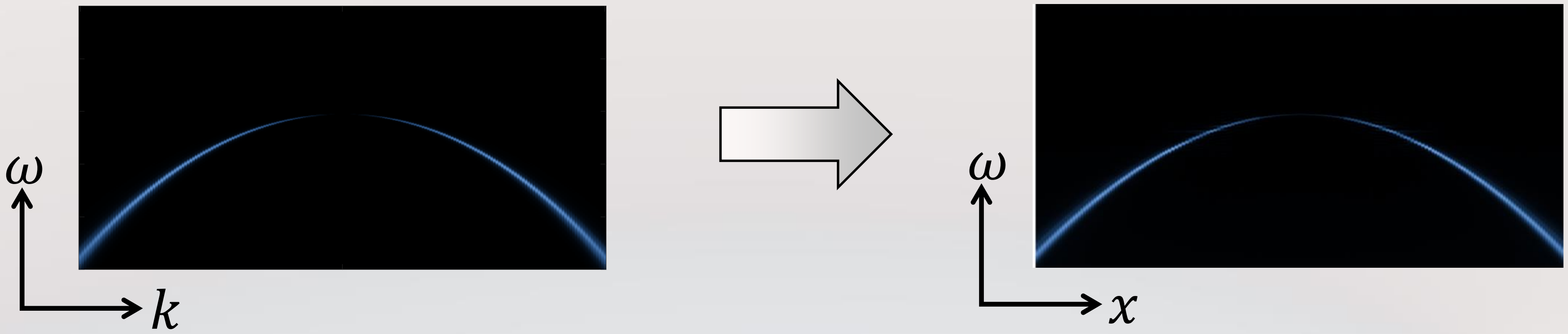
Nonlocal metasurfaces for control of light beyond the Generalized Snell's Law



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EM Portfolio Review, Dr. Arje Nachman

January 7, 2025

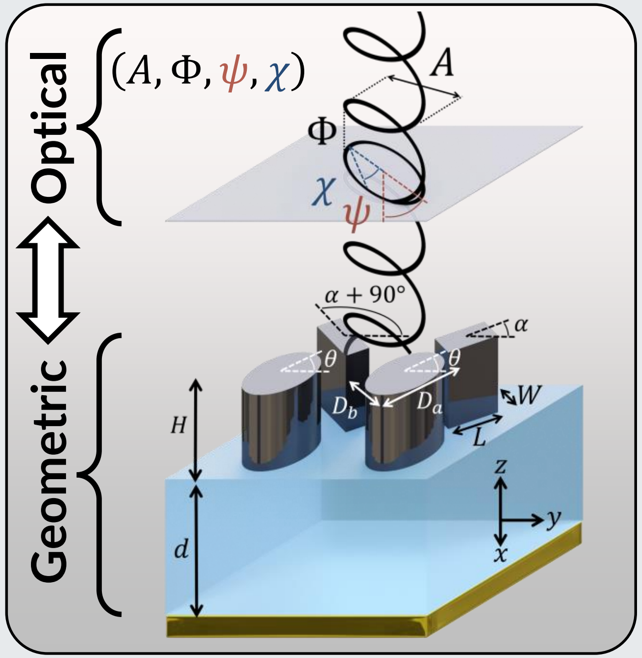
aovervig@stevens.edu

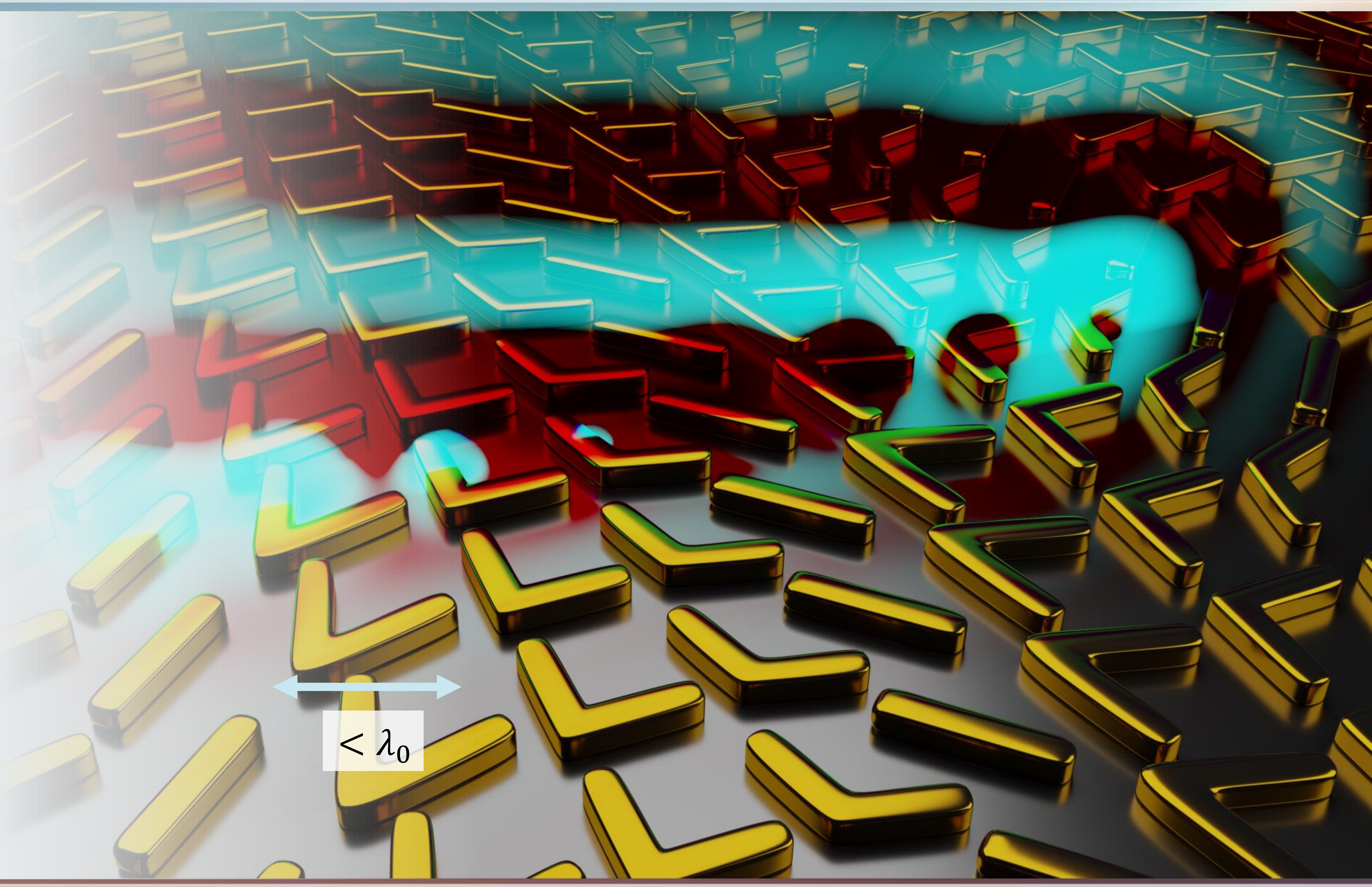
Field: Metasurfaces

‘**Meta-**’ era of optics

Less:
“how does light behave?”
More:
“how do we *make* light behave?”

Degrees of Freedom





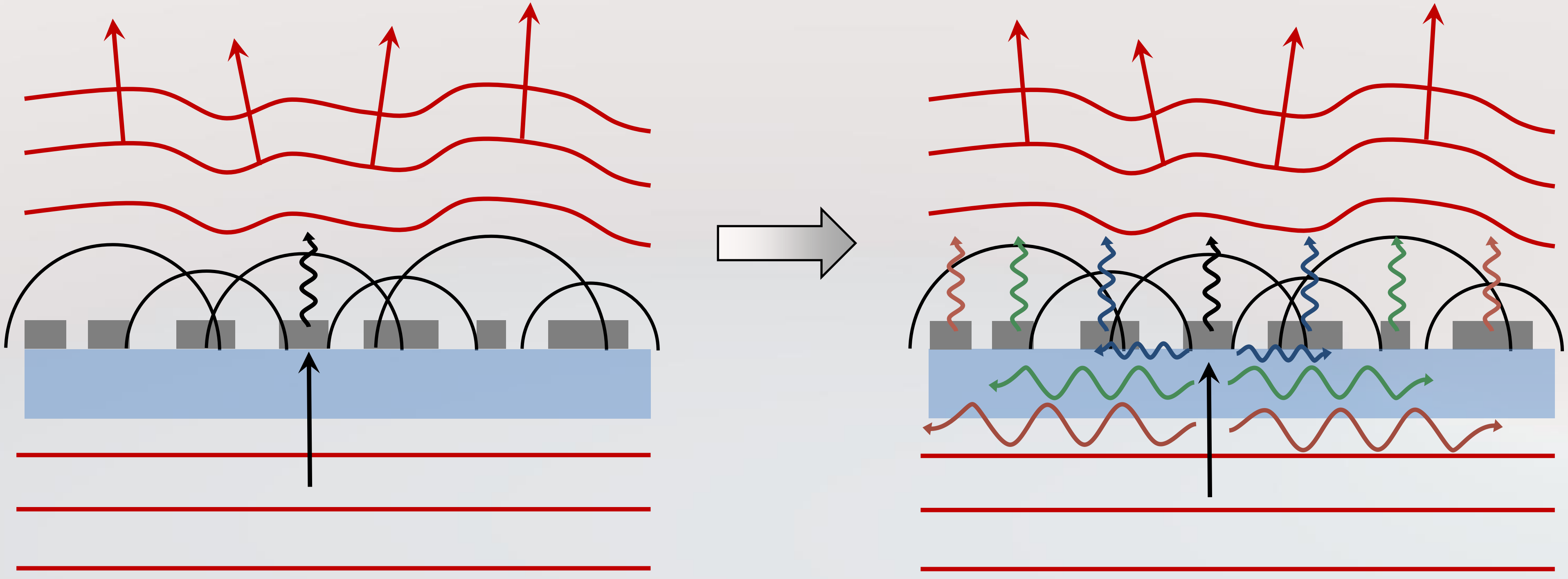
G. Gbur, “Forgotten milestones in the history of optics”

N. Yu *et al.*, Science **334**, 333 (2011).

Trend: From local to nonlocal

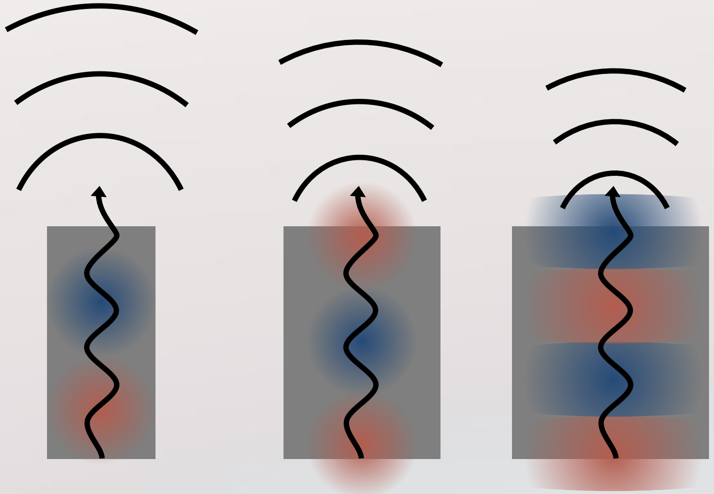
Local scattering
(ignore neighbors)

Nonlocal scattering
(include neighbors)



Challenge: Local control of nonlocal modes

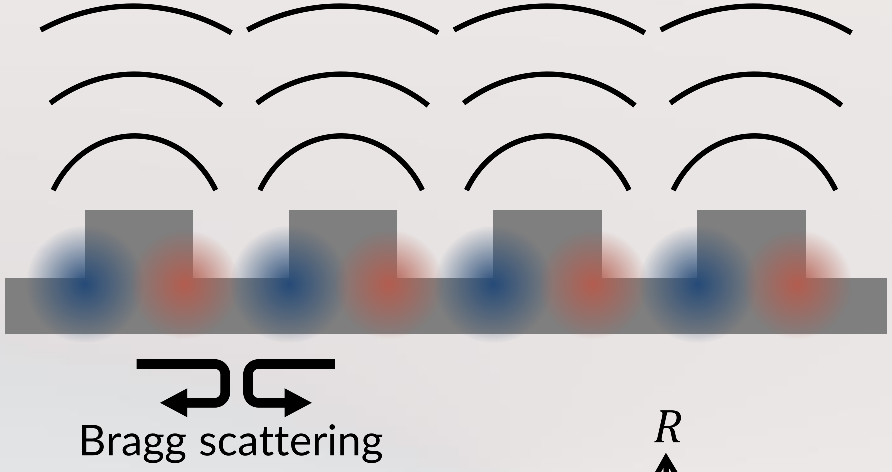
Metasurfaces



Control of

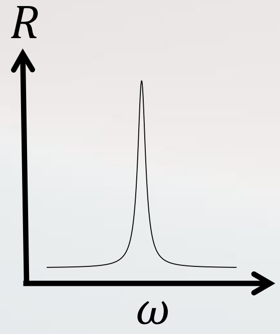
Local scattering	Yes
Inter-element coupling	No

Photonic crystal slabs



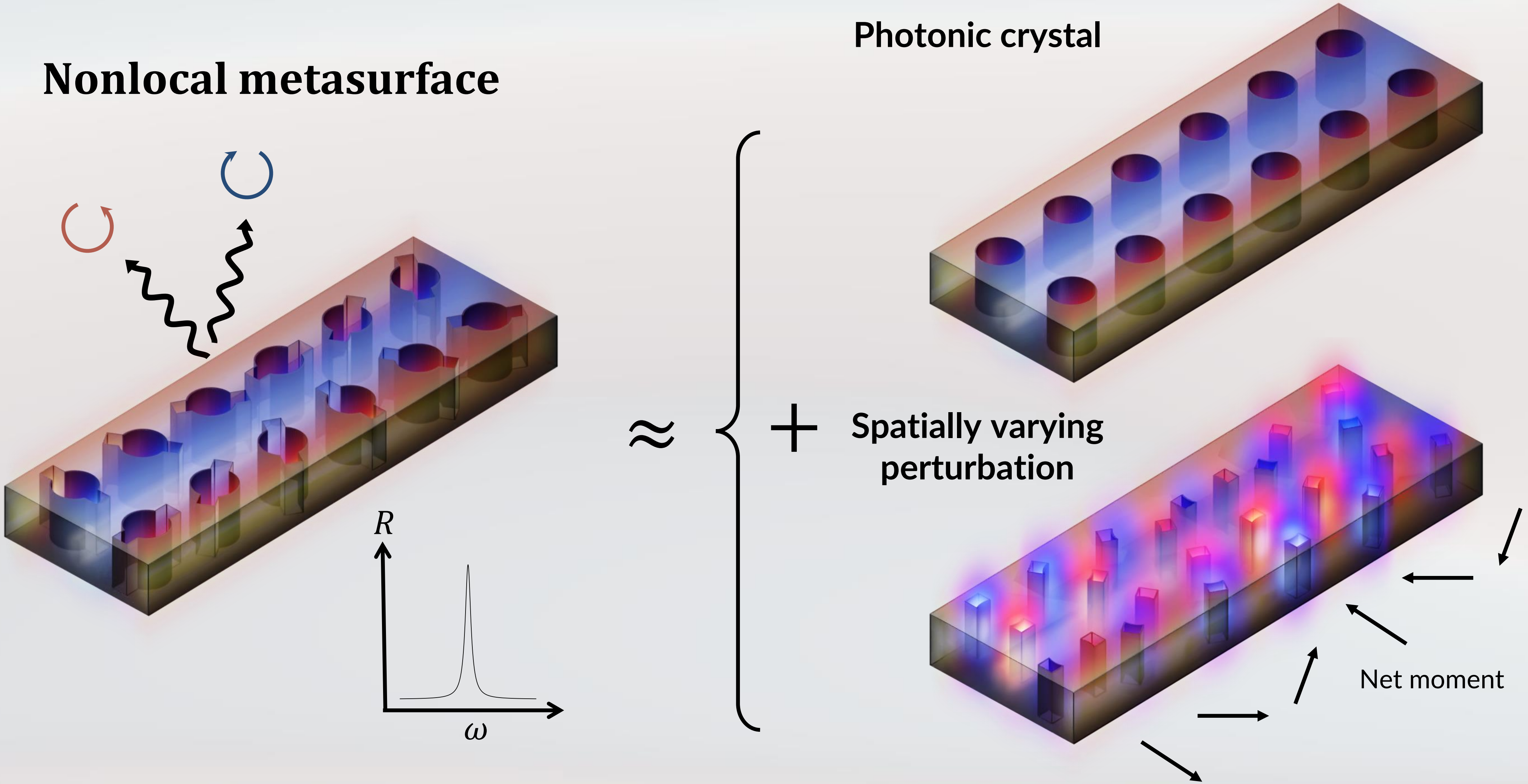
Control of

No	Local scattering
Yes	Inter-element coupling



How do we turn a 'bug' into a 'feature'?

Solution: Small perturbations

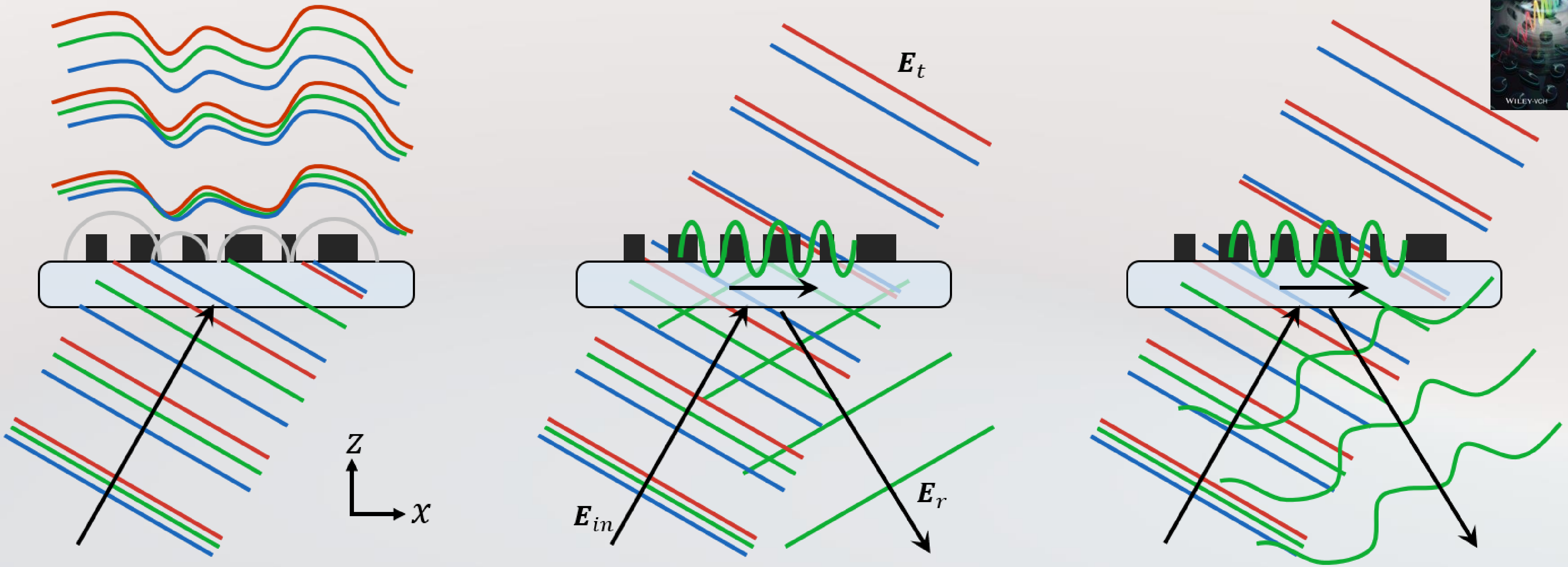


A. Overvig, S. Malek, and N. Yu, "Multifunctional nonlocal metasurfaces"
Phys. Rev. Lett. **125**, 017402 (2020)

Novelty: New class of device

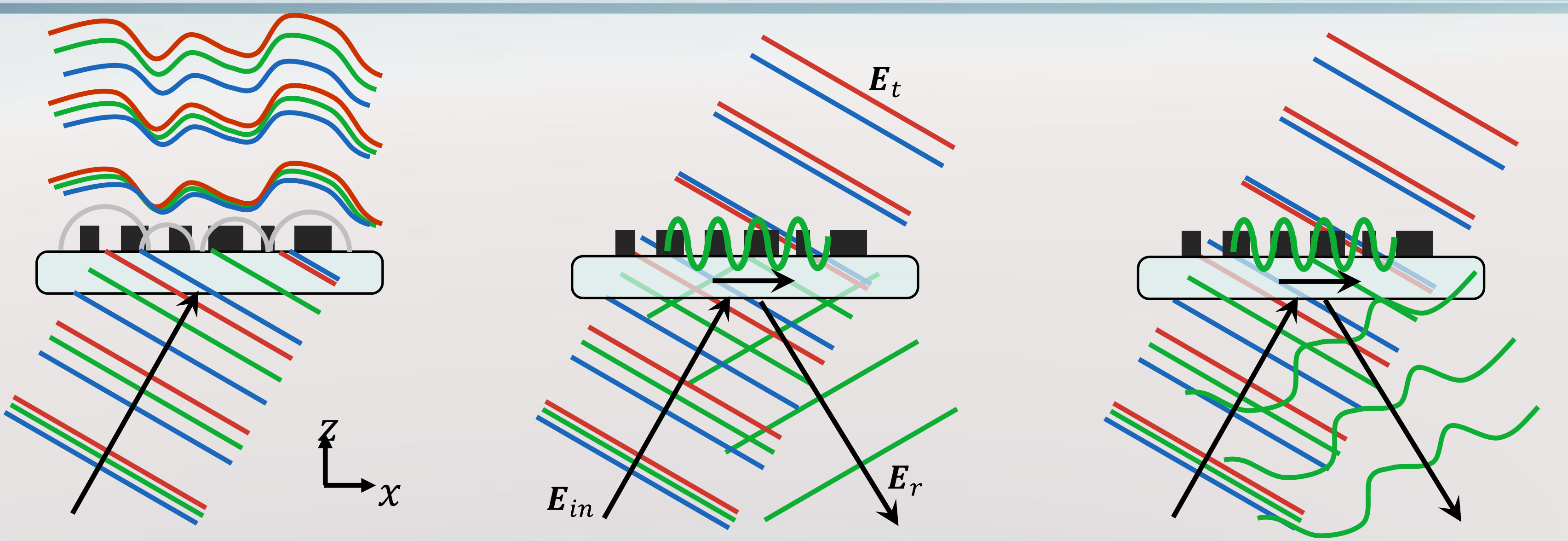
Nonlocal metasurfaces

Local metasurfaces | **Subdiffractive** | **Diffractive**



A. Overvig, A. Alù, "Diffractive Nonlocal Metasurfaces",
Laser & Photonics Reviews **16**, 2100633 (2022).

Significance: General scattering behavior



Space-frequency description:

$$E_r(x,\omega) = r(x,\omega)E_{in}(x,\omega)$$

$$E_t(x,\omega) = t(x,\omega)E_{in}(x,\omega)$$

Momentum-frequency description:

$$E_r(k,\omega) = r(k,\omega)E_{in}(k,\omega)$$

$$E_t(k,\omega) = t(k,\omega)E_{in}(k,\omega)$$

Space-frequency description:

$$E_r(x,\omega) = \int dx'\rho(x,x',\omega)\,E_{in}(x',\omega)$$

$$E_t(x,\omega) = \int dx'\tau(x,x',\omega)\,E_{in}(x',\omega)$$

Homogeneity:

$$\rho(x,x',\omega) = r(x-x',\omega)$$
$$\tau(x,x',\omega) = t(x-x',\omega)$$

Locality:

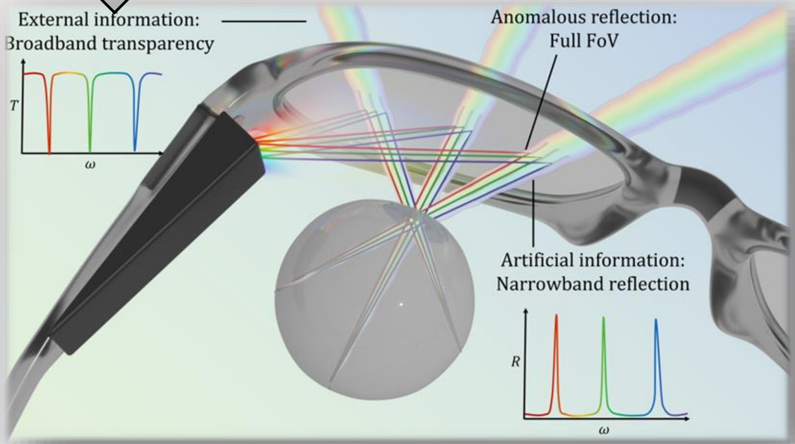
$$\rho(x,x',\omega) = r(x,\omega)\delta(x-x')$$
$$\tau(x,x',\omega) = t(x,\omega)\delta(x-x')$$

A. Overvig, A. Alù, "Diffractive Nonlocal Metasurfaces",
Laser & Photonics Reviews **16**, 2100633 (2022).

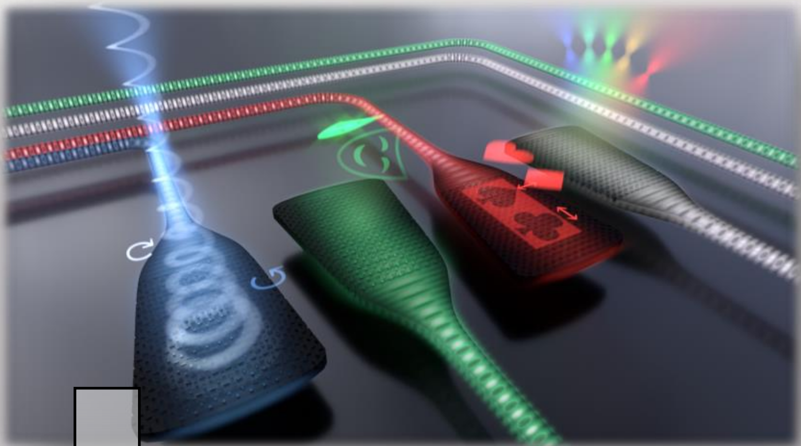
Applications: Controlling open systems with symmetries

Free space

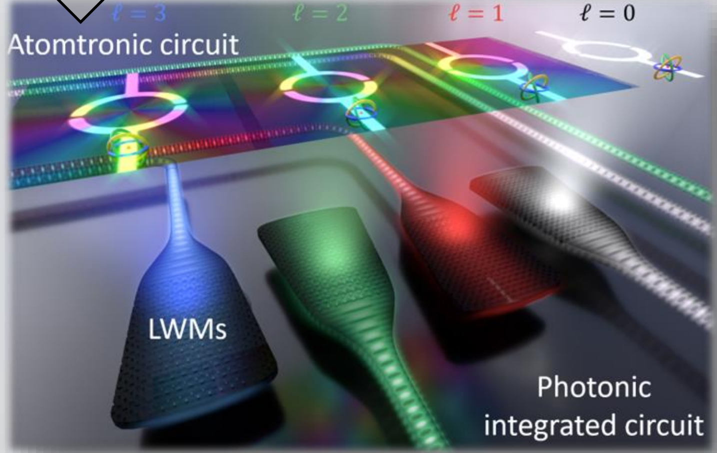
Augmented reality



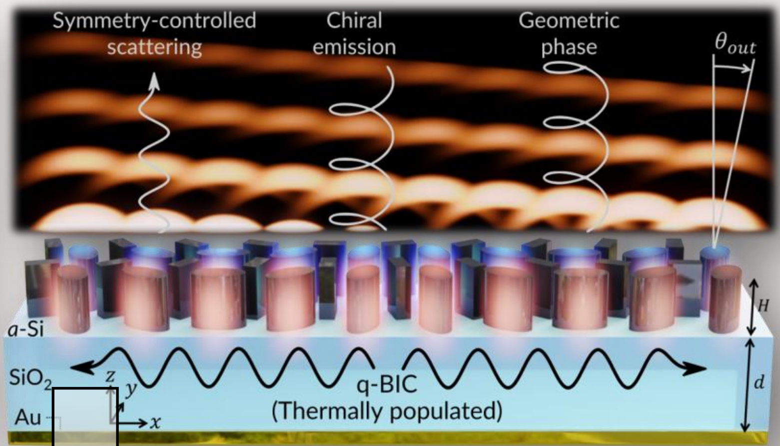
Integrated Photonics



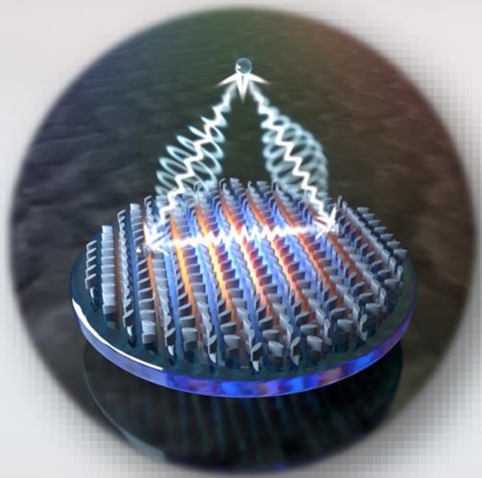
Quantum systems



Thermal Metasurfaces



Custom sources

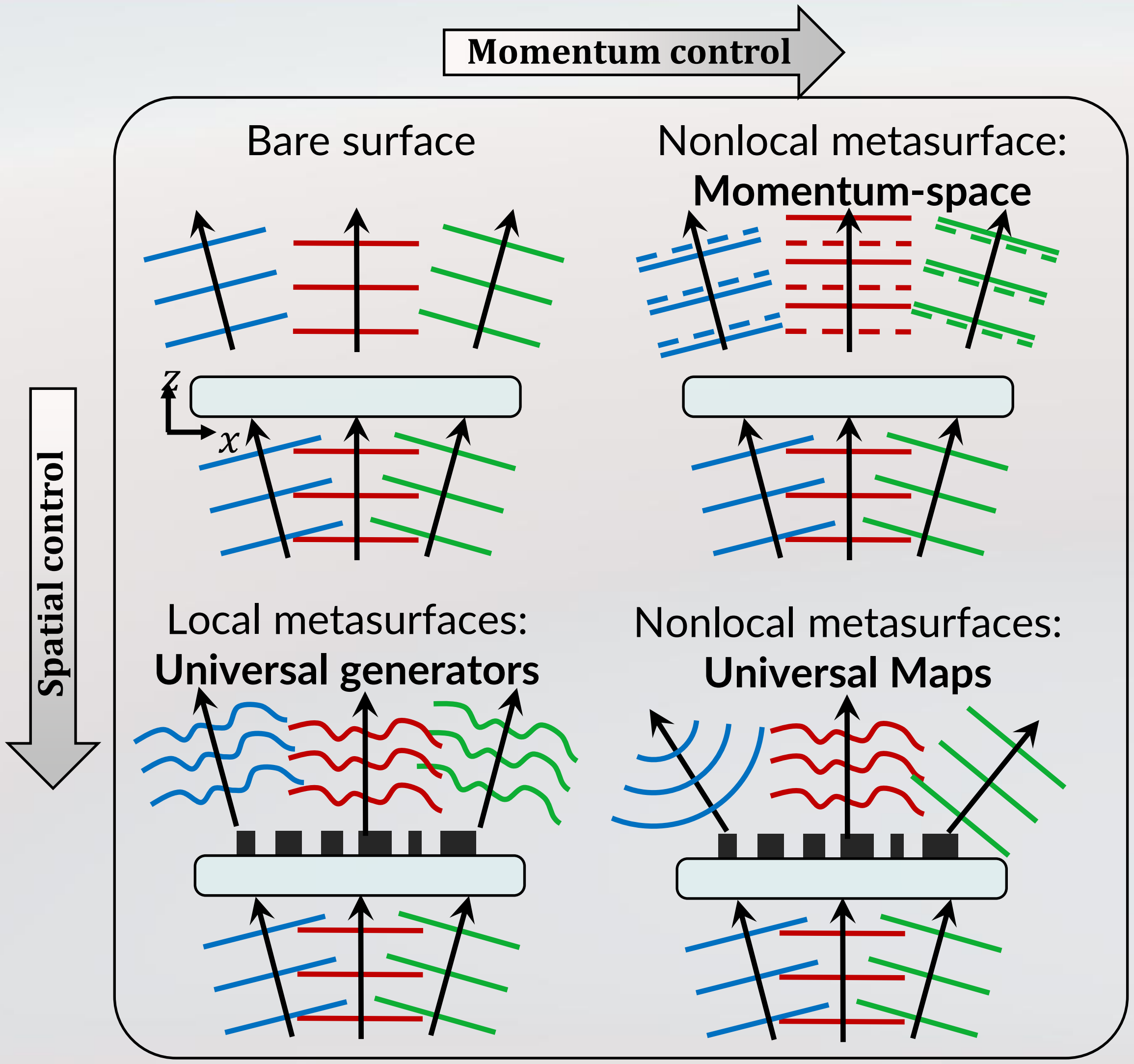


Light: Sci. & App. **11**, 246 (2022)

Nat. Nanotechnol. **18**, 580-588 (2023)

PRX **18**, 021050 (2021)
Nat. Nanotechnol. (2024)

Opportunity: Beyond the Generalized Snell's Law



Periodic thin film media:

$$S_{ij}(k_i, k_j') = \sum_m a_m(k_i, k_j')\delta[f_m(k_i, k_j')]$$

Conservation of quasi-momentum:

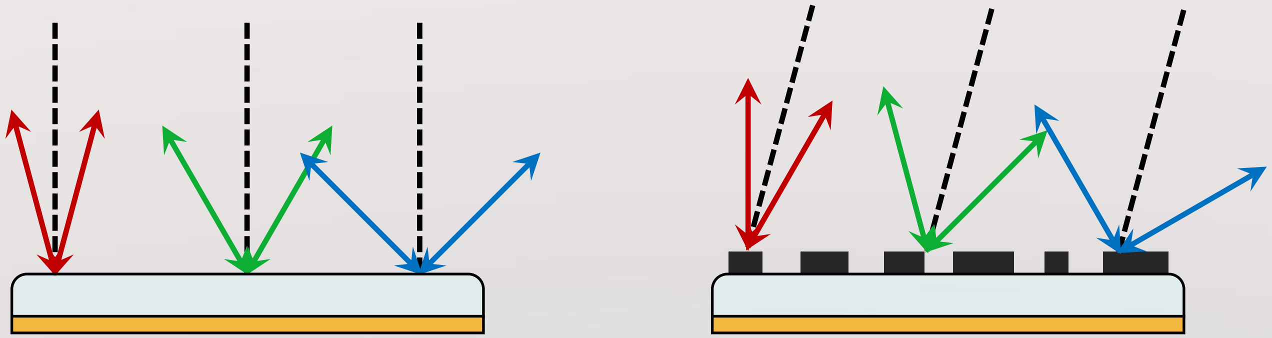
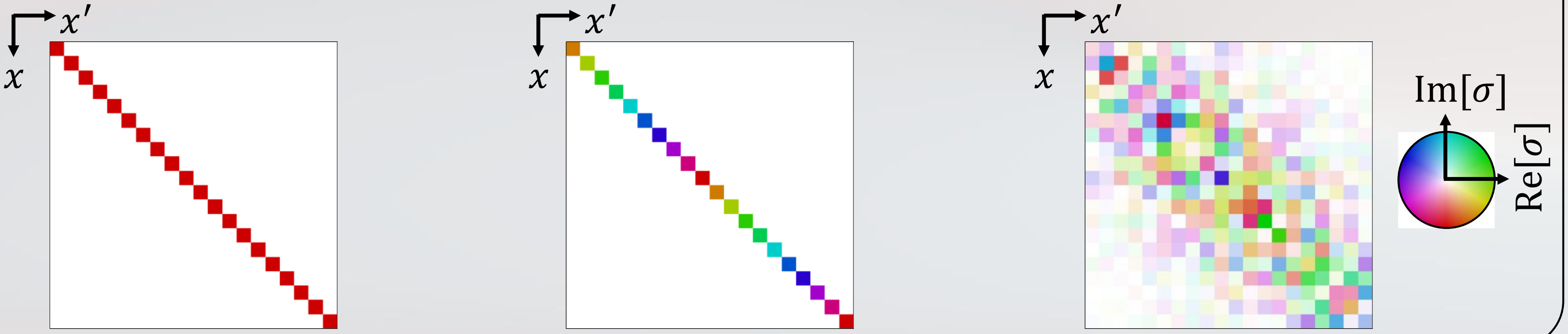
$$f_m(k_i, k_j') = k_i - k_j' - m\frac{2\pi}{P}$$

Case	$f(k_i, k_j')$
Snell's Law	$k_i - k_j'$
Generalized Snell's Law	$k_i - k_j' - \nabla\Phi$
Nonlocal Generalized Snell's Law	$k_i - k_j' - \nabla\Phi_{\mathrm{ij}}(k_j')$

Reciprocity:

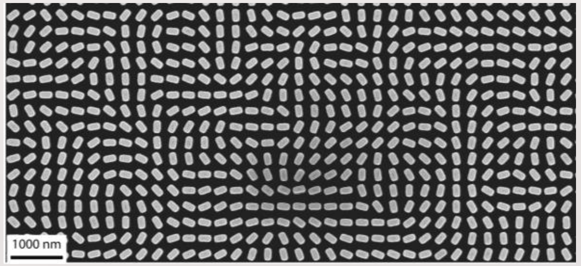
$$S_{ij}(k_a, k_b) = S_{ji}(-k_b, -k_a)$$
$$\nabla\Phi_{\mathrm{ij}}(k_b) = \nabla\Phi_{ji}(-k_a)$$

Opportunity: information density

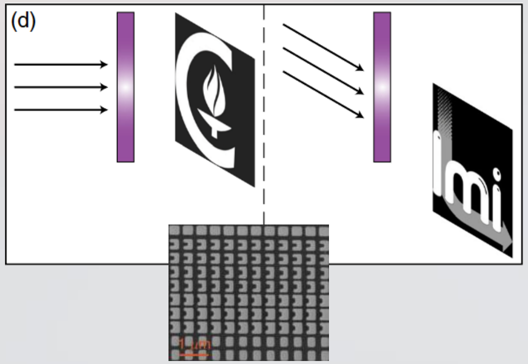
	Bare interface	Generalized Snell's Law	Nonlocal Generalized Snell's Law
Law	$\sin(\theta_{out}) = \sin(\theta_{in})$	$\sin(\theta_{out}) = \sin(\theta_{in}) + \frac{1}{k_0}\frac{d\Phi}{dx}$	$\sin(\theta_{out}) = \sin(\theta_{in}) + \frac{1}{k_0}\frac{d\Phi}{dx}(\theta_{in})$
Functionality			
Information density			

Unexplored regime

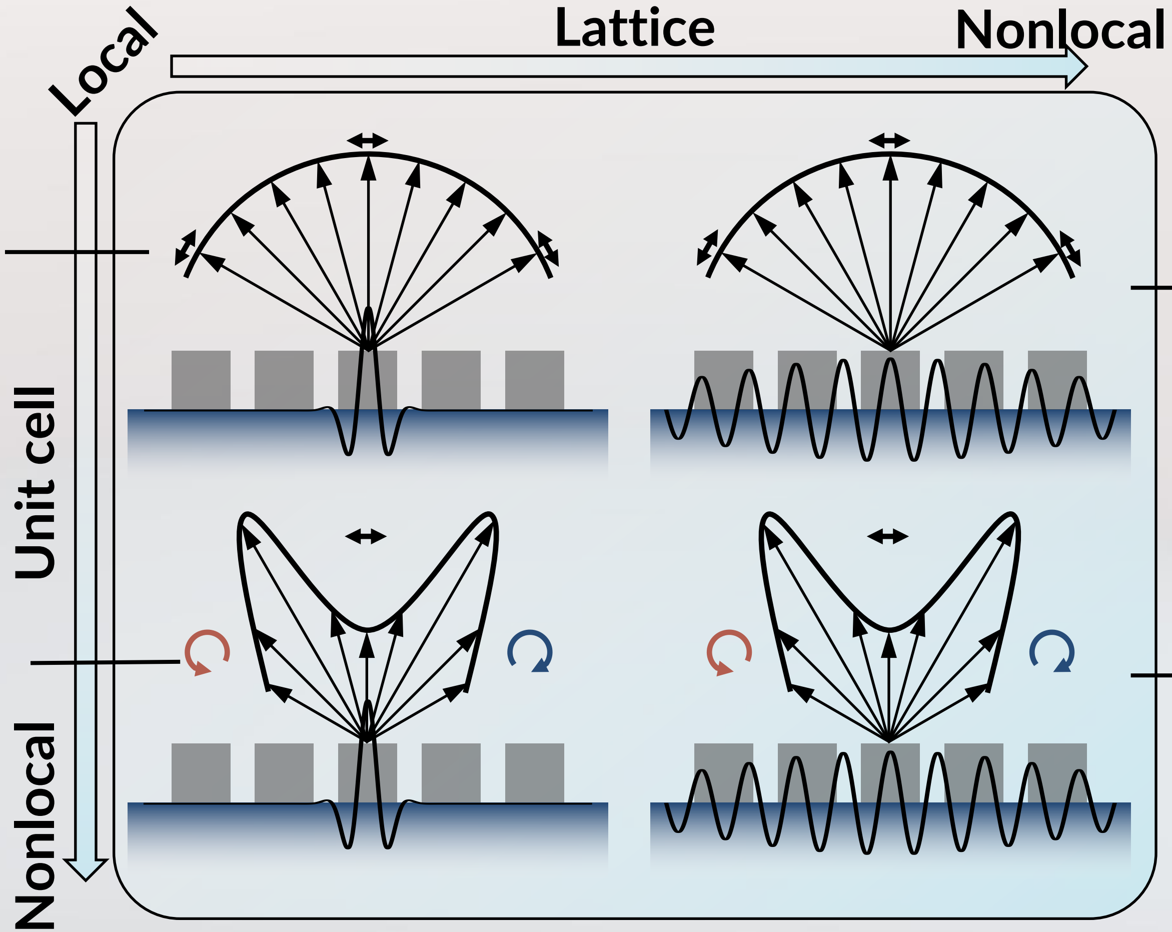
Nonlocality in spatially varying metasurfaces



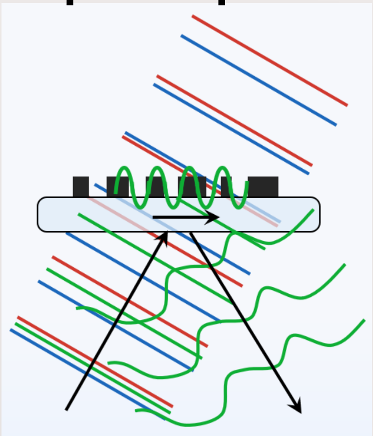
Capasso group



Faraon group



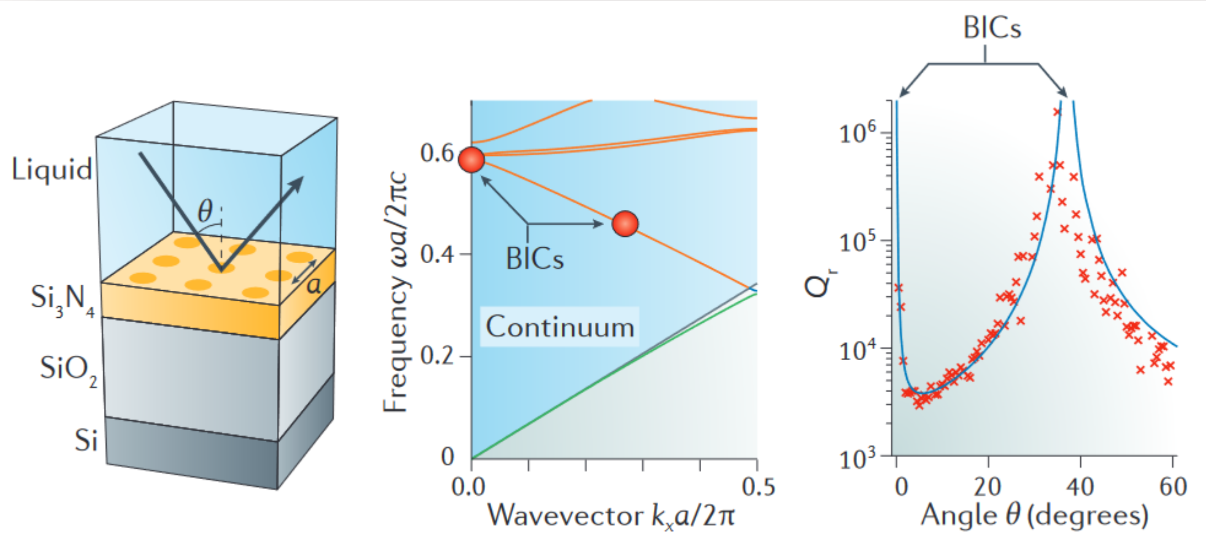
Dipolar q-BICs



??

Hot topic: Bound states in the continuum

Diverging Q-factors

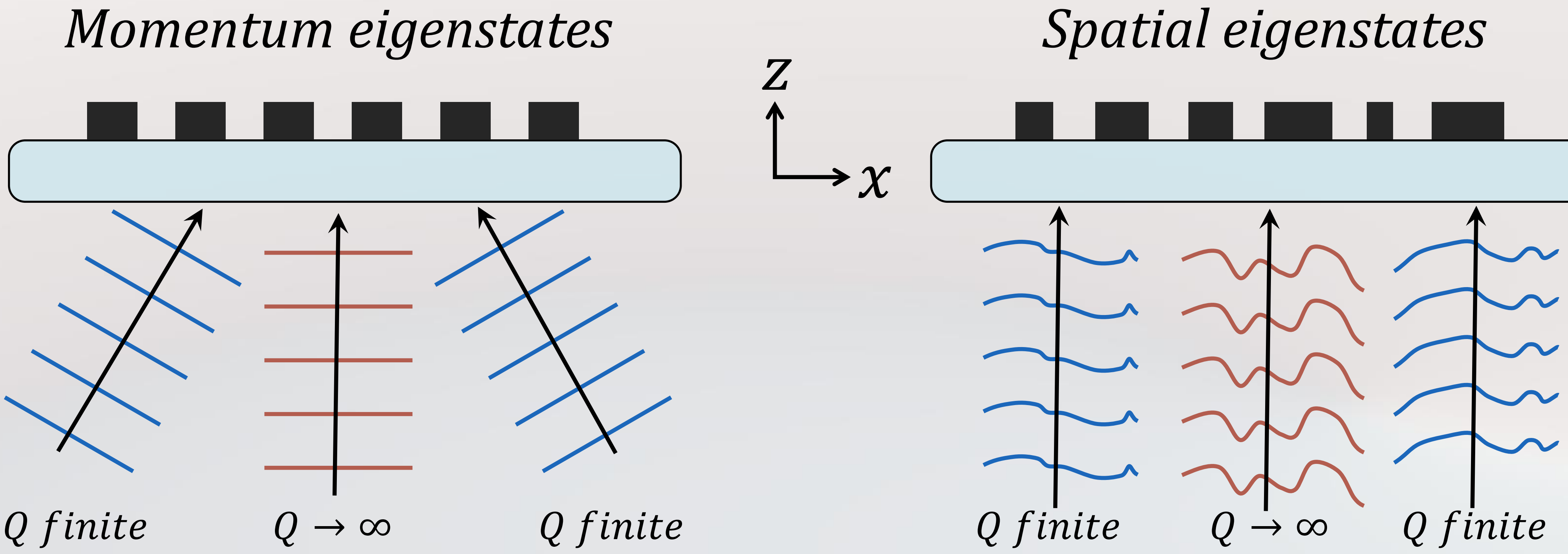


C. Hsu, et al. *Nat. Rev. Mater*. **1**, 16048 (2016).

Types:

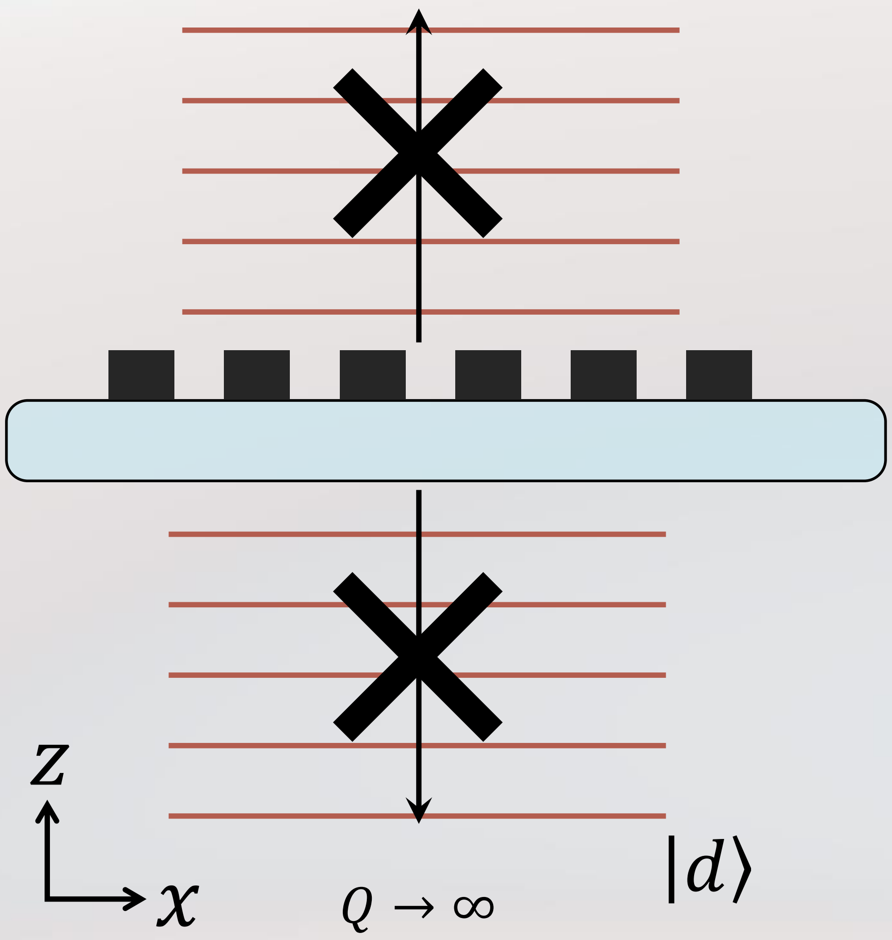
- **Symmetry-protected BICs**
- **Accidental BICs**
- **Friedrich-Wintgen BICs**
- **Unidirectional Guided Resonances**

New idea: Spatial eigenstates in the continuum



Spatial eigenstates in the continuum

Momentum eigenstate



Hamiltonian:

$$Ha = \omega a$$

$$H = \omega_0 - \left(\frac{b - i\gamma_q}{2}\right)\frac{\partial^2}{\partial x^2}$$

Outgoing waves:

$$|s_-(x)\rangle = |d(x\,)\rangle\frac{\partial a(x)}{\partial x}$$

Solutions:

$$a = e^{ikx}$$

$$\omega_k = \omega_0 + \frac{b - i\gamma_q}{2}k^2$$

As

$$a \to 1$$

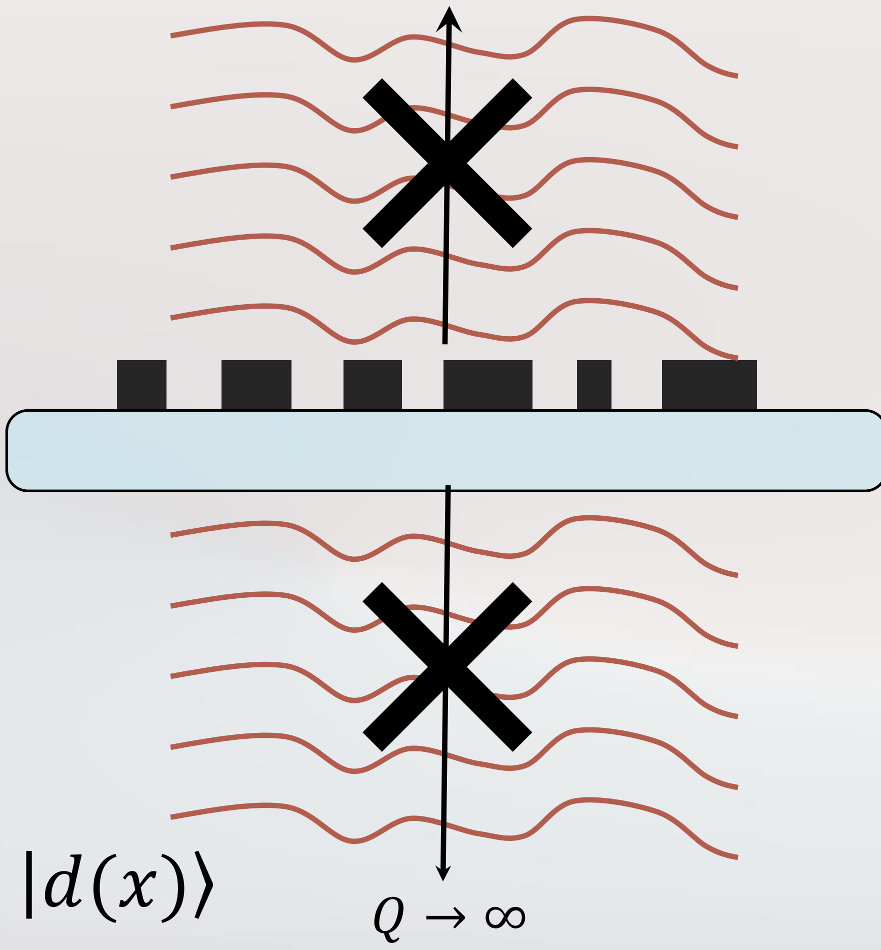
We have

$$Q \to \infty$$

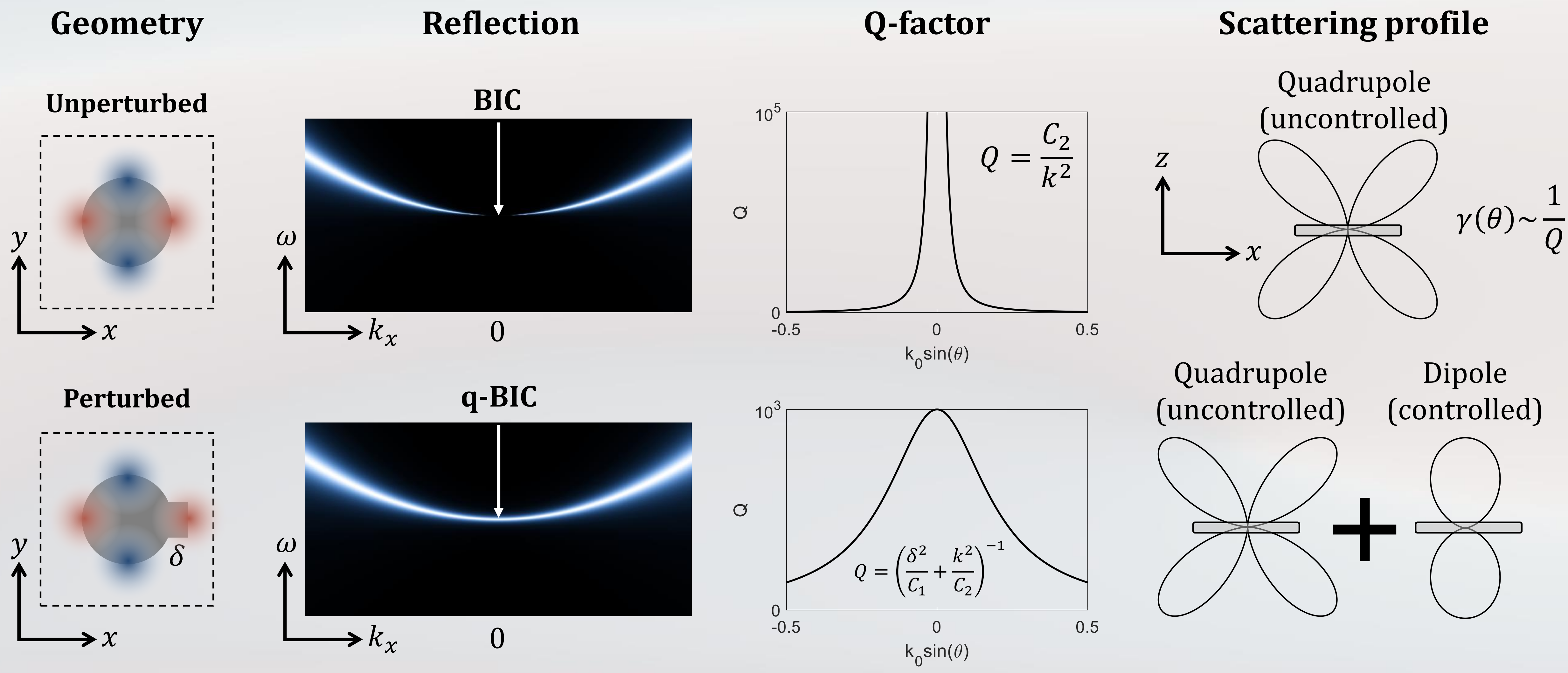
For the wave

$$|s_-(x)\rangle \to 0 \times |d(x\,)\rangle$$

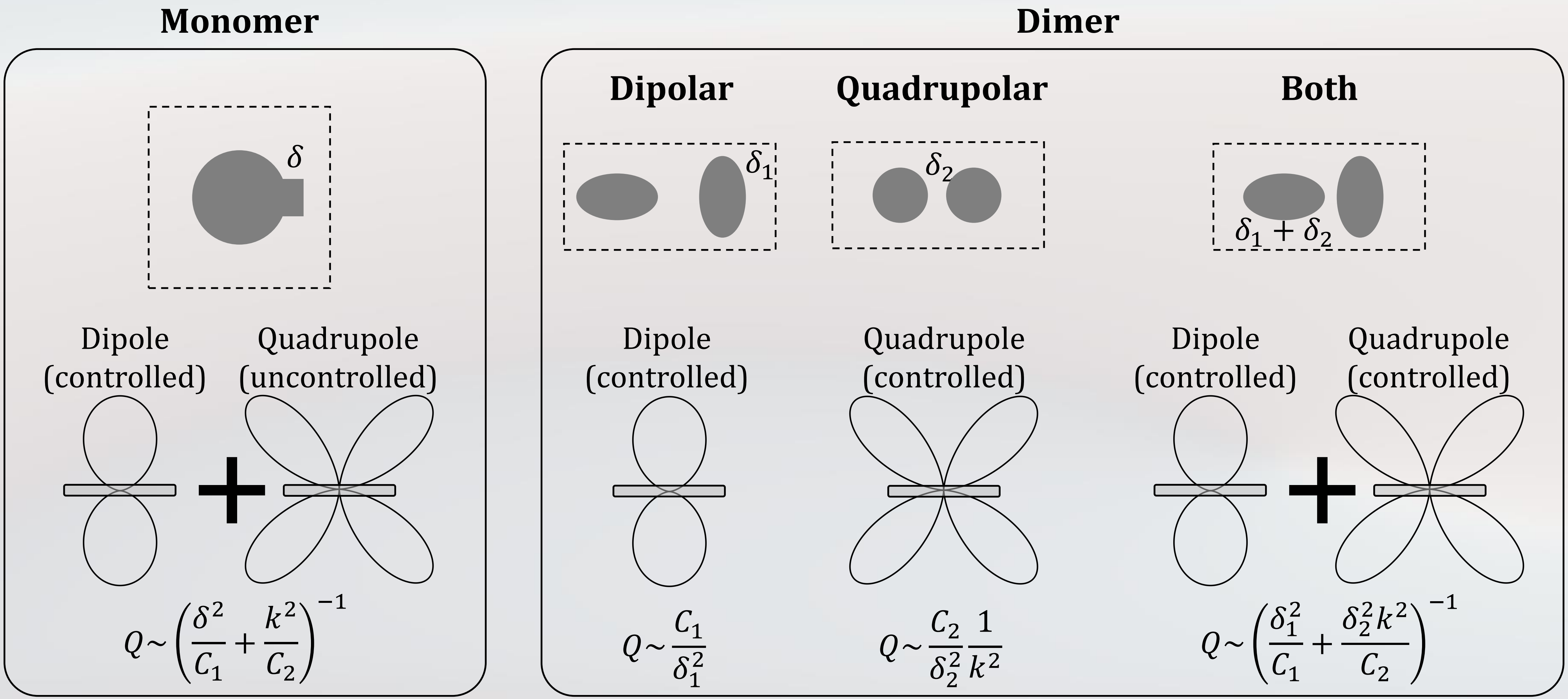
Spatial eigenstate



Conventional monomer lattices



BICs and q-BICs: perturbation approaches

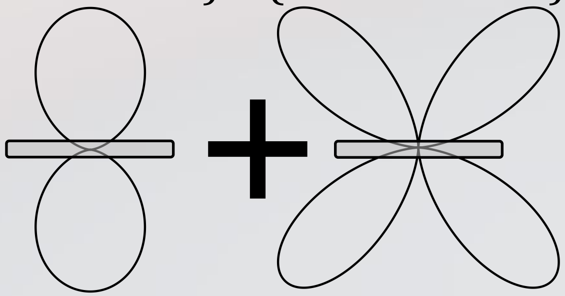


BICs and q-BICs: perturbation approaches

Monomer

Common approach in the literature

Dipole (controlled) | Quadrupole (uncontrolled)



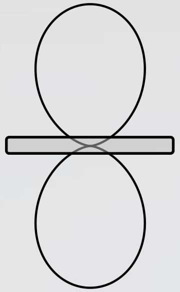
$$Q \sim \left(\frac{\delta^2}{C_1} + \frac{k^2}{C_2}\right)^{-1}$$

Dimer

Dipolar

Past work

Dipole (controlled)

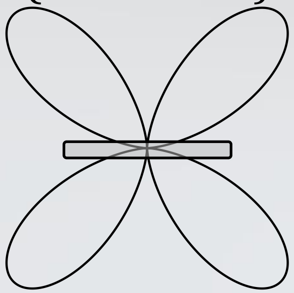


$$Q \sim \frac{C_1}{\delta_1^2}$$

Quadrupolar

Today's main topic

Quadrupole (controlled)

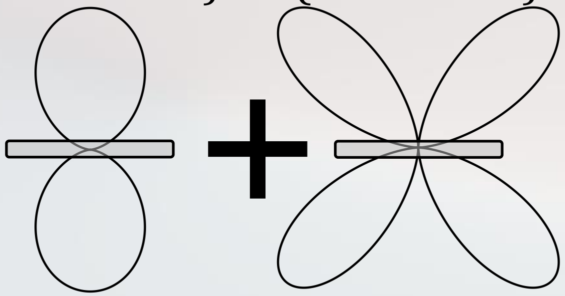


$$Q \sim \frac{C_2}{\delta_2^2} \frac{1}{k^2}$$

Both

Ongoing work

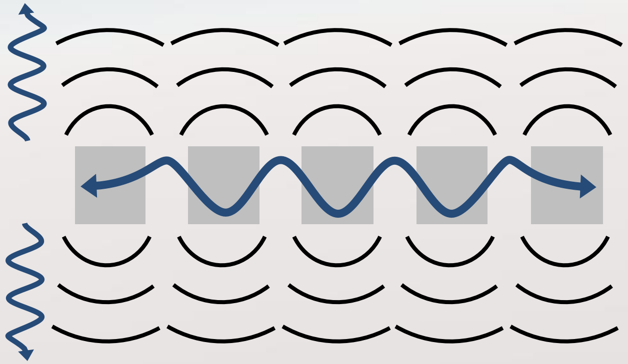
Dipole (controlled) | Quadrupole (controlled)

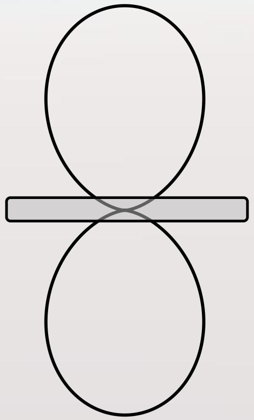


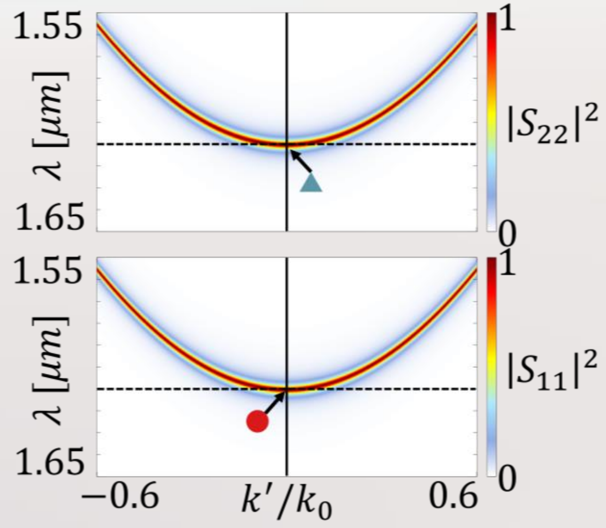
$$Q \sim \left(\frac{\delta_1^2}{C_1} + \frac{\delta_2^2 k^2}{C_2}\right)^{-1}$$

Past work: Dipolar nonlocal phase gradients

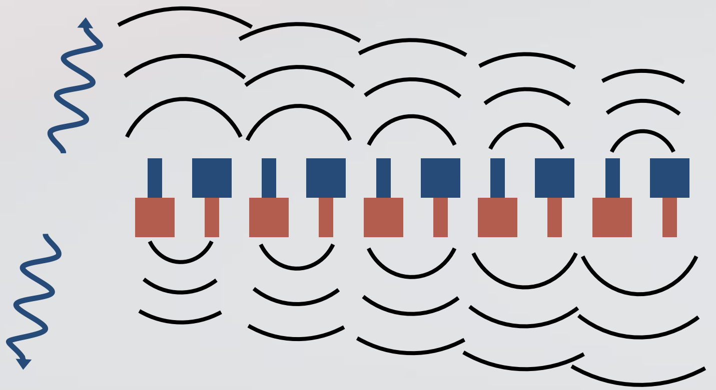
Periodic

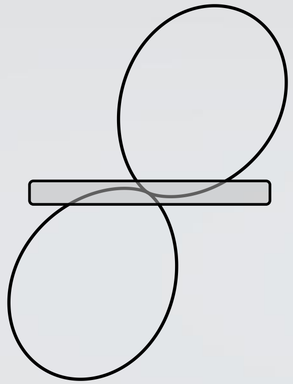


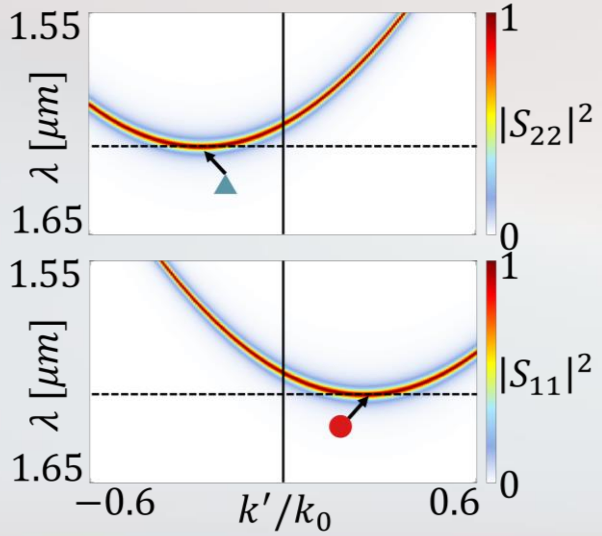




Nonlocal metasurface



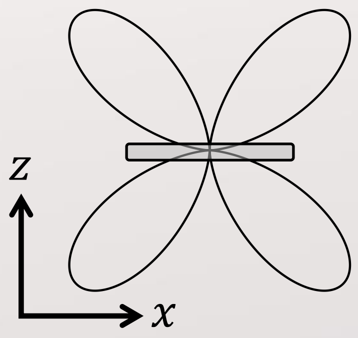




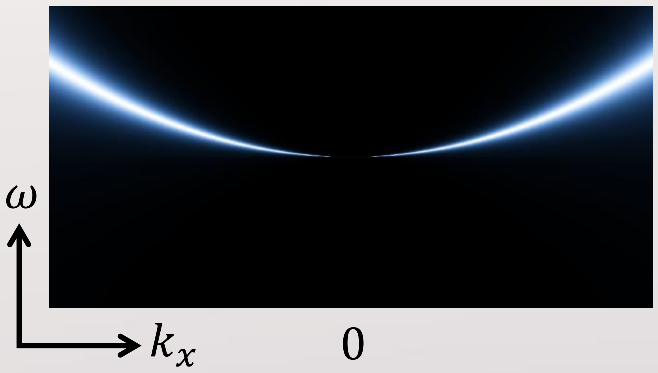
A. Overvig, S. Mann, and A. Alù, "Spatiotemporal Coupled Mode Theory",
Light: Science & Applications, **13**, 28 (2024).

Now apply this to quadrupolar states

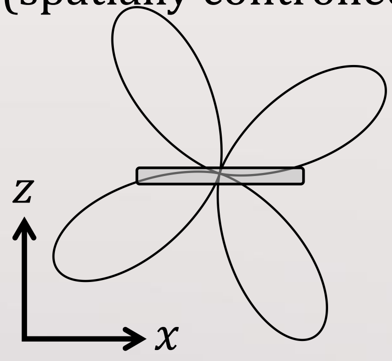
Quadrupole



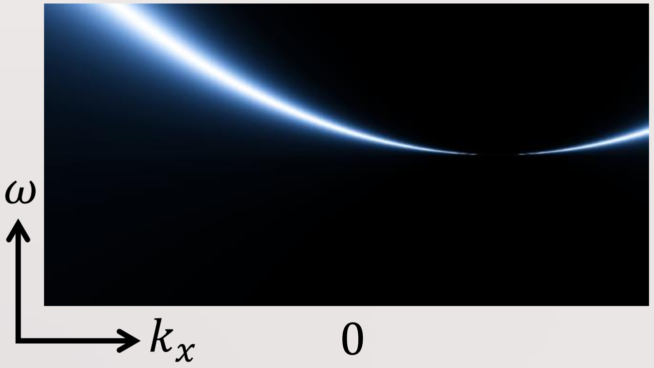
Quadrupolar q-BIC



Quadrupole
(spatially controlled)



**Quadrupolar q-BIC +
phase gradient**



Momentum BICs:

$$|d\rangle = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$$

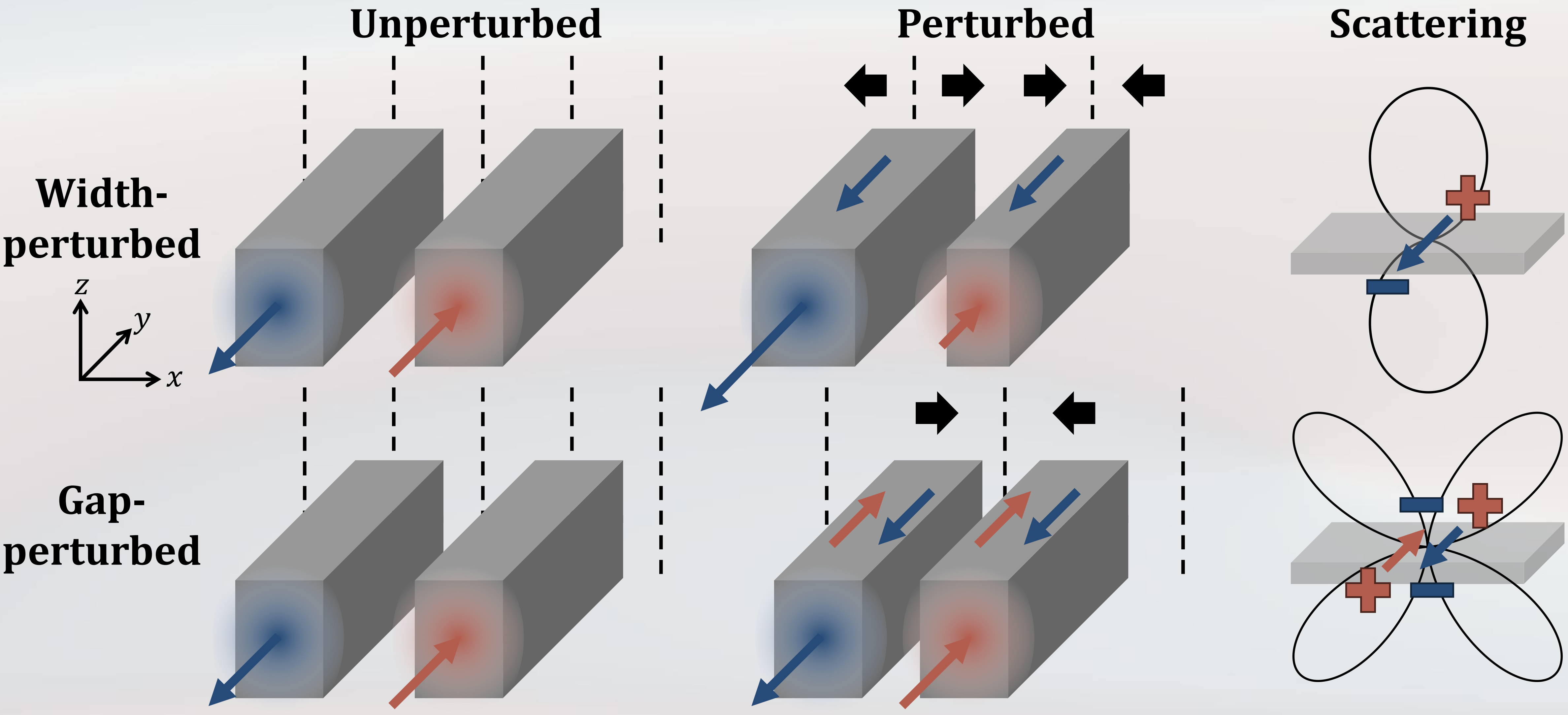
= Planewaves

Spatial BICs:

$$|d\rangle = \sqrt{\frac{\gamma_q}{2}} \begin{bmatrix} \exp\big(-i\Phi(x)\big) \\ -i\exp\big(i\Phi(x)\big) \end{bmatrix}$$

= Custom waves

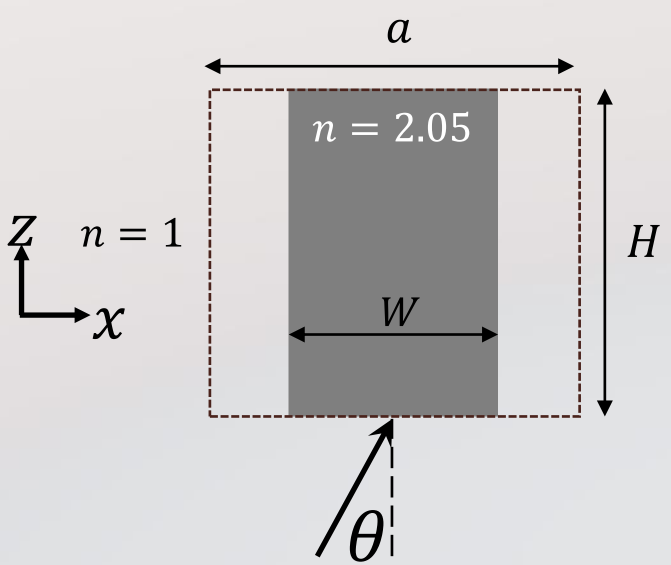
Perturbations for fundamental TE mode



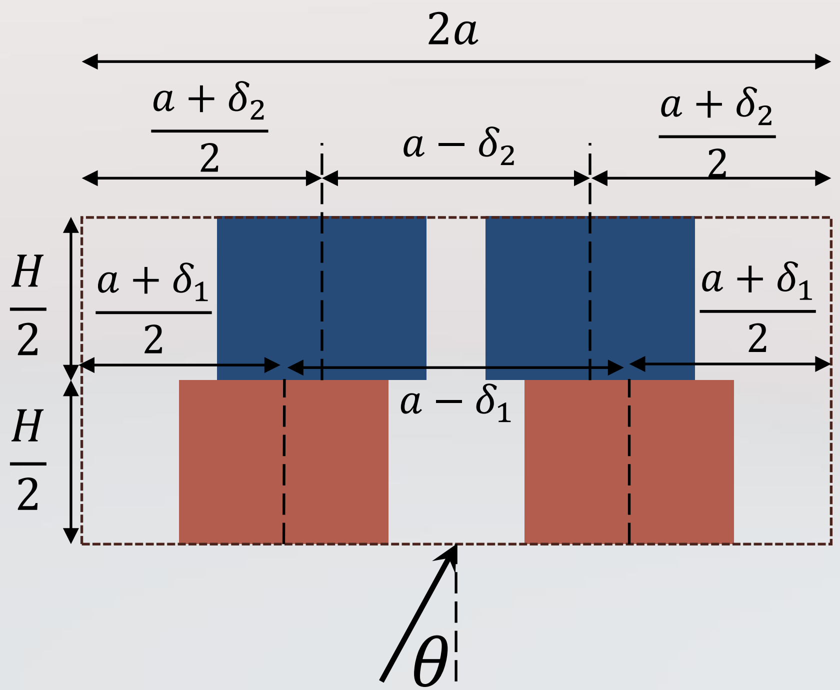
A. Overvig, S. Shrestha, and N. Yu
"Dimerized High Contrast Gratings", *Nanophotonics* **7**, 1157-1168 (2018)

Perturbation scheme: dual-layer gap-perturbed

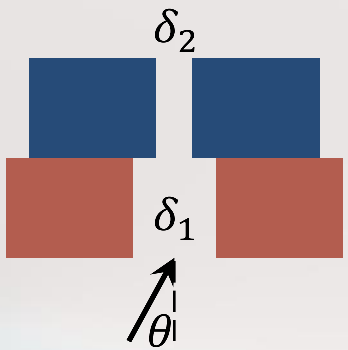
Unperturbed



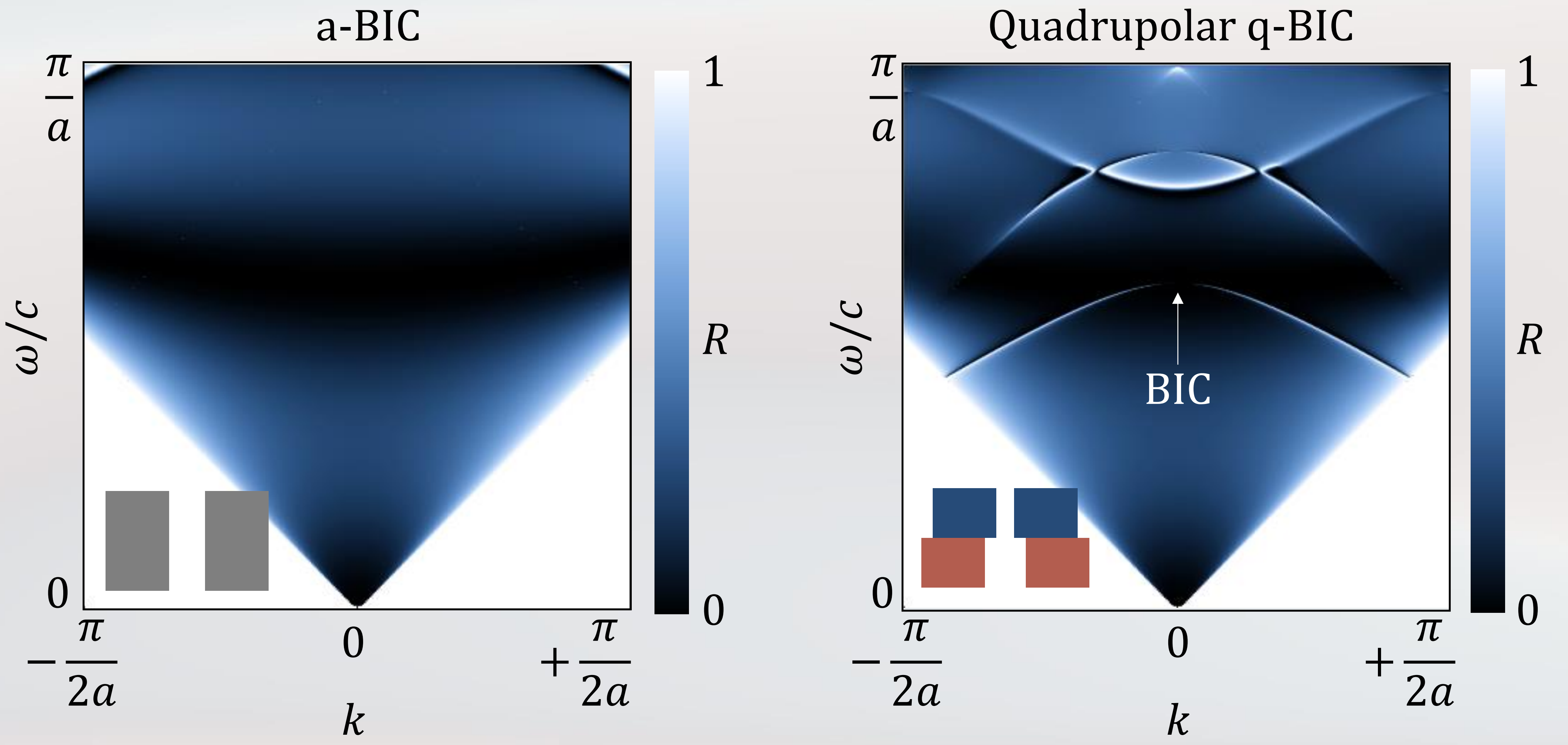
Perturbed



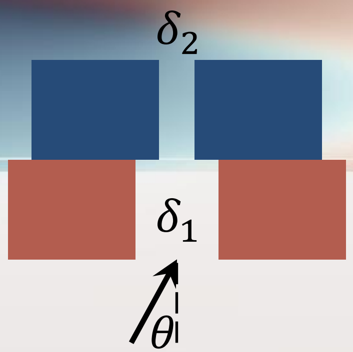
Simplified schematic:



Zone-folded, symmetry-protected BIC

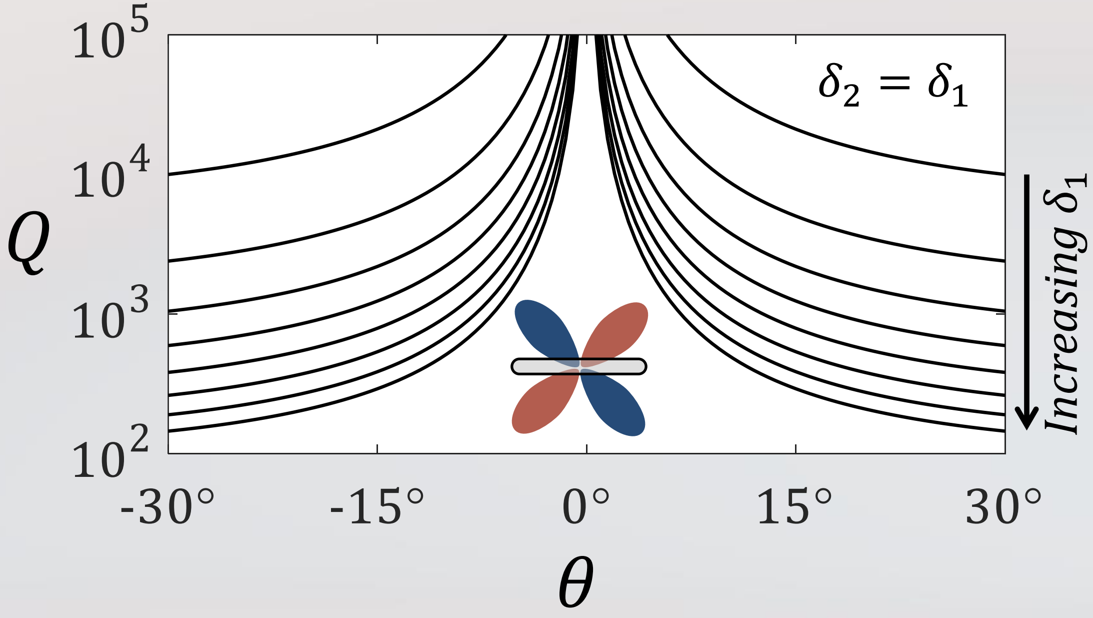


Quadrupolar scattering

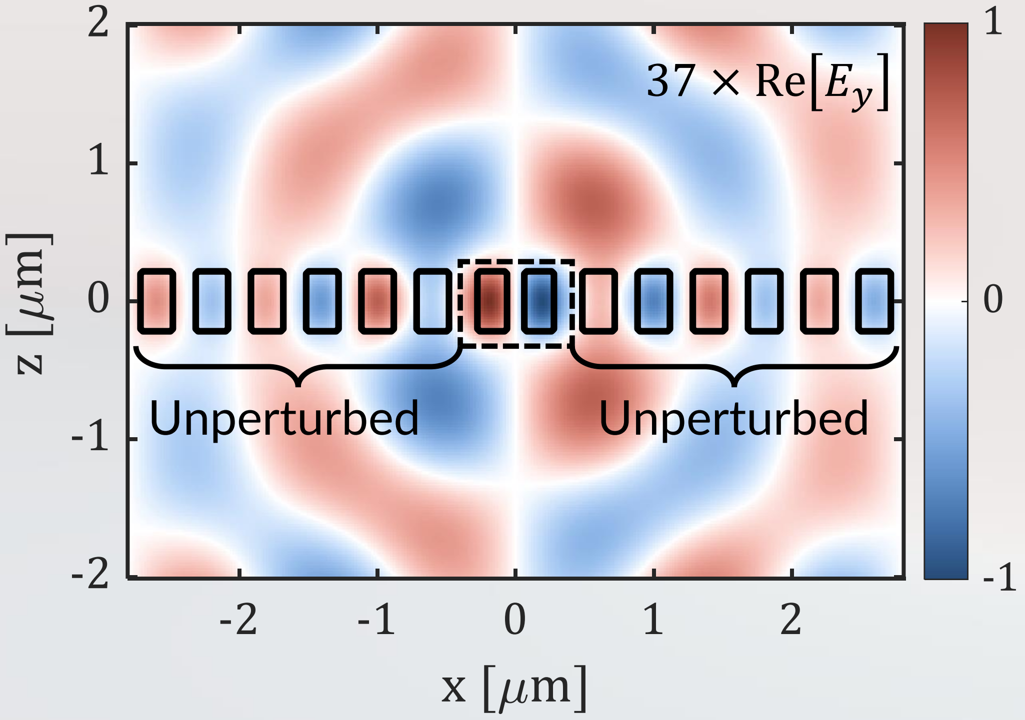


Controllable Q-factor (nonlocal property)

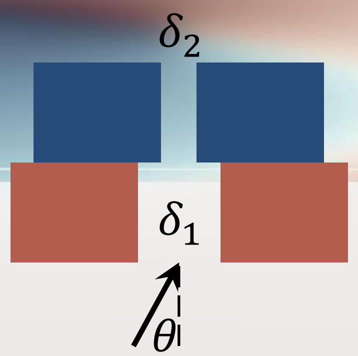
$$Q \propto \frac{1}{k^2}\frac{1}{\delta_1^2+\delta_2^2}$$



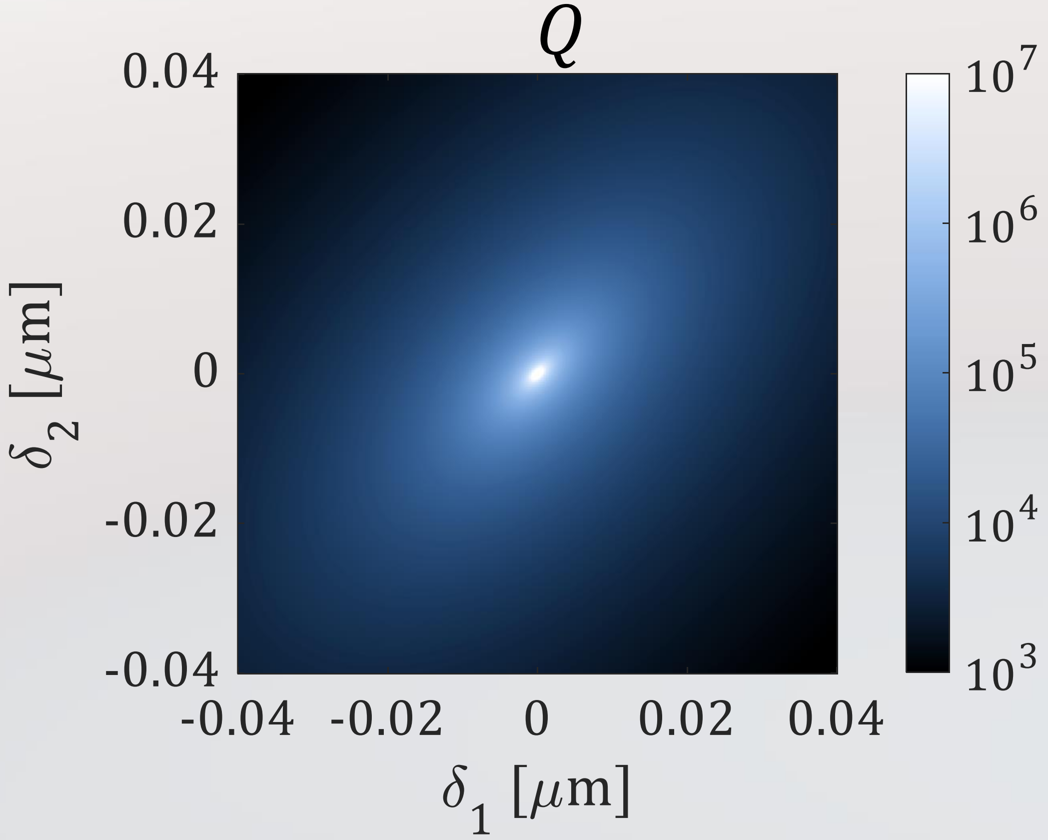
Local leakage (local property)

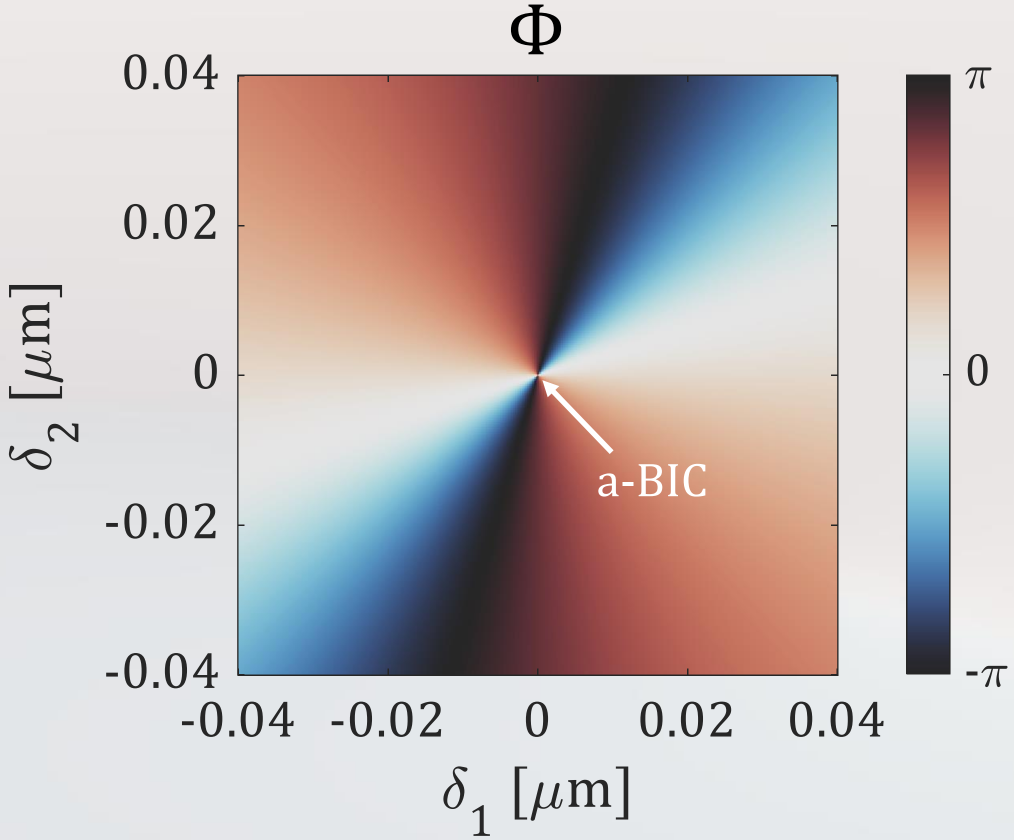


Arbitrary Q-factor and phase

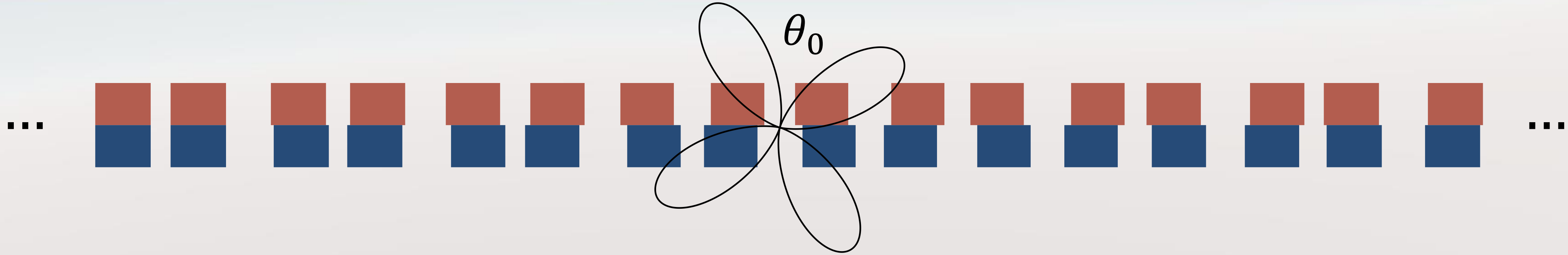


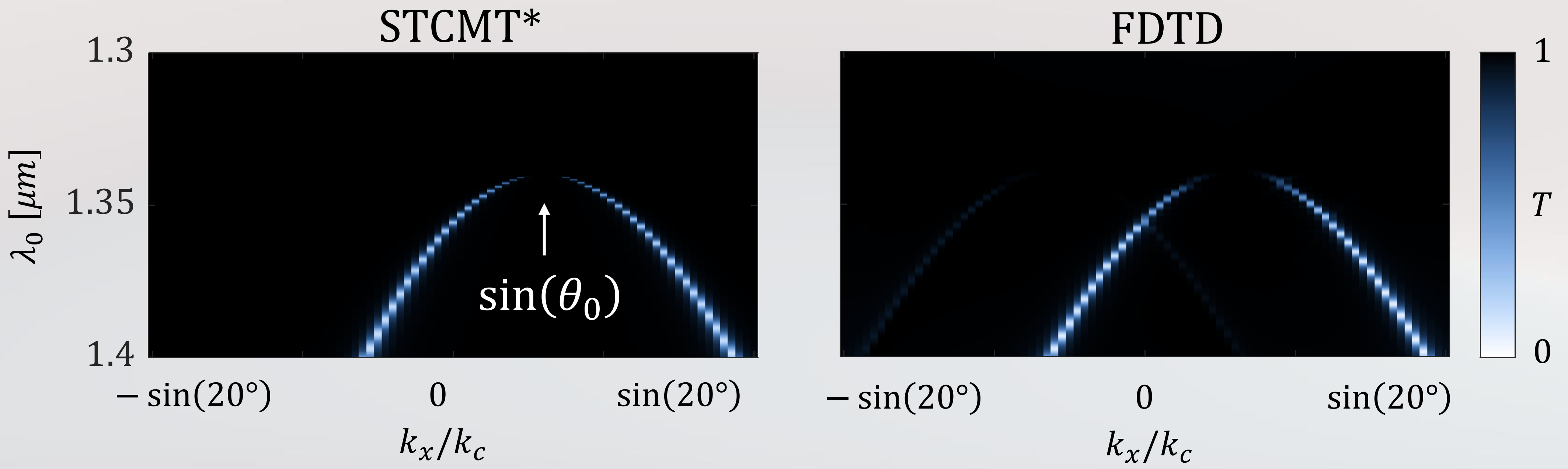
$\theta = 2°$





Quadrupolar phase gradient

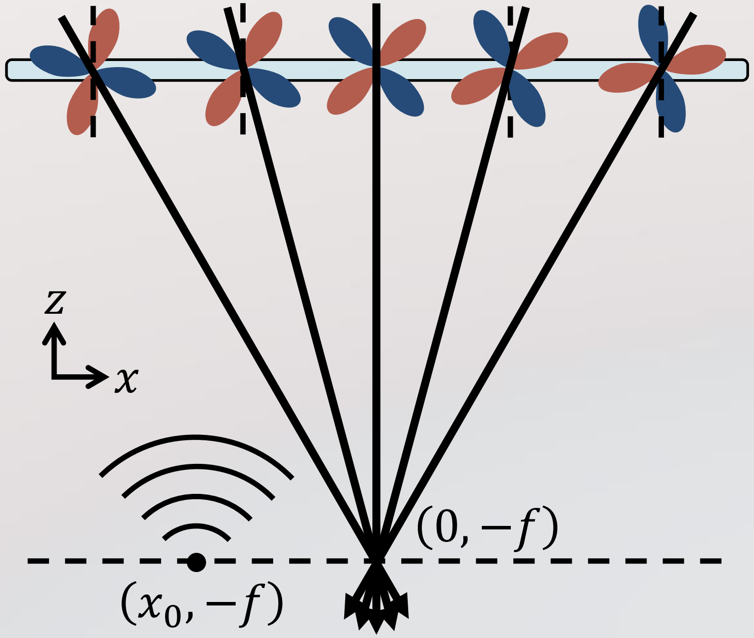




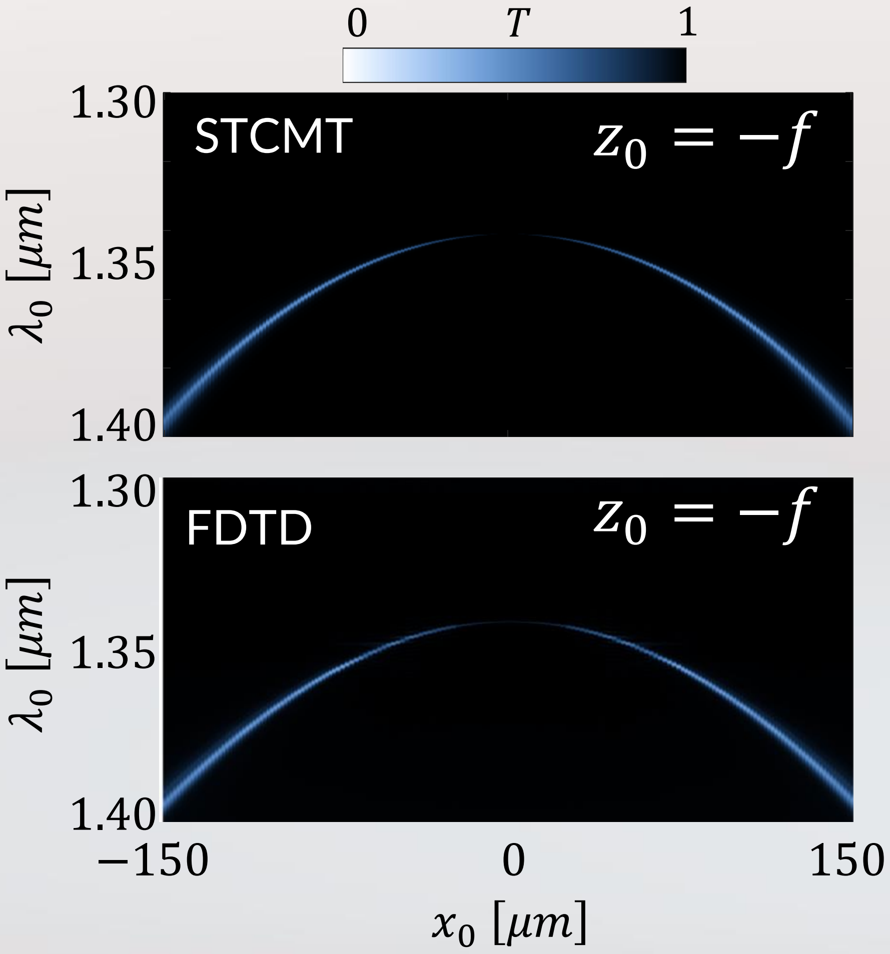
*A. Overvig, S. Mann, and A. Alù, "Spatiotemporal Coupled Mode Theory", *Light: Science & Applications*, **13**, 28 (2024).

BIC in the *spatial domain*

Scan the focal plane

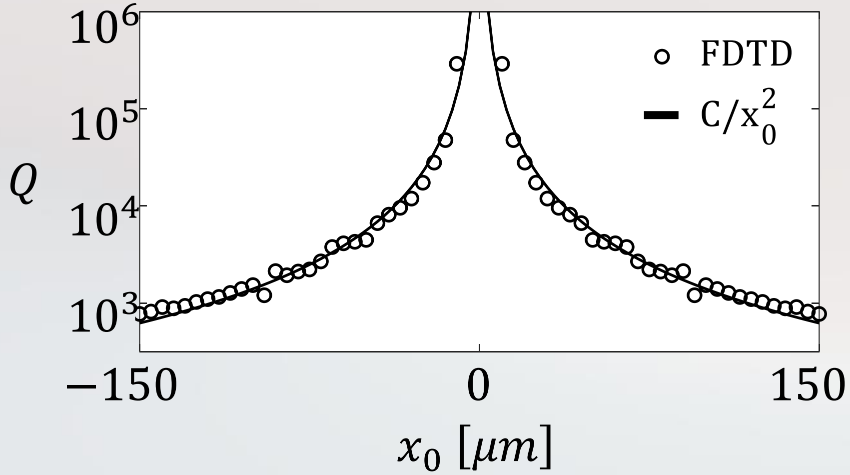


Response



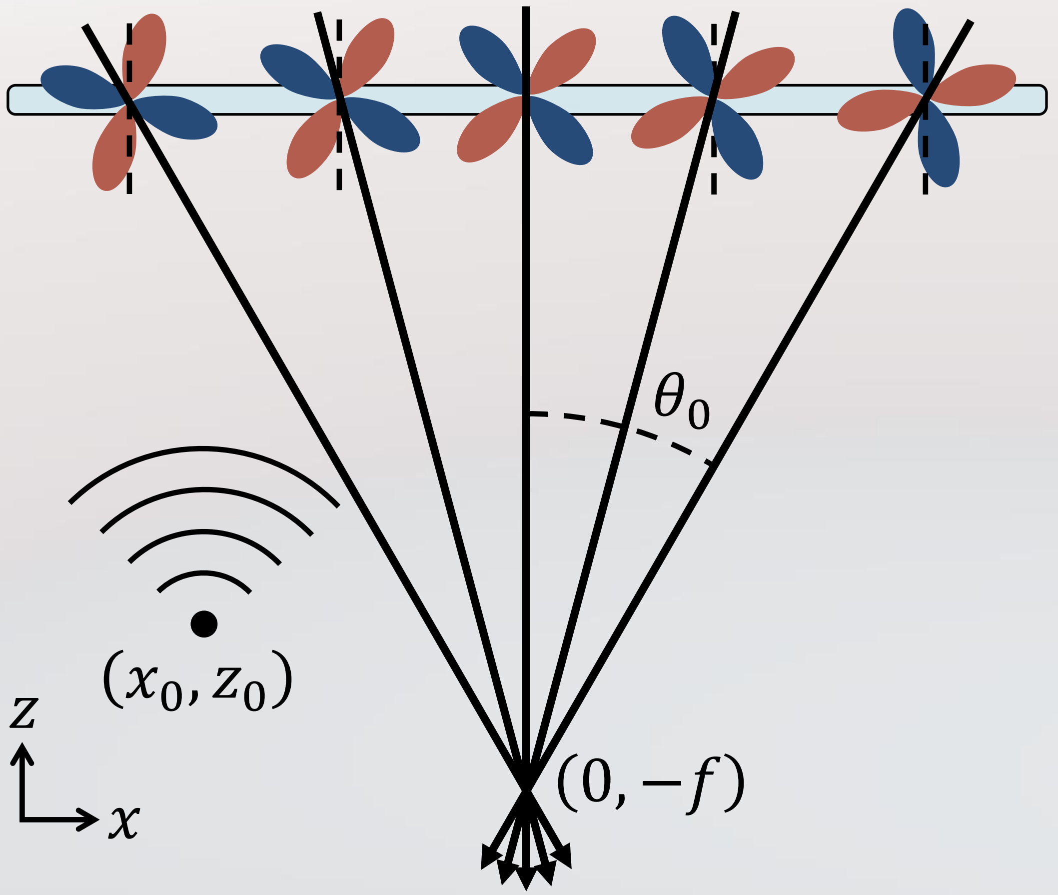
Momentum space
→
Real space

$$Q \sim \frac{1}{k^2} \quad \rightarrow \quad Q \sim \frac{1}{x_0^2}$$

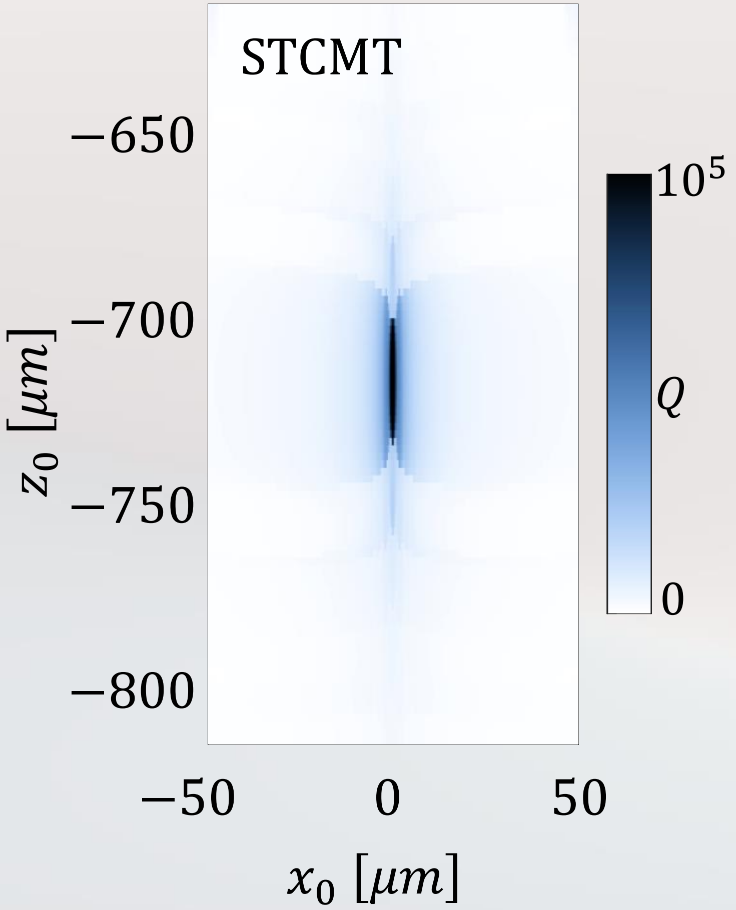


Away from the focal plane

BIC 'Metalens'

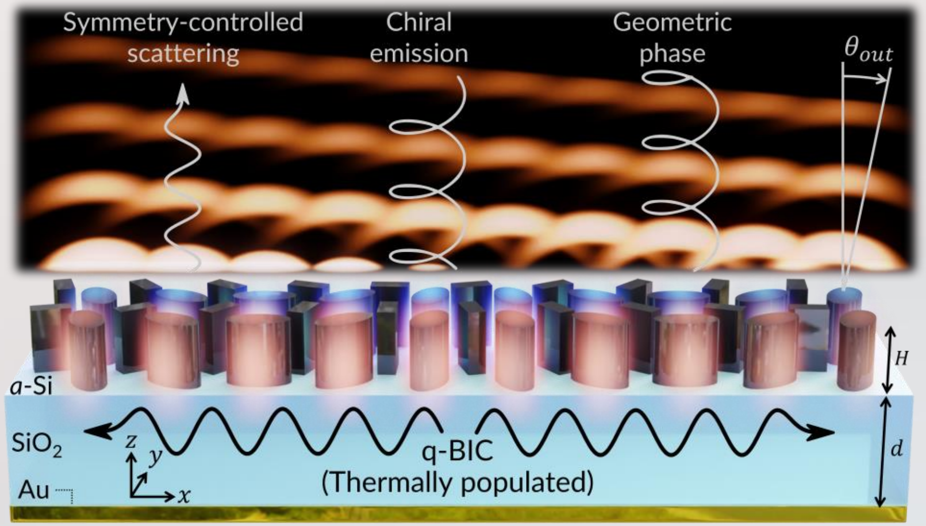


Dark spot

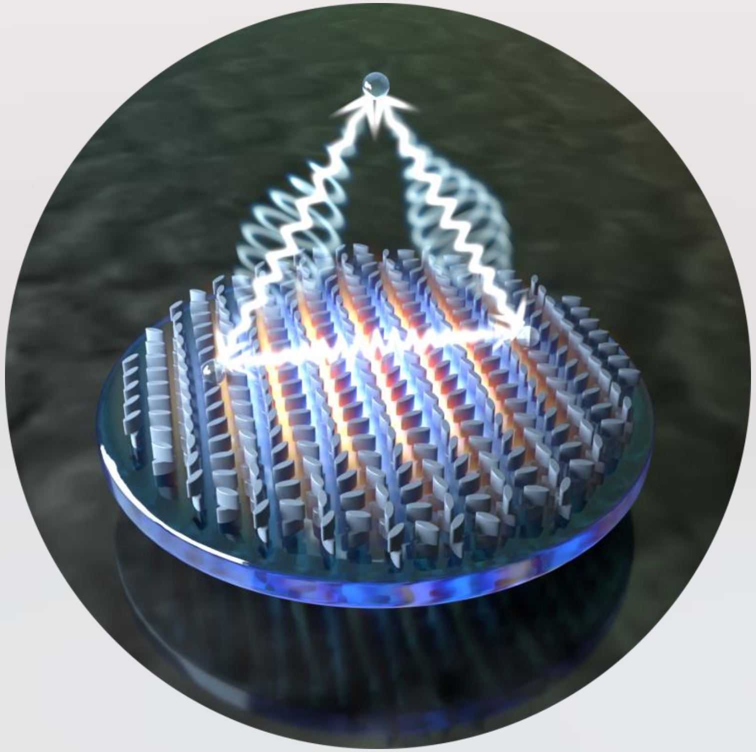


Potential applications: custom sources

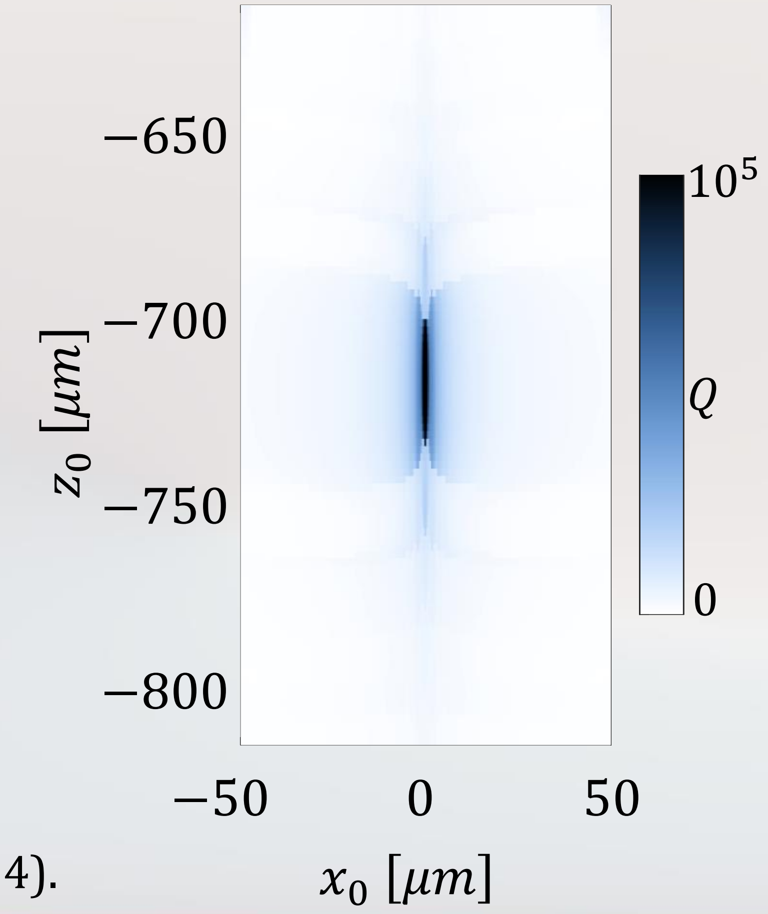
Thermal emission



Laser emission



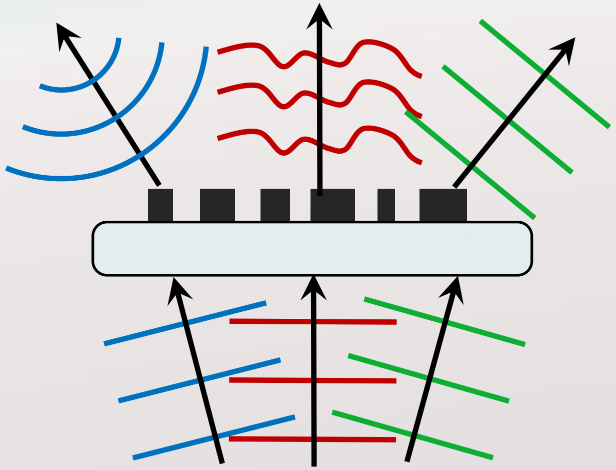
...focused

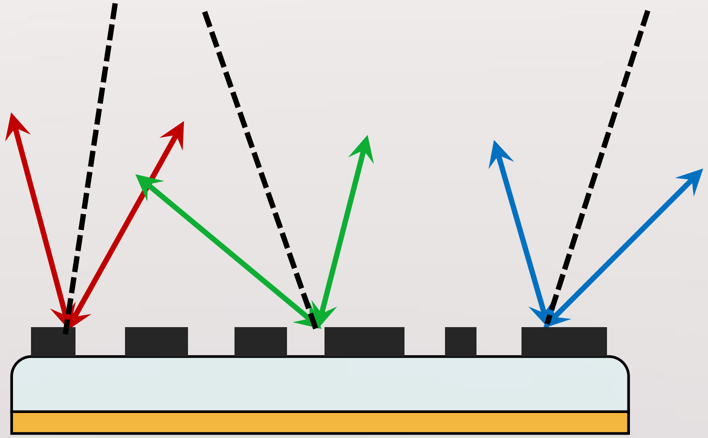


A. Overvig, S. Mann, A. Alu, *PRX* **18**, 021050 (2021)
J. Nolen, A. Overvig, M. Cotrufo, A. Alu, *Nature Nanotechnology* **19**, 1627-1634 (2024).

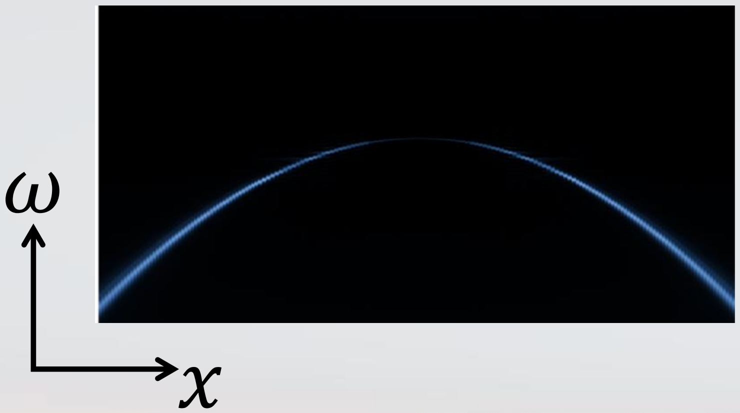
Summary

Nonlocal metasurfaces = opportunities beyond Generalized Snell's Law





Generalizes BICs from the *momentum* eigenstates to *spatial* eigenstates



Publications, 2024

[1] A. Overvig, S. Mann, and A. Alù, "Spatiotemporal Coupled Mode Theory", *Light: Science & Applications*, **13**, 28 (2024).
[2] J. Nolen, A. Overvig, M. Cotrufo, A. Alu, *Nature Nanotechnology* **19**, 1627-1634 (2024).
[3] A. Overvig, F. Monticone, in preparation
[4] A. Overvig, in preparation

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