

Probing topological states and their robustness in photonic crystals

Ewold Verhagen

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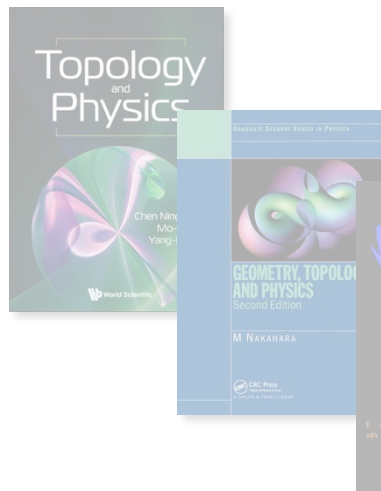
www.optomechanics.nl

René Barczyk
Nikhil Parappurath
Ewold Verhagen

Sonakshi Arora
Thomas Bauer
Filippo Alpeggiani
Kobus Kuipers



Topology in physics

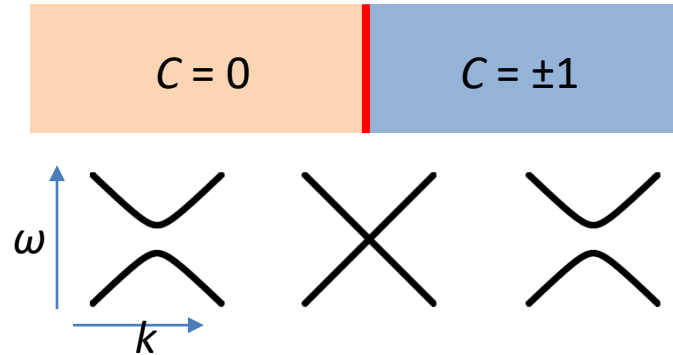


Nobel prize announcement 2016



- Topological invariant: can only take integer values
- Topological invariant of gapped system (insulator) cannot change without closing the gap

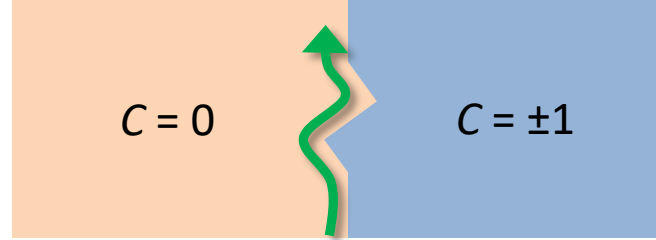
$$C = \int d\mathbf{k} f(\psi) \in \mathbb{Z}$$



→ **Protected edge states at interfaces between materials with different topological invariants**

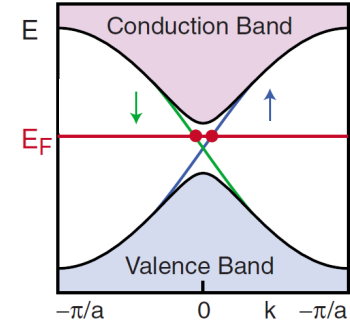
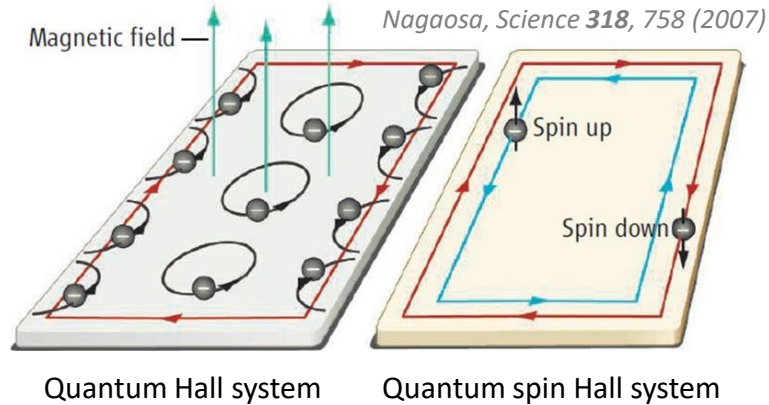
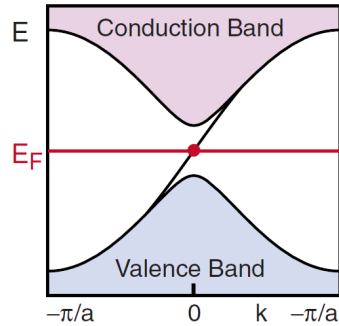
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$$C = \int d\mathbf{k} f(\psi) \in \mathbb{Z}$$



→ ***Protected edge states at interfaces between materials with different topological invariants***

Types of topological insulators



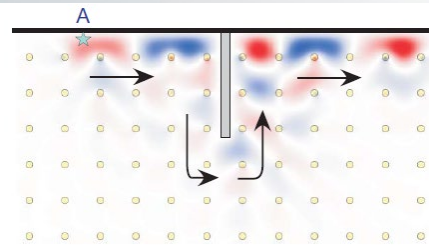
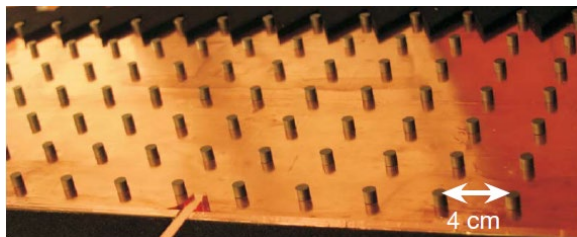
Quantum Hall Effect

- **Magnetic field** breaks time-reversal symmetry
- Unidirectional edge states allow conduction

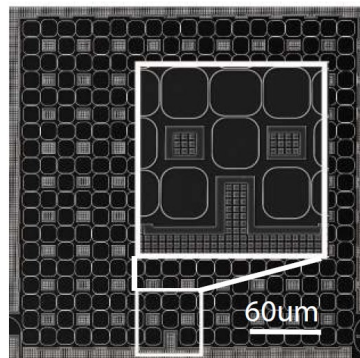
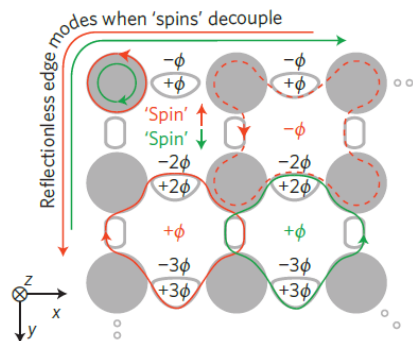
Quantum Spin Hall Effect (QSHE)

- **Spin-orbit coupling** creates pseudomagnetic field for each spin
- Time-reversal symmetry protects edge states

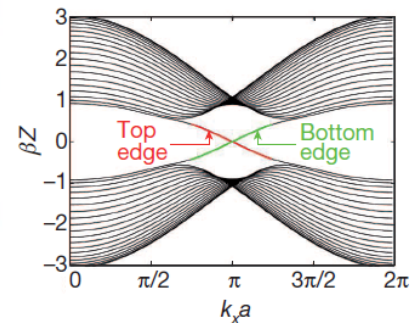
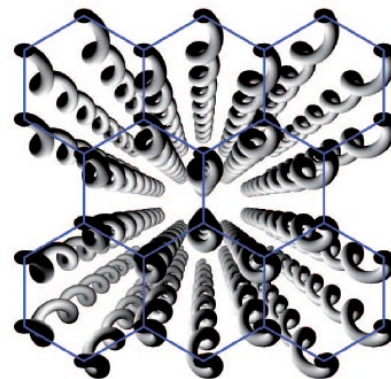
Photonic topological insulators



Soljačić group



Hafezi, Taylor groups



Rechtsman, Segev, Szameit groups

reviews: *Nat. Photon.* **8**, 821 (2014), *Rev. Mod. Phys.* **91**, 015006 (2019), *Nanophoton.* **10**, 425 (2021)

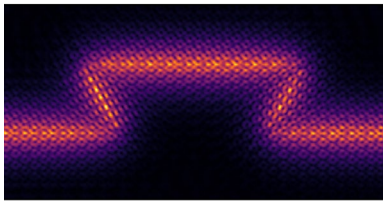
Topological light *at the nanoscale?*

How?

Limits to protection?

What functions can we protect?

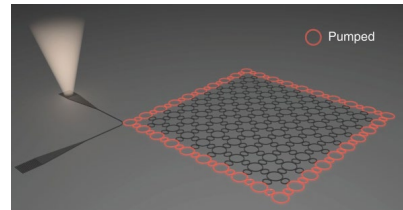
guiding & routing



Arora et al., Light Sci. Appl. 10, 9 (2021)

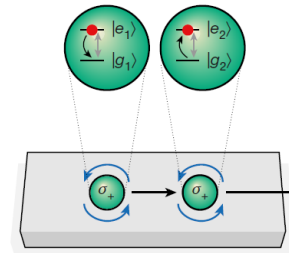
Nanolight 2022

lasing



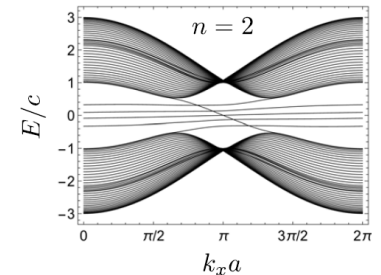
Bandres et al., Science 359, 1231 (2018)

quantum networks



Lodahl et al., Nature 541, 473 (2017)

slow light



Guglielmon & Rechtsman, PRL 122, 153904 (2019)

Ewold Verhagen

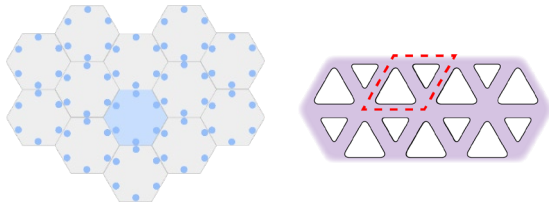
Mimicking QSHE using (photonic) crystals

Fu, PRL 106, 106802 (2011)

Wu & Hu, PRL 114, 223901 (2015)

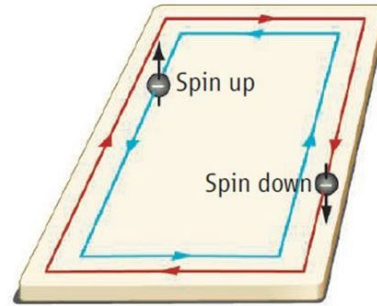
Barik et al., NJP 18, 113013 (2016)

Ma & Shvets, NJP 18, 025012 (2016)



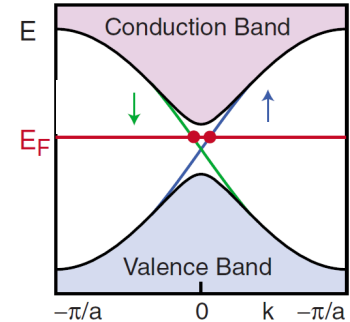
- Crystal symmetry protects edge states

Nagaosa, Science 318, 758 (2007)



Quantum spin Hall system

Hasan & Kane, RMP 82, 3045 (2010)



Quantum Spin Hall Effect (QSHE)

- **Spin-orbit coupling** creates pseudomagnetic field for each spin
- Time-reversal symmetry protects edge states

Photonic topological insulators

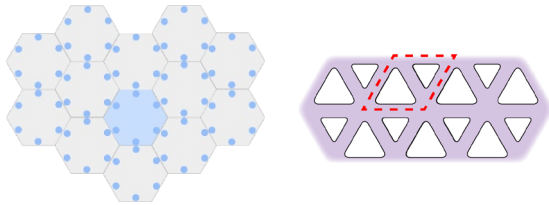
Mimicking QSHE using (photonic) crystals

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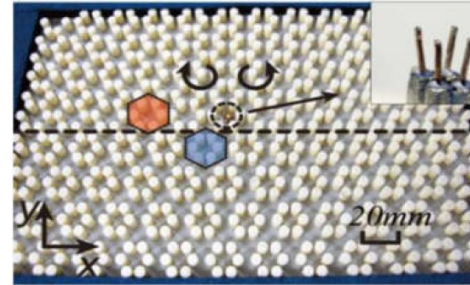
Wu & Hu, PRL 114, 223901 (2015)

Barik et al., NJP 18, 113013 (2016)

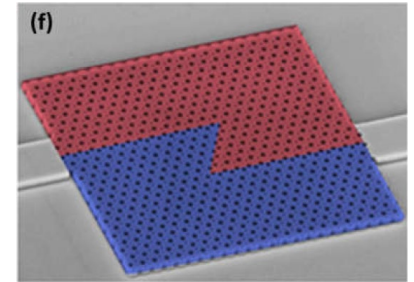
Ma & Shvets, NJP 18, 025012 (2016)



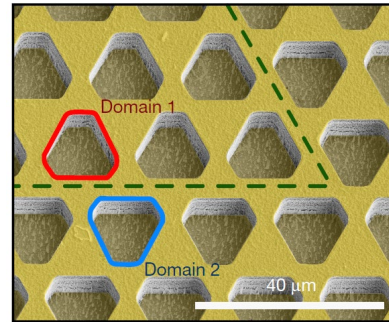
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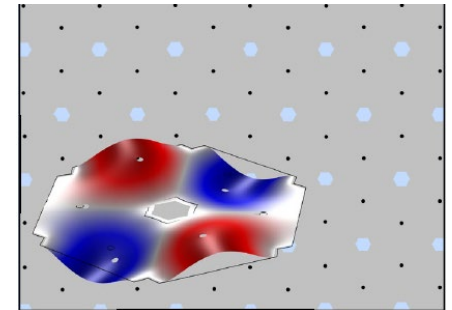
Yang et al., PRL 120, 217401 (2018)



He et al., Nat. Commun. 10, 872 (2019)



Zeng et al., Nature 578, 246 (2020)



Cha et al., Nature 564, 229 (2018)

Parappurath et al.,
Sci. Adv. 6, eaaw4137 (2020)

theoretical concept:

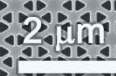
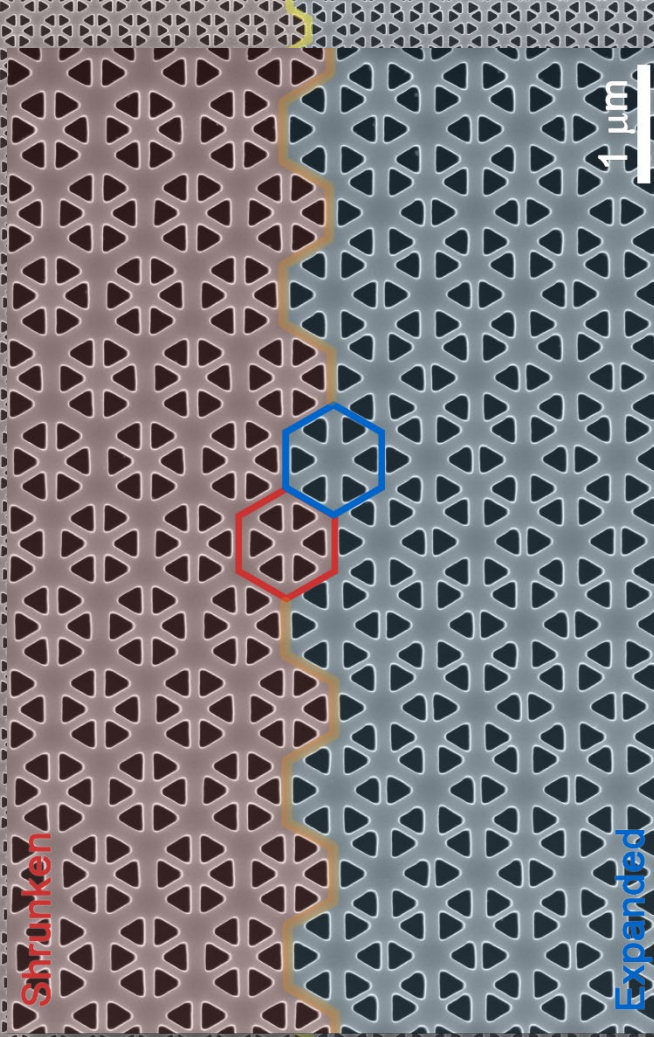
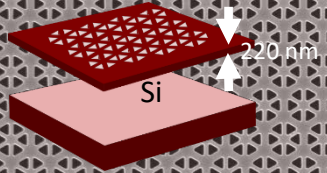
Wu and Hu, *PRL* 114, 223901 (2015)

Barik et al., *NJP* 18, 113013 (2016)

see other experimental work by:

Gorlach et al., *Nat. Commun.* 9, 909 (2018)

Barik et al., *Science* 359, 666 (2018)

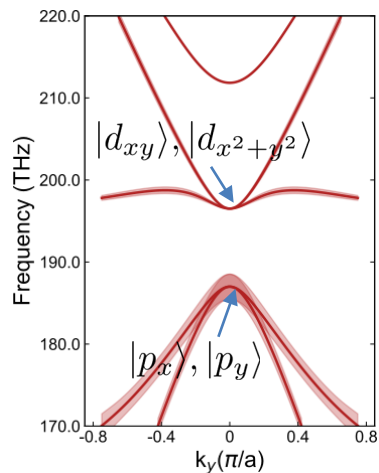


Parappurath et al.,
Sci. Adv. 6, eaaw4137 (2020)

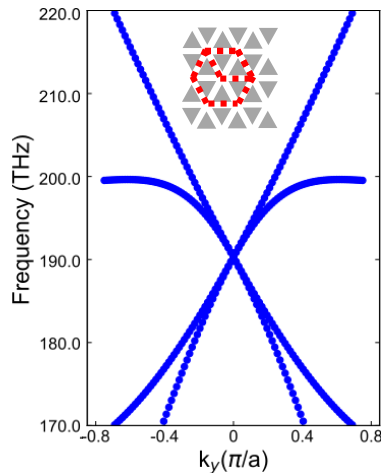
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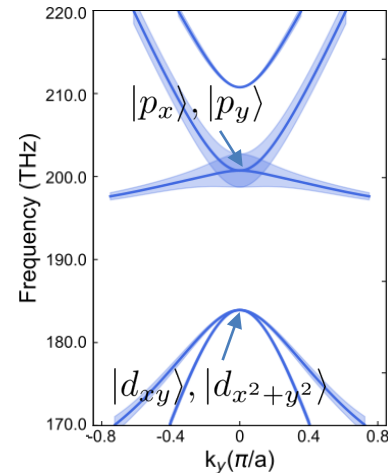
'shrunken' lattice



'ordinary' lattice



'expanded' lattice



Shrunken

Expanded

Parappurath et al.,
Sci. Adv. 6, eaaw4137 (2020)

theoretical concept:

Wu and Hu, PRL 114, 223901 (2015)
Barik et al., NJP 18, 113013 (2016)

see other experimental work by:

Gorlach et al., Nat. Commun. 9, 909 (2018)
Barik et al., Science 359, 666 (2018)

$|p_x\rangle + i|p_y\rangle$

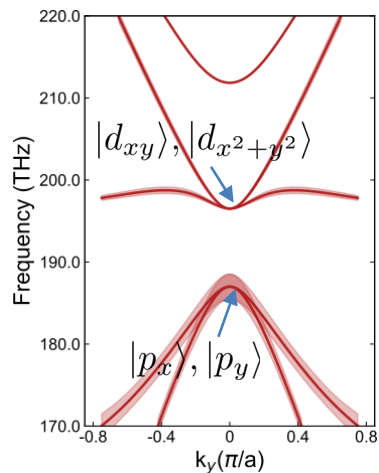
$|p_x\rangle - i|p_y\rangle$

1 μm

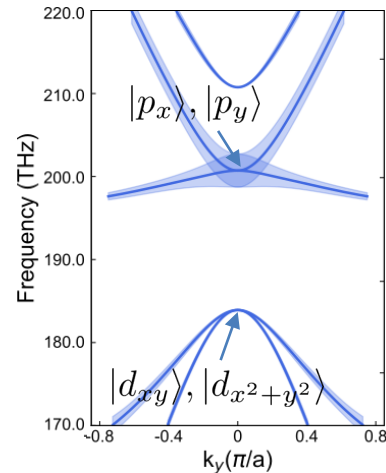
Shrunken

Expanded

'shrunken' lattice

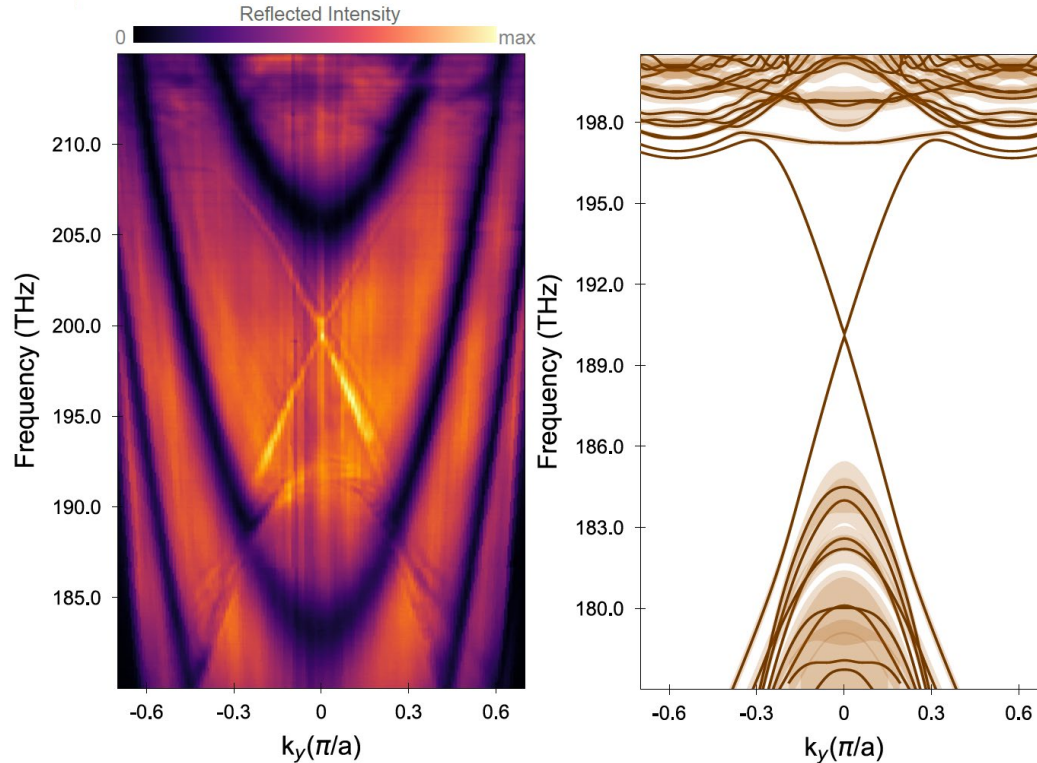


'expanded' lattice



Edge state dispersion

Reflection spectroscopy:

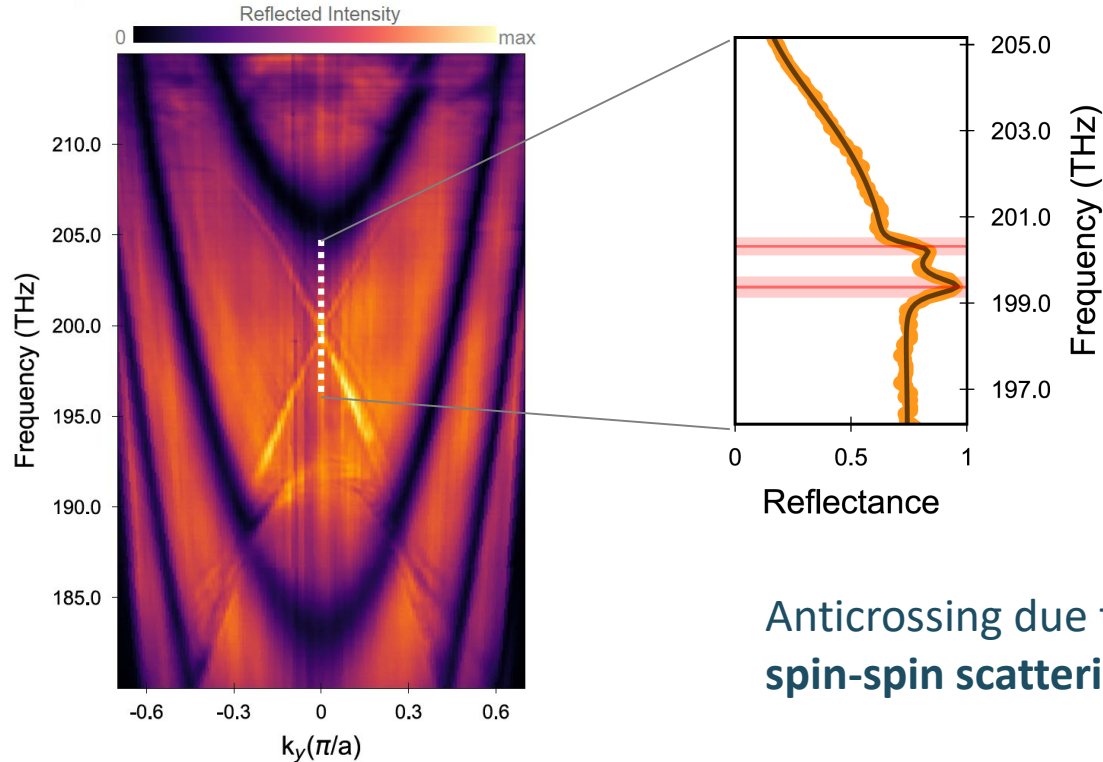


Far-field Fourier spectroscopy shows characteristic linear dispersion of QSHE edge states

$$v_g \approx c/6$$
$$Q \approx 450$$

Edge state dispersion

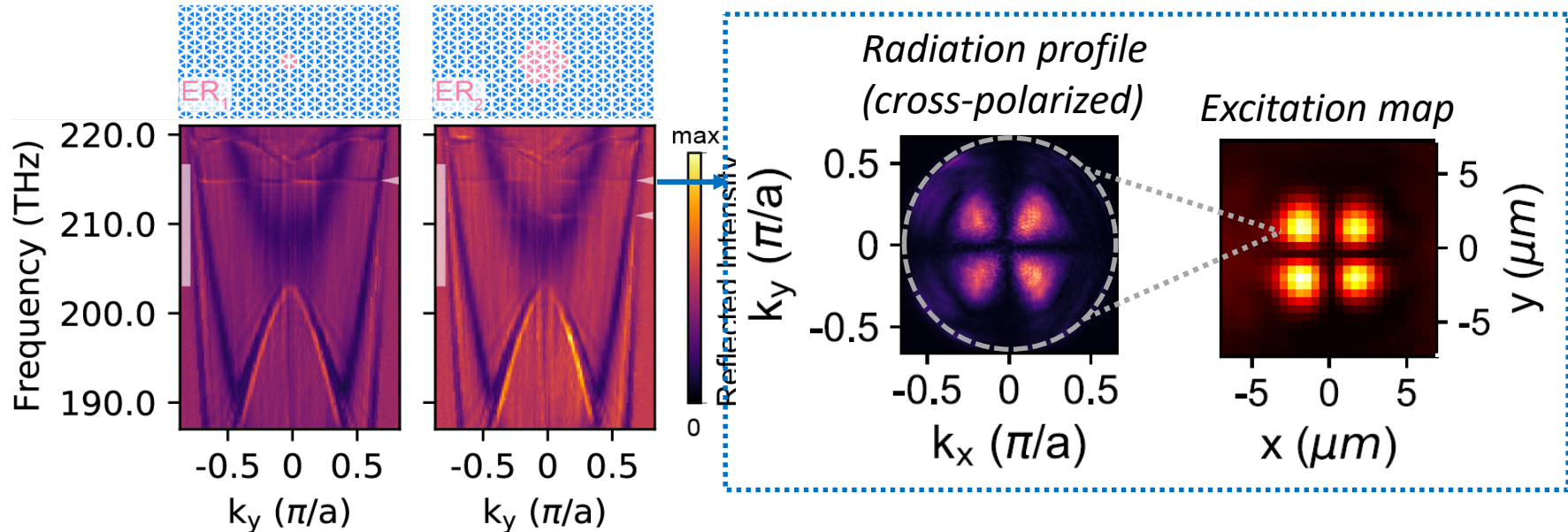
Reflection spectroscopy:



*C_6 symmetry
inherently
broken at edge*

Anticrossing due to **intrinsic spin-spin scattering** observed

Characterizing topological cavities through leakage radiation

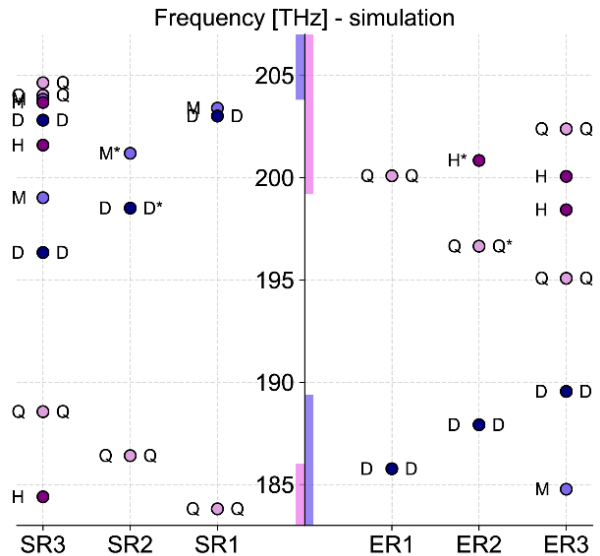
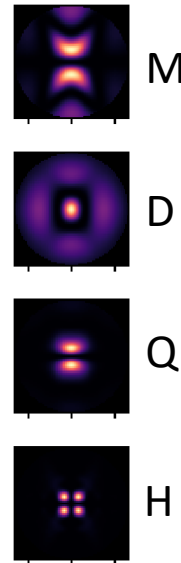
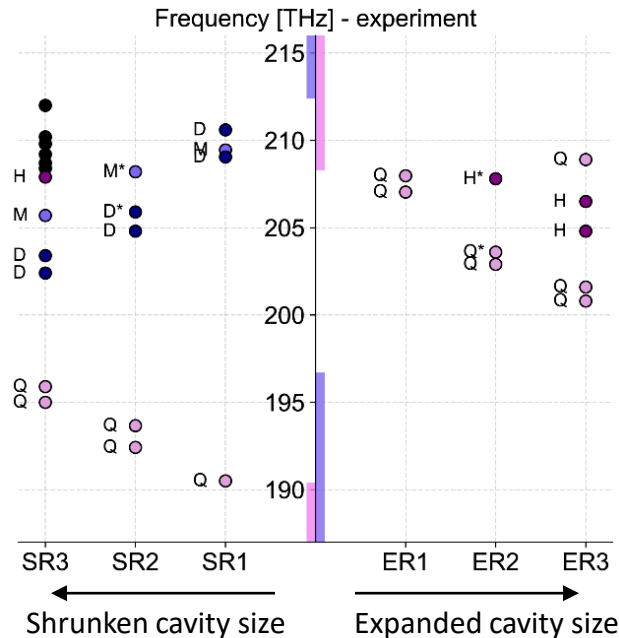


Topological cavities

Characterizing topological cavities through leakage radiation

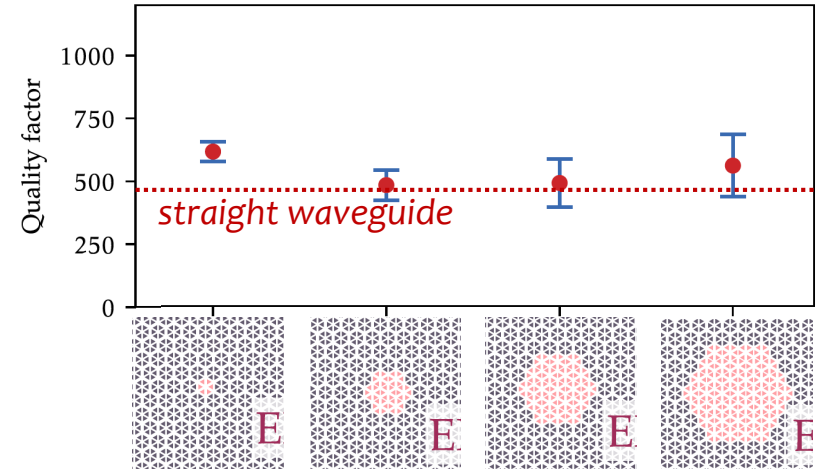
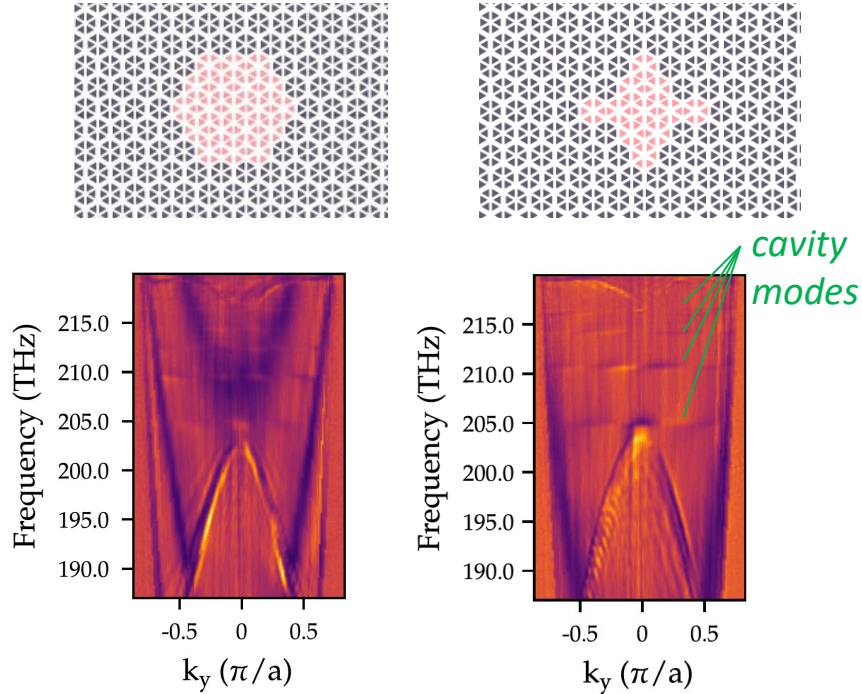
→ multipolar nature linked to band inversion

cf. Yu et. al. Natl. Sci. Rev. 8, nwa262 (2021)



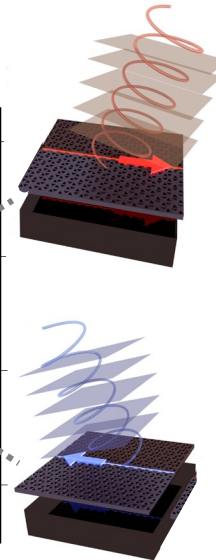
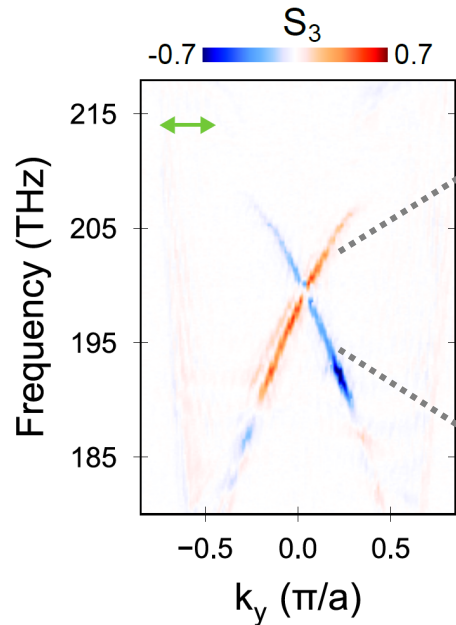
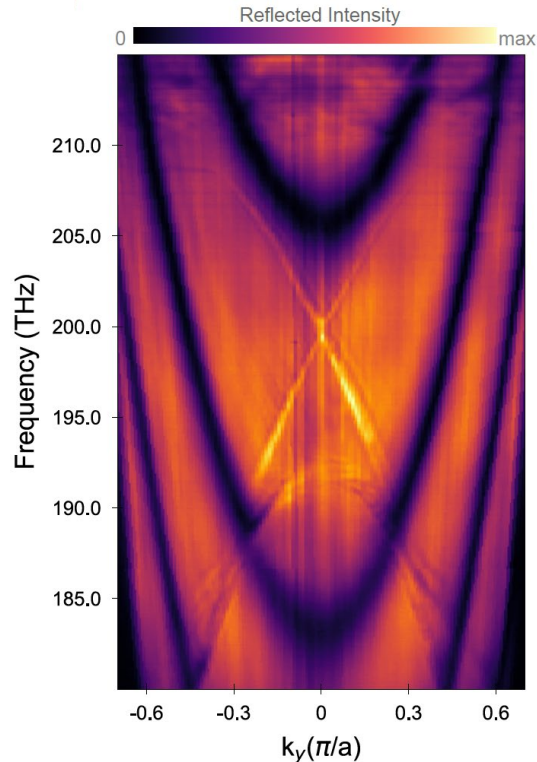
Barczyk et al., arXiv:2202.07620

Topological cavities



Topological cavity Q is independent
of size and shape

Edge state polarimetry



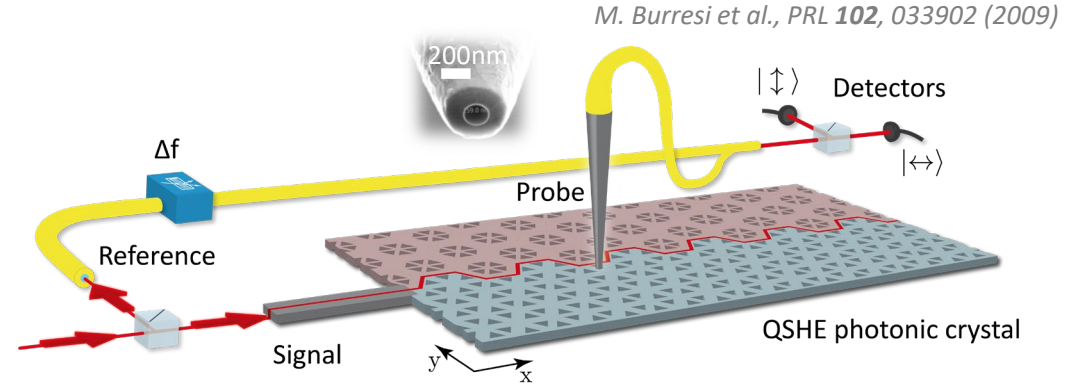
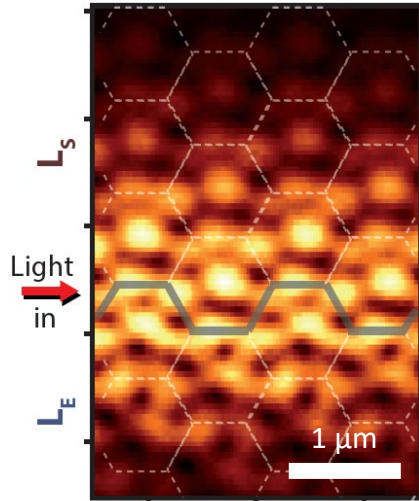
Tight-binding
Hamiltonian block-
diagonal in basis

$$|p_{\pm}\rangle = (|p_x\rangle \pm i|p_y\rangle)/\sqrt{2}$$

Polarimetry reveals
edge state pseudospin
as polarization
handedness of far field

Topological photonic near fields

Near-field scanning optical microscopy

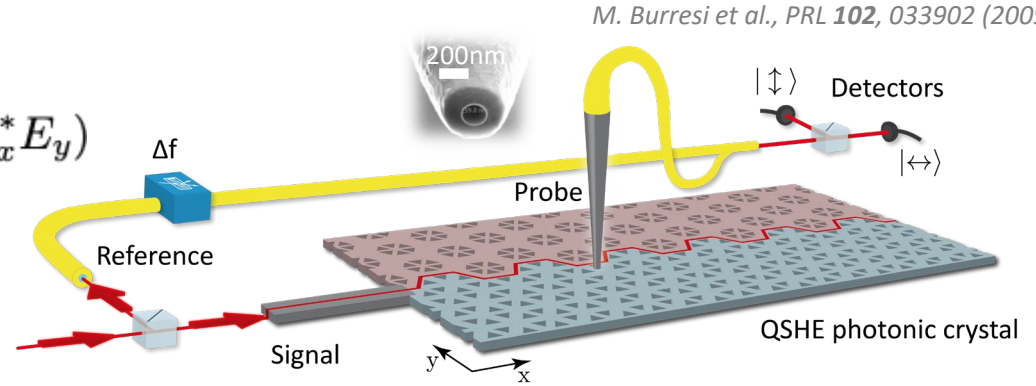
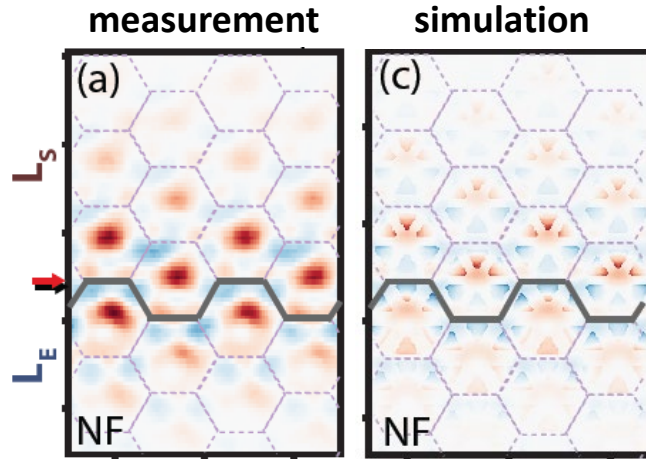


Arora et al., arXiv:2202.04402

Spin and helicity at the nanoscale

Near-field scanning optical microscopy

Determine local spin density $\sigma_z \sim \Im(E_x^* E_y)$



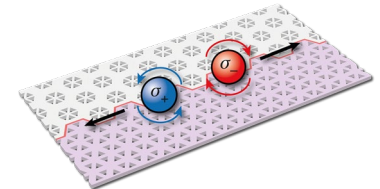
M. Burrese et al., *PRL* **102**, 033902 (2009)

Near-field spin density is highly structured

cf. Proctor, Craster, Maier, Giannini, Huidobro,
ACS Photon. **6**, 2985 (2019)

Spin-photon interface?

Barik et al., "A topological quantum optics
interface," *Science* **359**, 666 (2018)

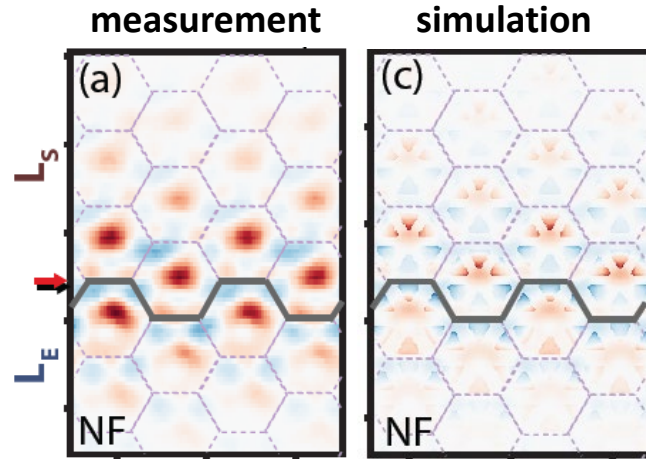


Arora et al., *arXiv:2202.04402*

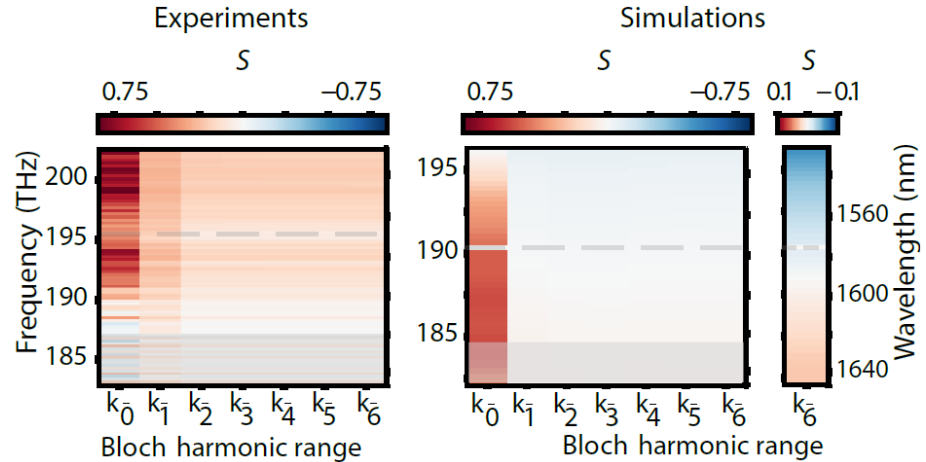
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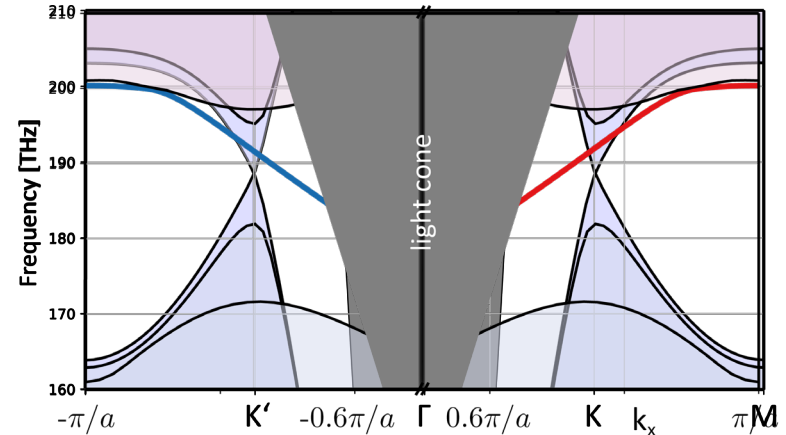
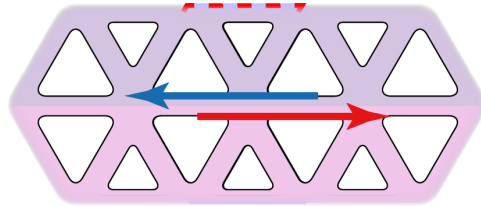
Integrated spin density vs range of included spatial frequencies:



Breakdown of spin-helicity locking at nanoscale

Photonic analogue of quantum valley Hall effect (QVHE)

- Dirac cone at K/K' points with two-fold degeneracy
- Breaking symmetry opens gap – with valley-dependent local topological invariant
- Domain walls result in **edge states**, associated with valley pseudospin

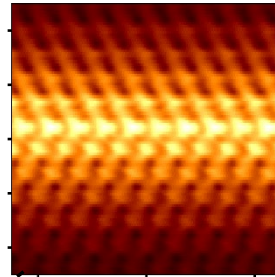


Ma & Shvets, *New J. Phys.* **18**, 025012 (2016)

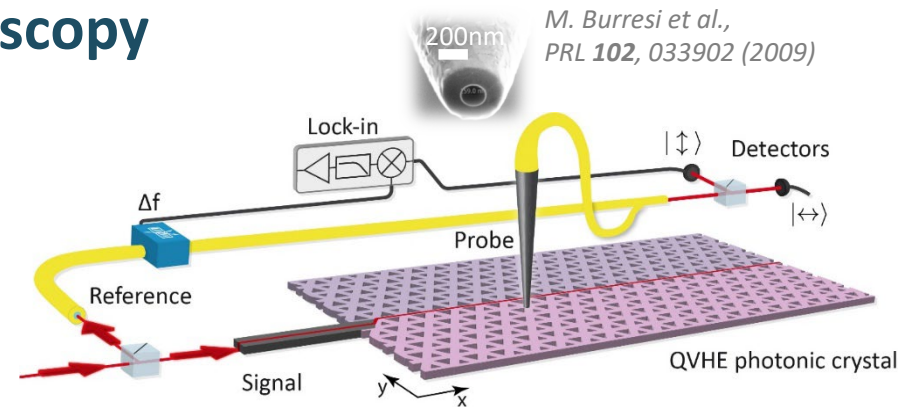
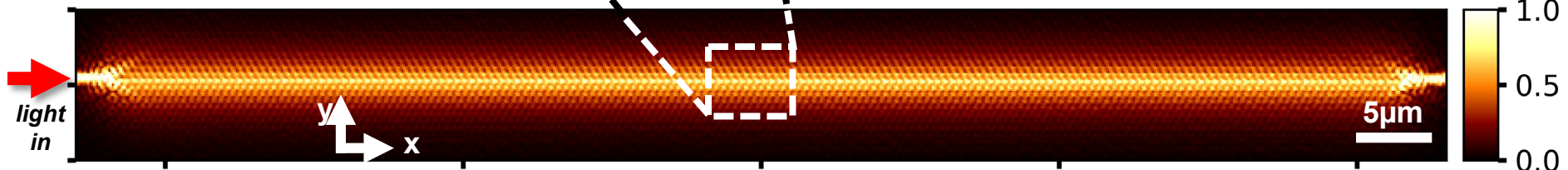
Shalaev et al., *Nature Nanotech.* **14**, 31 (2019)

Near-field scanning optical microscopy

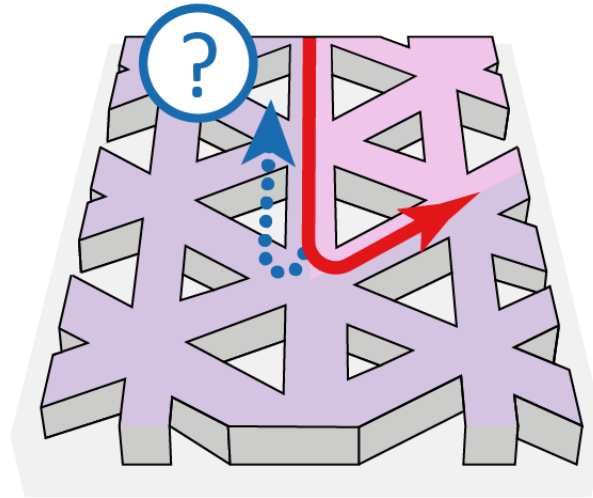
- QVHE-like edge state with in-plane momentum **outside the light cone**
- Observe negligible propagation loss



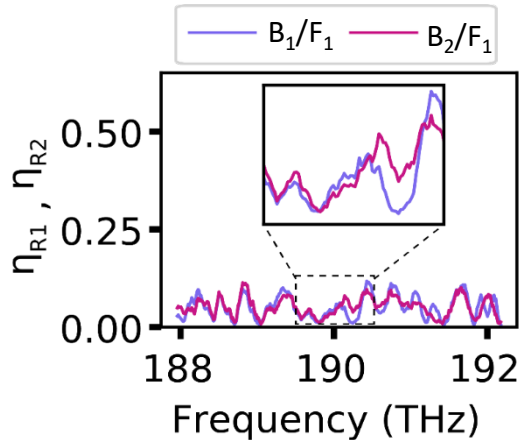
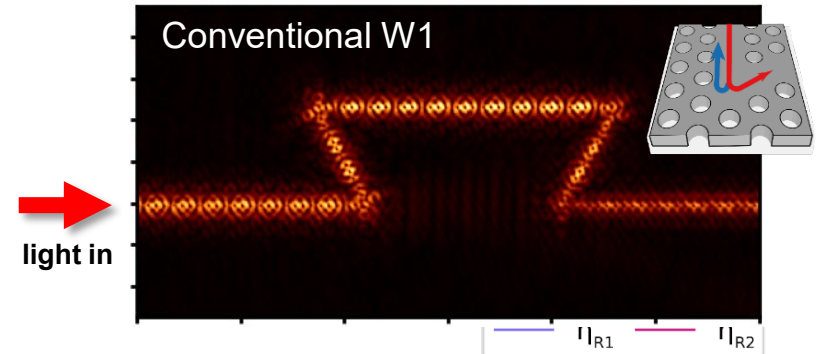
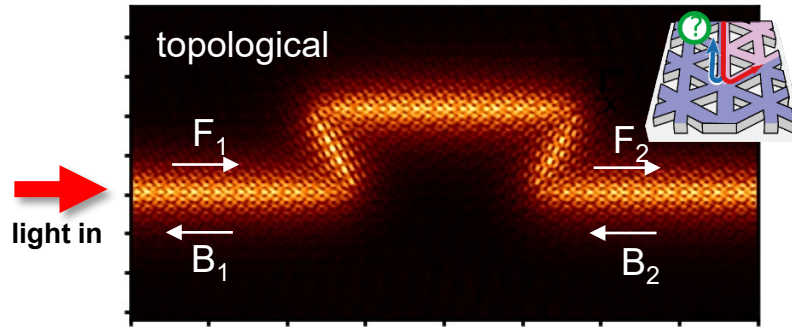
Measured amplitude @1600 nm:



Topological protection at sharp corners?



Quantifying topological protection

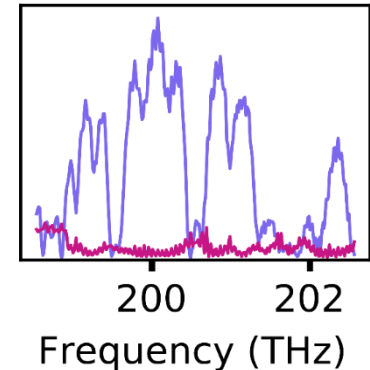


Topological:

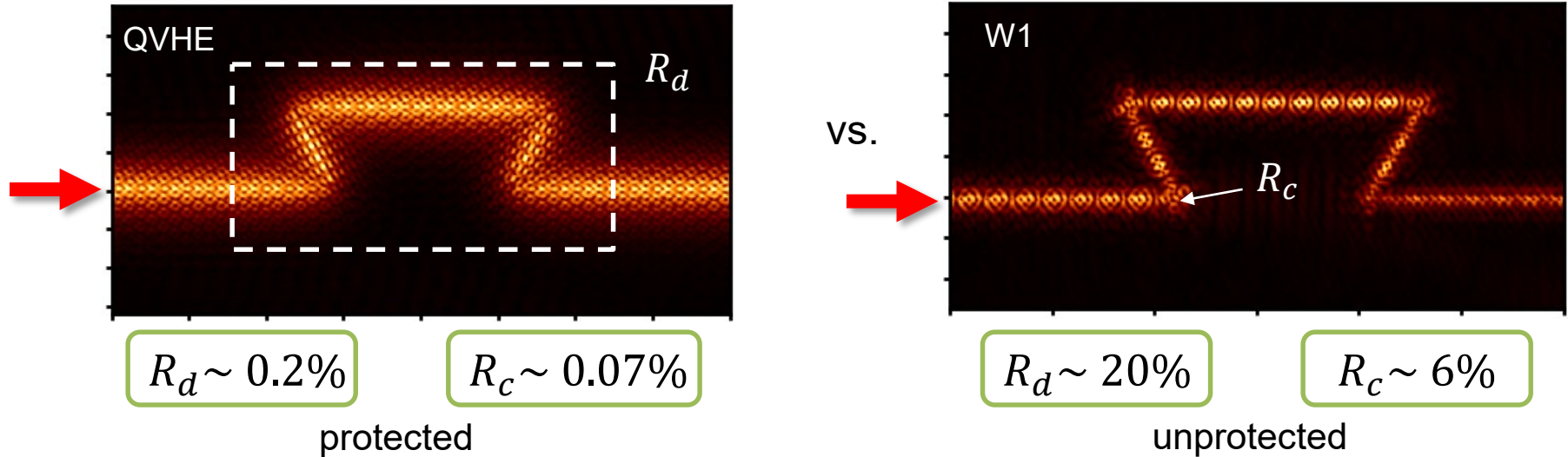
Reflection dominated by end facet

Conventional W1 waveguide:

Strong reflection from each corner



Quantifying topological protection



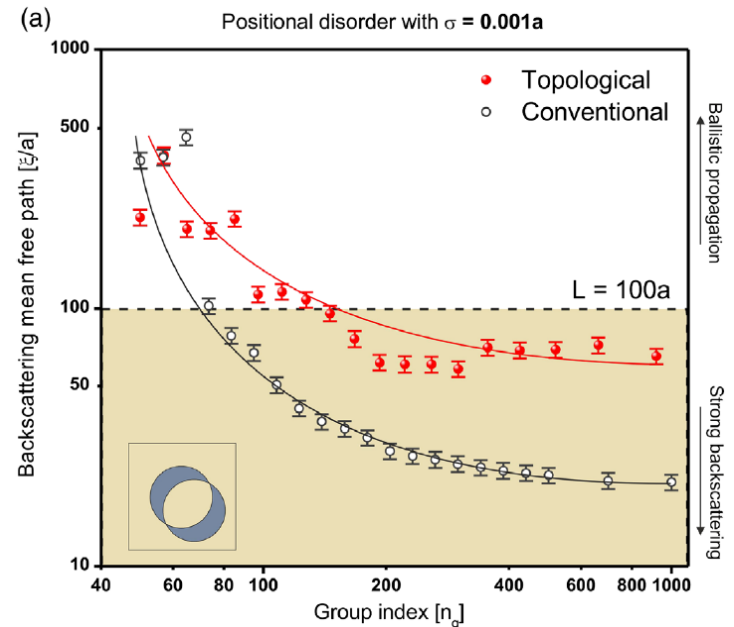
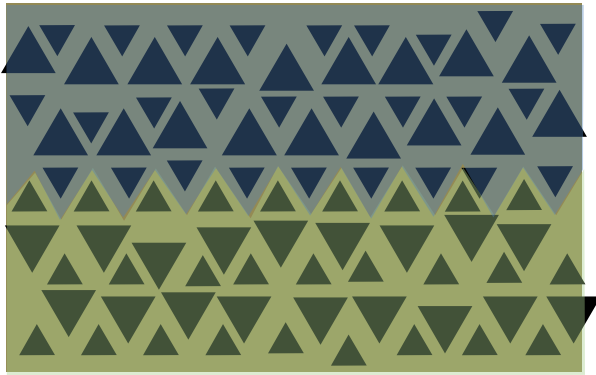
Comparison to transfer matrix model:

Frequency-averaged corner reflectance: $<0.1\%$

What about disorder that breaks the protecting crystal symmetry?

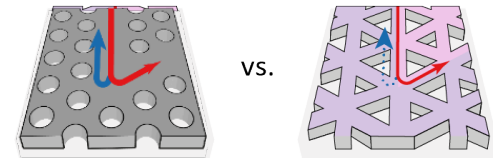
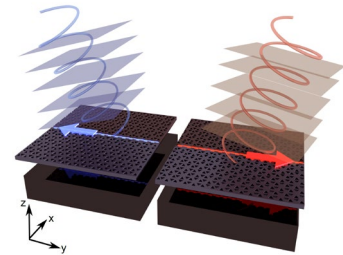
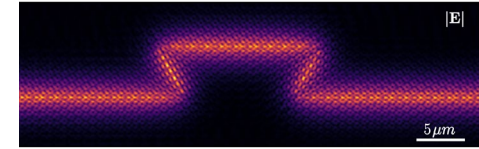
Orazbayev & Fleury, Nanophotonics 8, 1433 (2019)

Arregui, Gomiz-Bresco, Sotomayor-Torres, David Garcia,
PRL 126, 027403 (2021)



Conclusions

- Topological photonic crystals: design paradigm for controlling fields & propagation
- Band inversion & spin-orbit coupling control far-field emission
- Breakdown of spin-helicity connection at the nanoscale
- Topological robustness quantified through phase-resolved near-field imaging



Parappurath et al., *Sci. Adv.* 6, eaaw4137 (2020)
Arora et al., *Light Sci. Appl.* 10, 9 (2021)

Arora et al., arXiv:2202.04402
Barczyk et al., arXiv:2202.07620

Thank you

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Michele Cotrufo

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Thomas Bauer
Filippo Alpeggiani
Kobus Kuipers



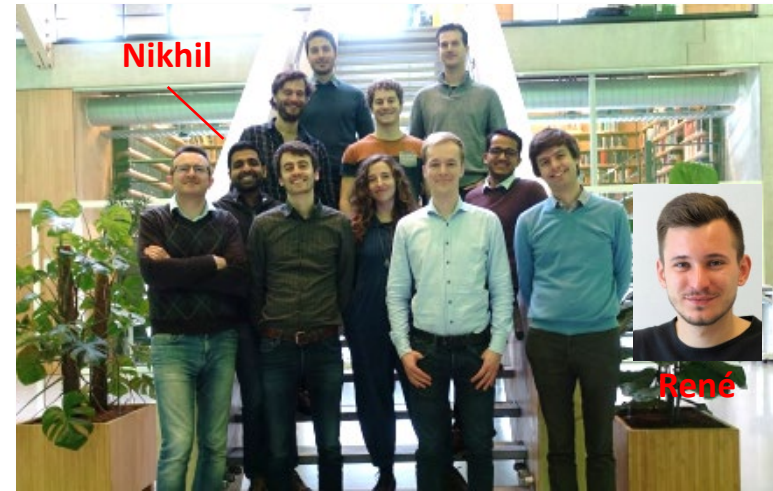
Sonakshi



Thomas



Kobus



www.optomechanics.nl

