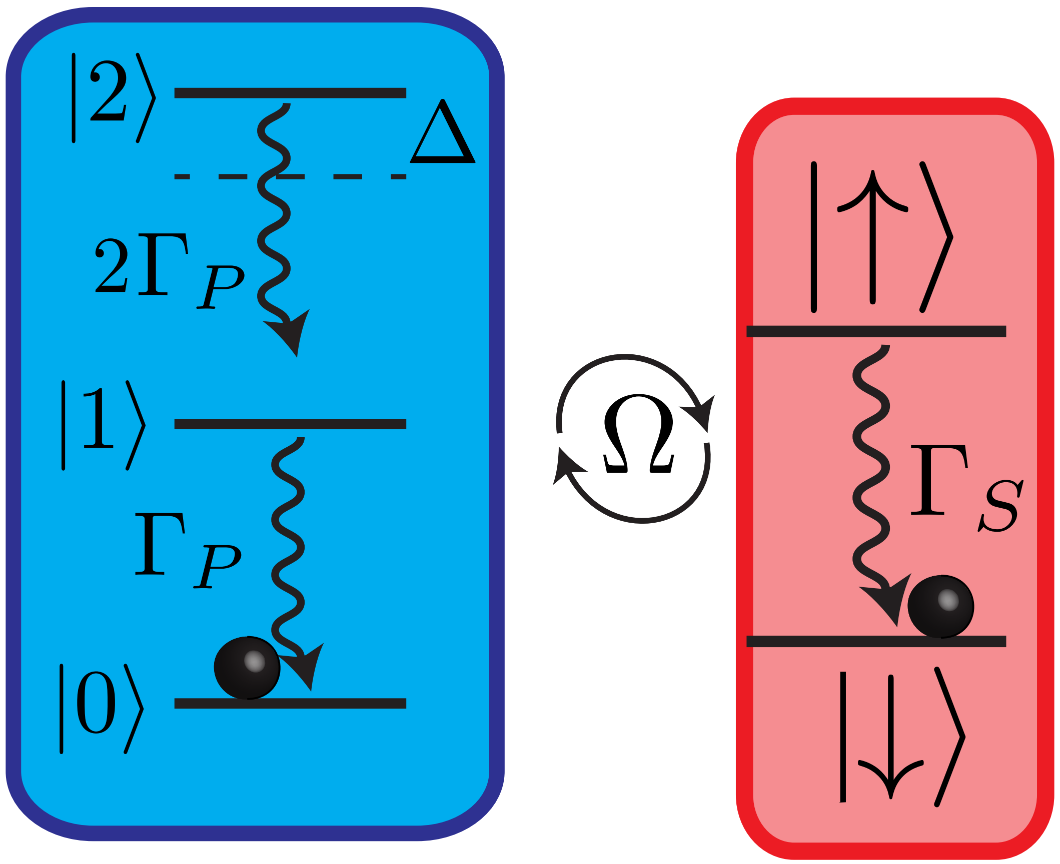
Good for a few-photon states, can not be generalized to many-body

New Journal of Physics 15, 063001 (2013)
see also: Angelakis, Carusotto, Umucalilar, Greentree, Kapit, …

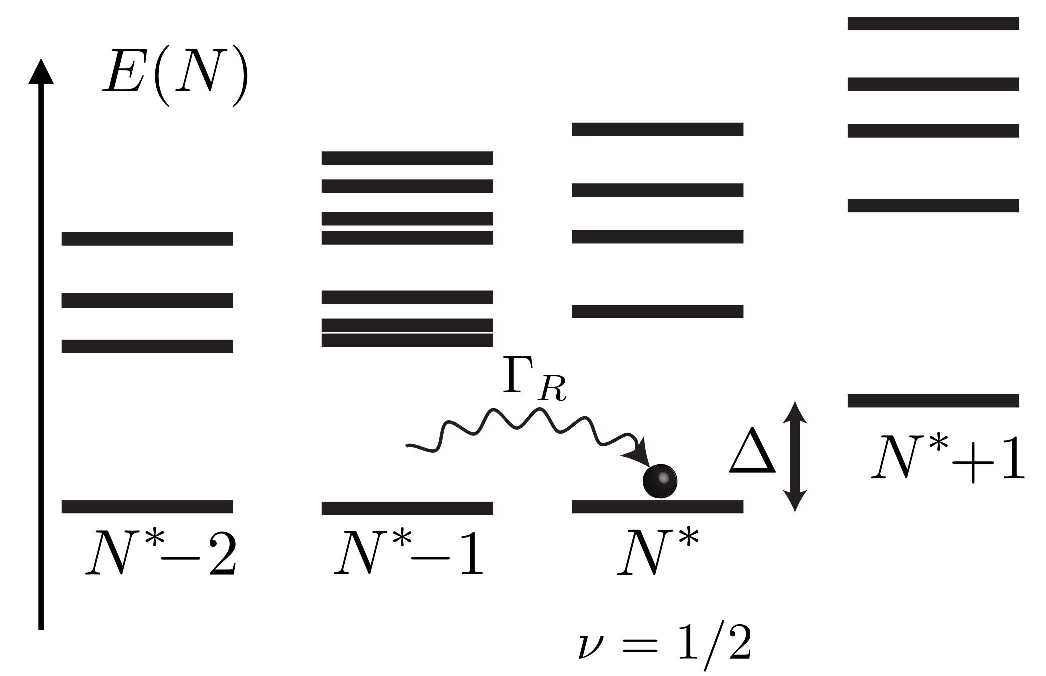
Use incompressibility (blockade) to prepare many-body states of photons

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

How to prepare a cavity in the single photon state:



Generalize to many-body case



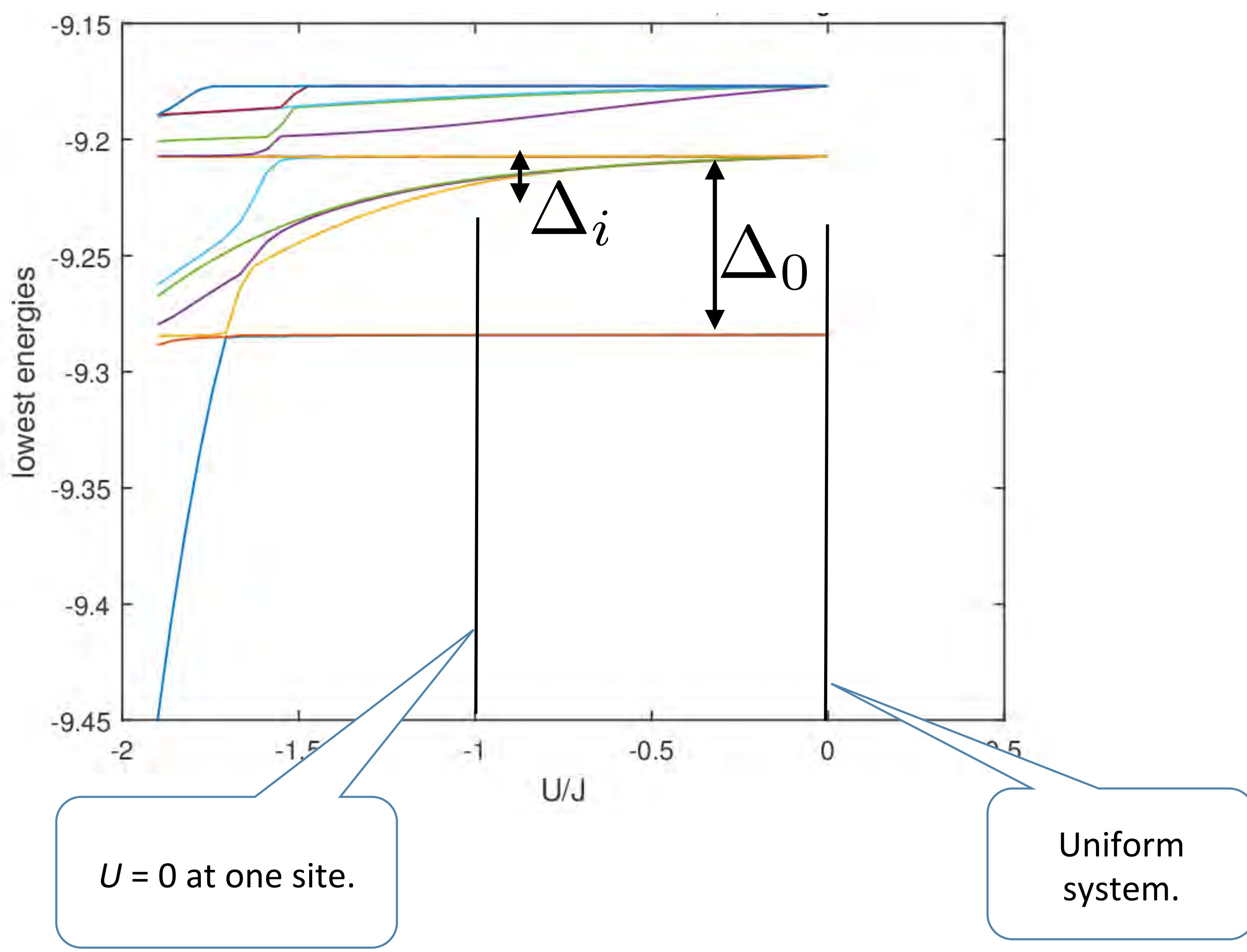
$$\Omega \cos(2\omega_0 t) \left[a_P^\dagger \sigma_S^+ + a_P \sigma_S^- \right]$$

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

E. Kapit, MH and S. Simon
PRX 2014

Stability of fractional quantum Hall states in the presence of disorder

✘ Interaction is synthetic, the hard-core condition may be violated,
e.g. some sites are non-interacting B. Anderson arXiv:1605.03177



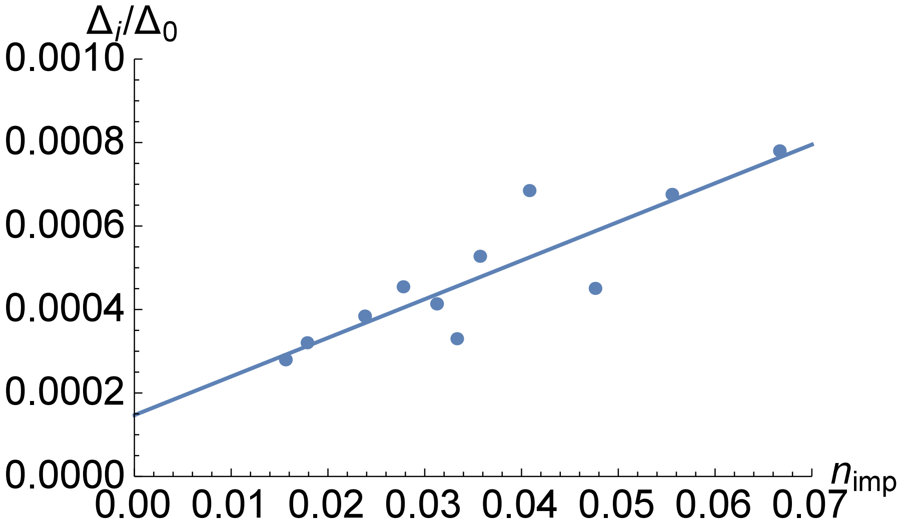
Can we expected the tunneling to save the quantum Hall states?

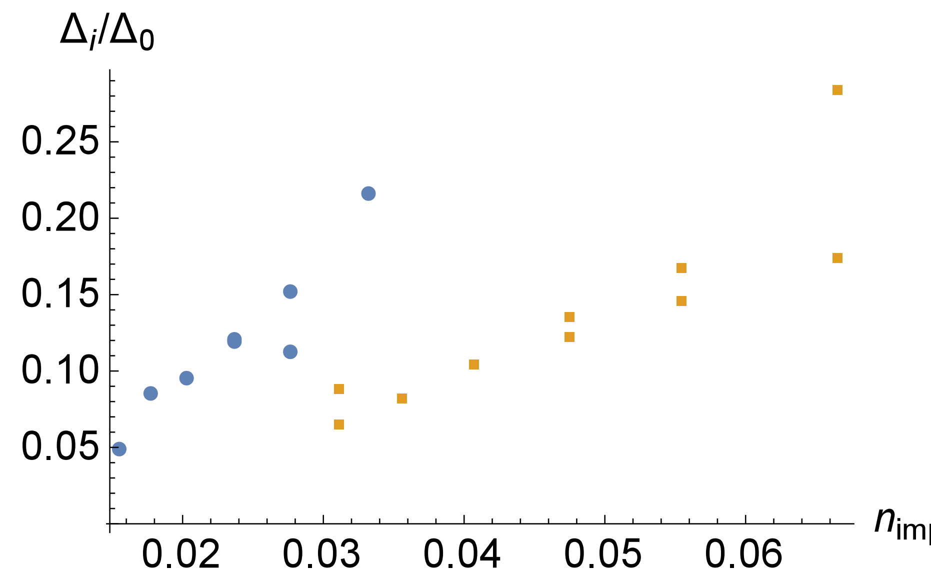
- Laughlin state remains an eigenstate, regardless of the impurity
- quasi-particles becomes energetically favorable and dive down

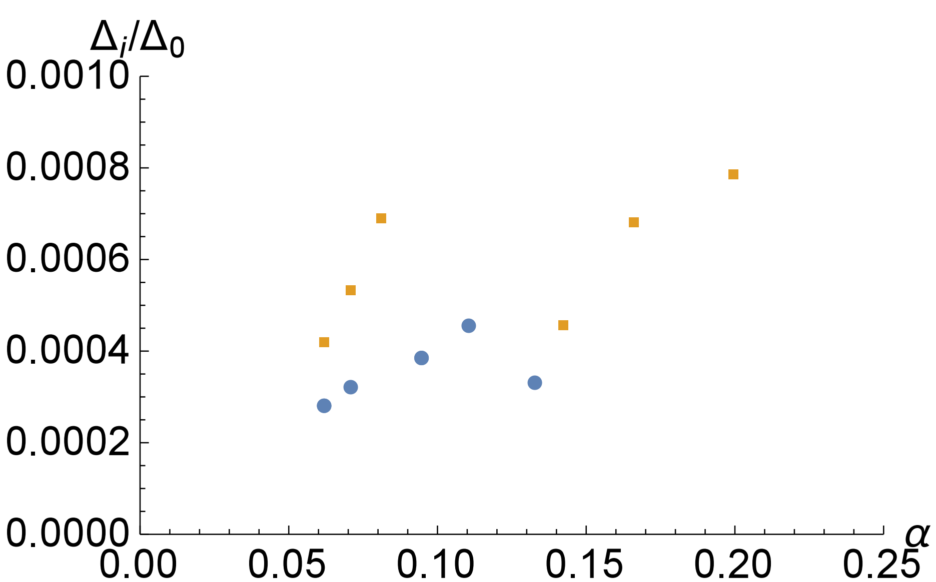
with Wade DeGottardi

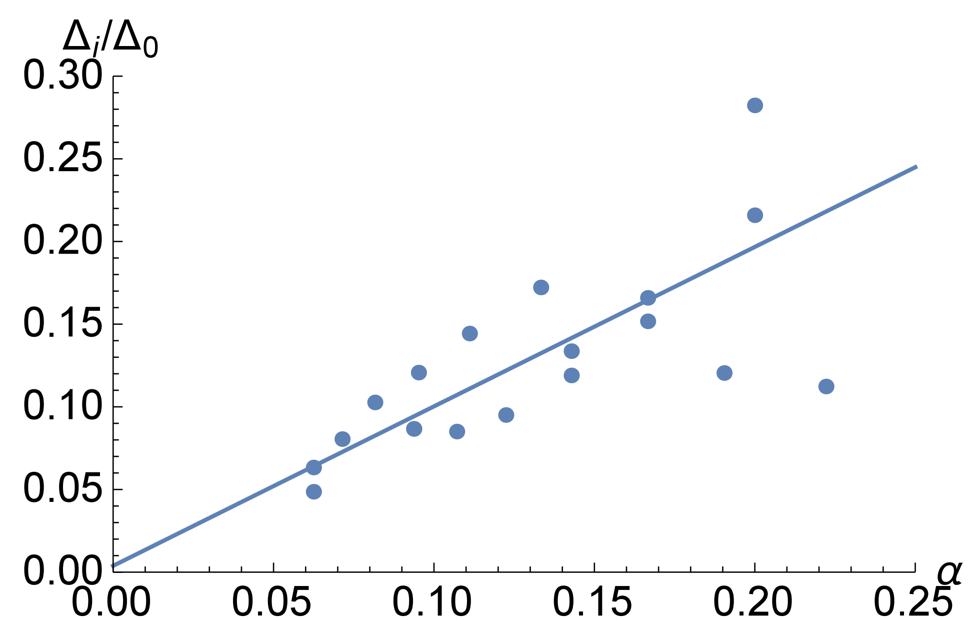
Weak impurity $U_{imp} = -0.01U$

Strong impurity $U_{imp} = -U$







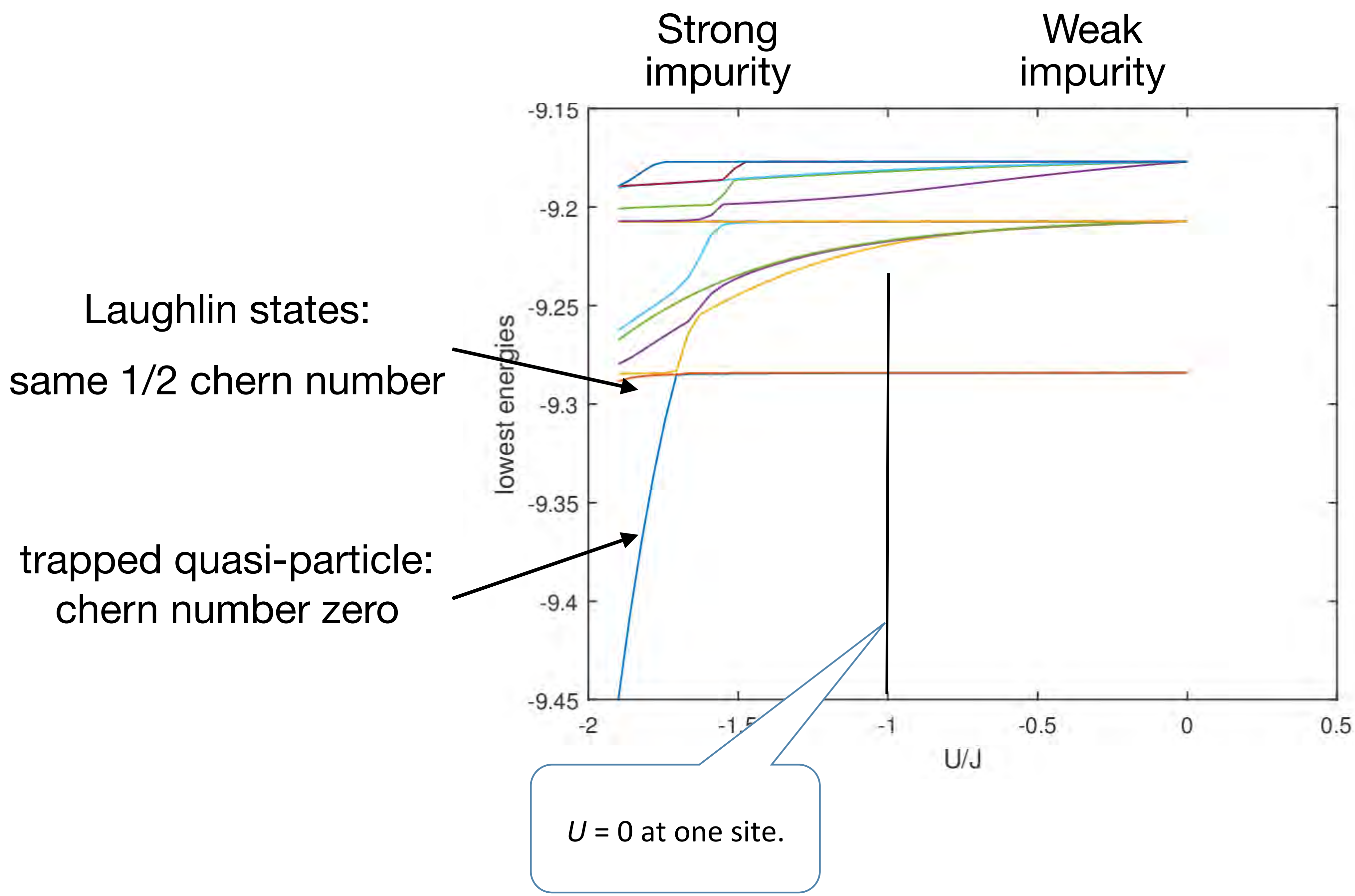


quasi-particles sample over the system:

gap is modified by the density of impurities

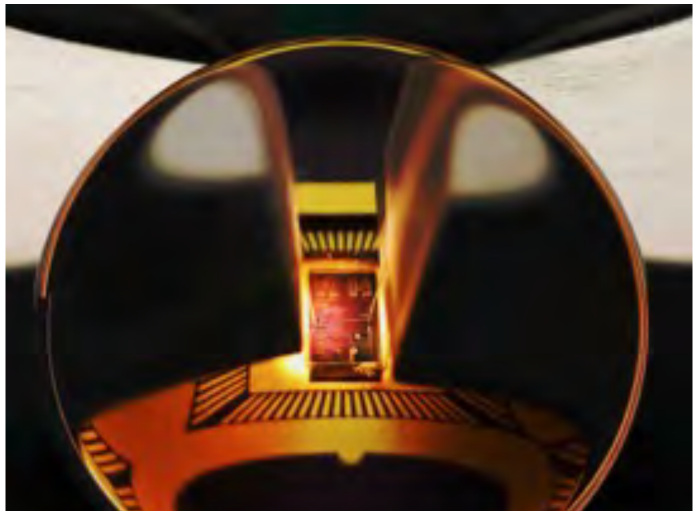
quasi-particles are trapped in one site:

gap is modified by the overlap between q-particle wavefuction and the impurity



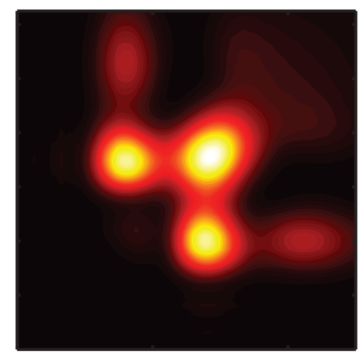
Wavefunction/ground state is modified,
transport properties remain intact ✓

Measuring topological invariants



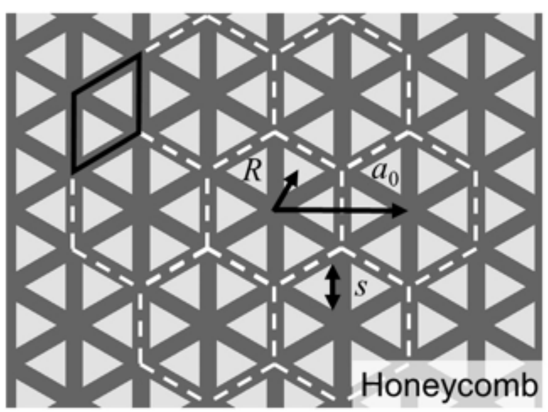
S. Mittal, S. Ganeshan, J. Fan, A. Vaezi, MH Nature Photonics 10, 180 (2016)

Propagation of non-classical light



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

Topological photonic crystals



E. Kapit, MH and S. Simon PRX 2014

S. Barik, H. Miyake, W. DeGottardi, E. Waks, M.H. arXiv:1605.08822