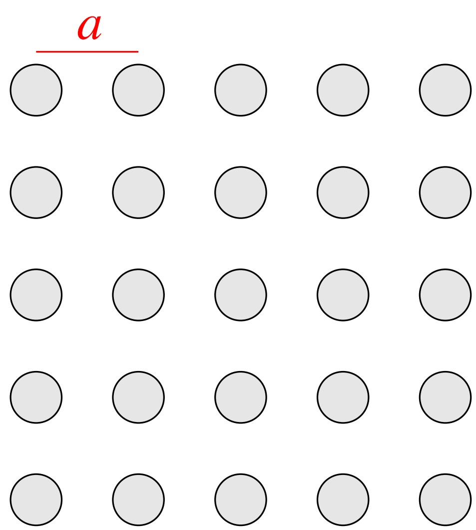
2d photonic crystals

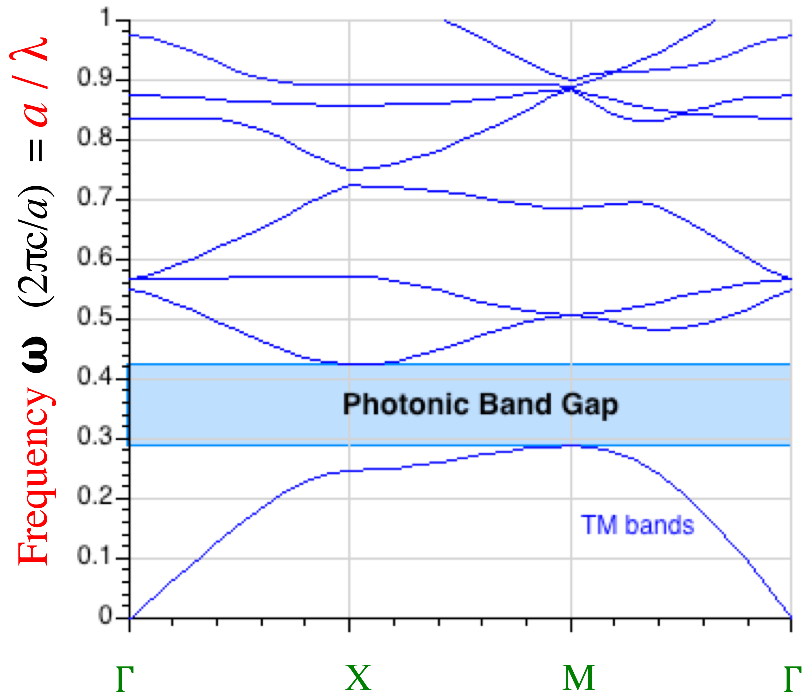
Steven G. Johnson, MIT

18.369/8.315, Spring 2018

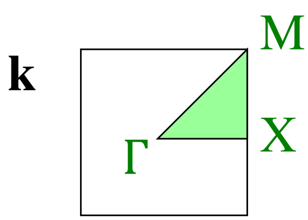
See also chapters 5 and 10 of *Photonic Crystals: Molding the Flow of Light*

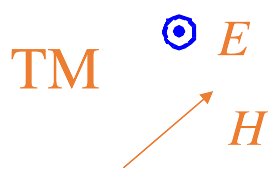
2d periodicity, ε=12:1





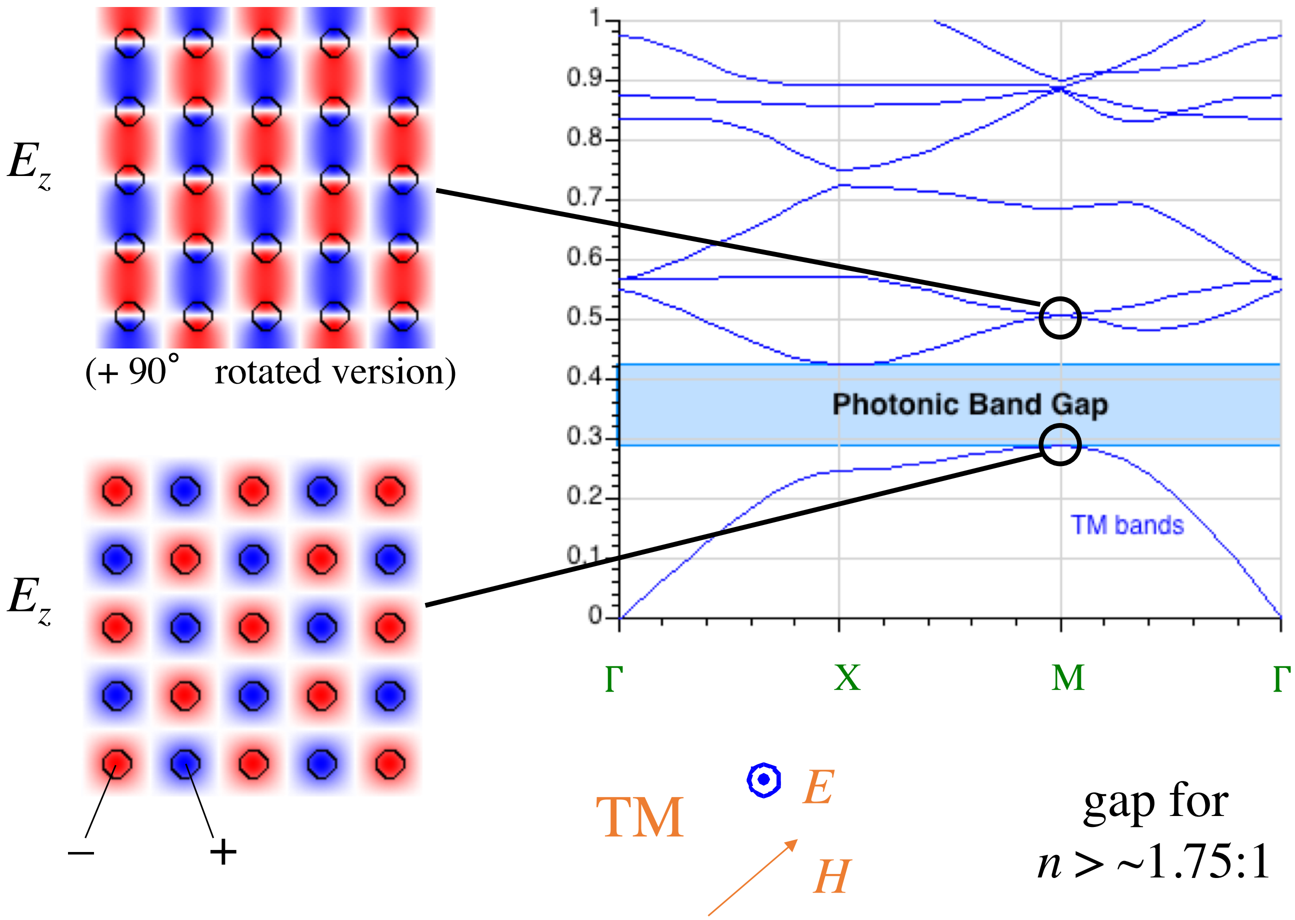
irreducible Brillouin zone





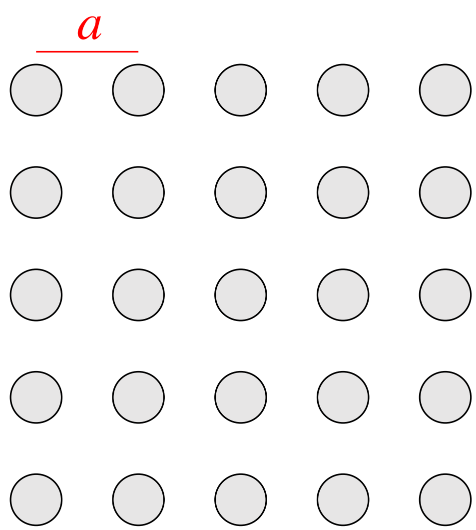
gap for
n > ~1.75:1

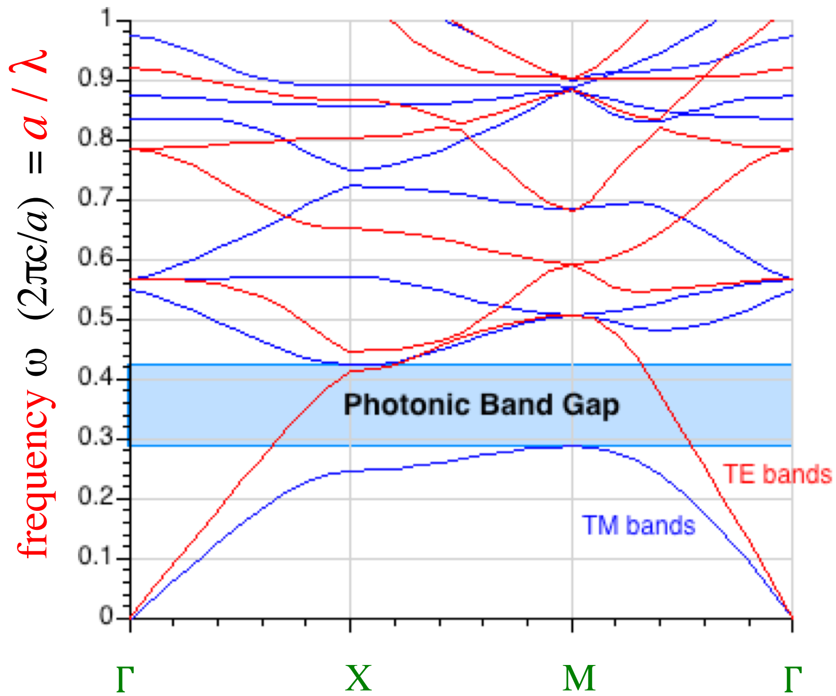
2d periodicity, ε=12:1



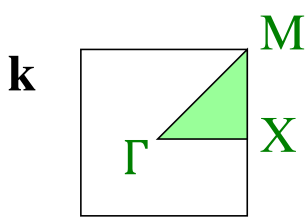
gap for
$n > \sim 1.75:1$

2d periodicity, ε=12:1

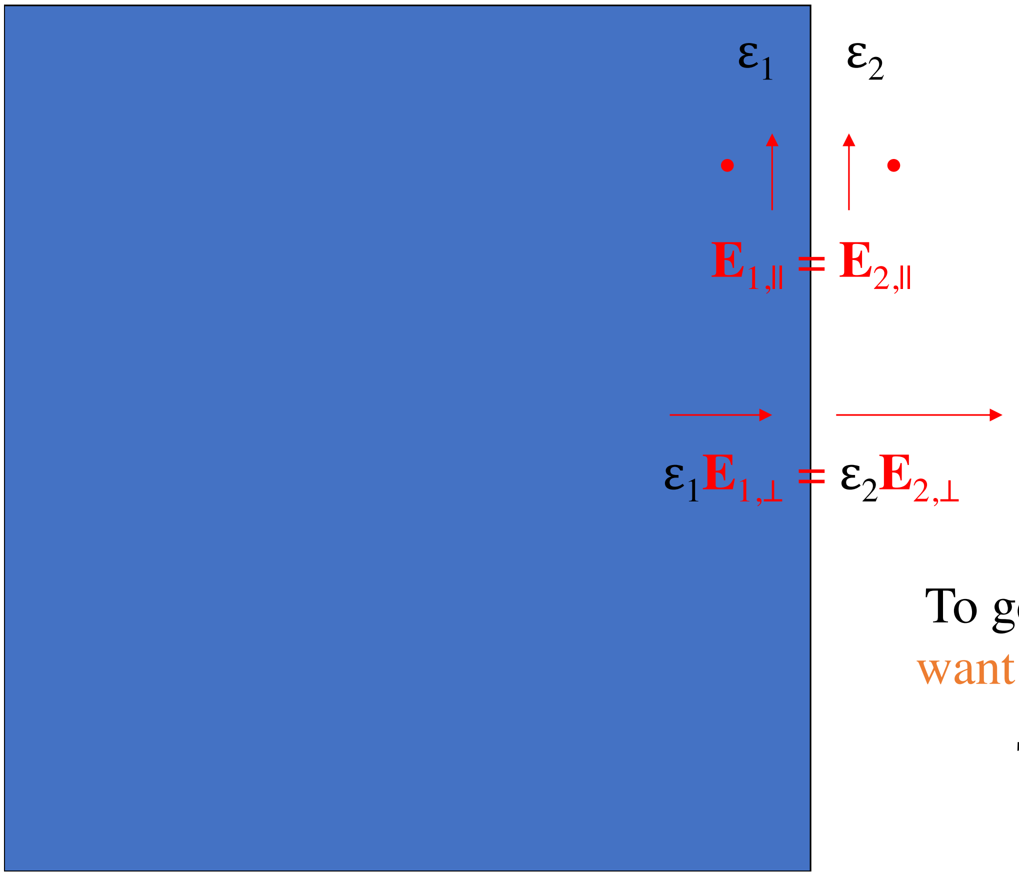




irreducible Brillouin zone



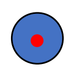
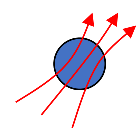
What a difference a boundary condition makes…



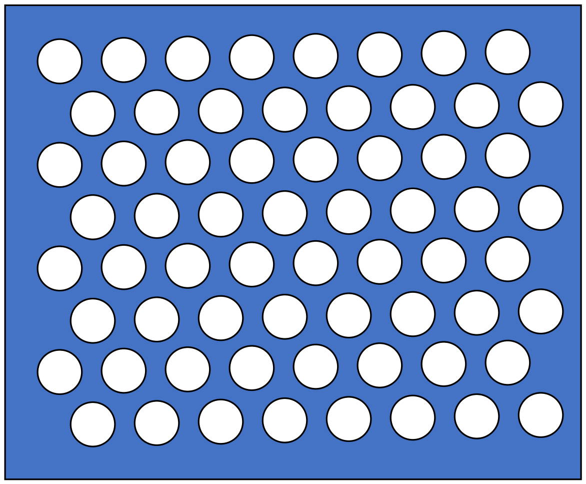
$\mathbf{E}_{\parallel}$ is continuous:
energy density $\varepsilon|\mathbf{E}|^2$
more in larger ε

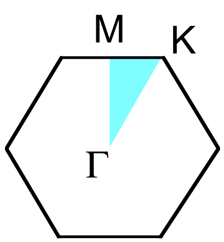
$\varepsilon\mathbf{E}_{\perp}$ is continuous:
energy density $|\varepsilon\mathbf{E}|^2/\varepsilon$
more in smaller ε

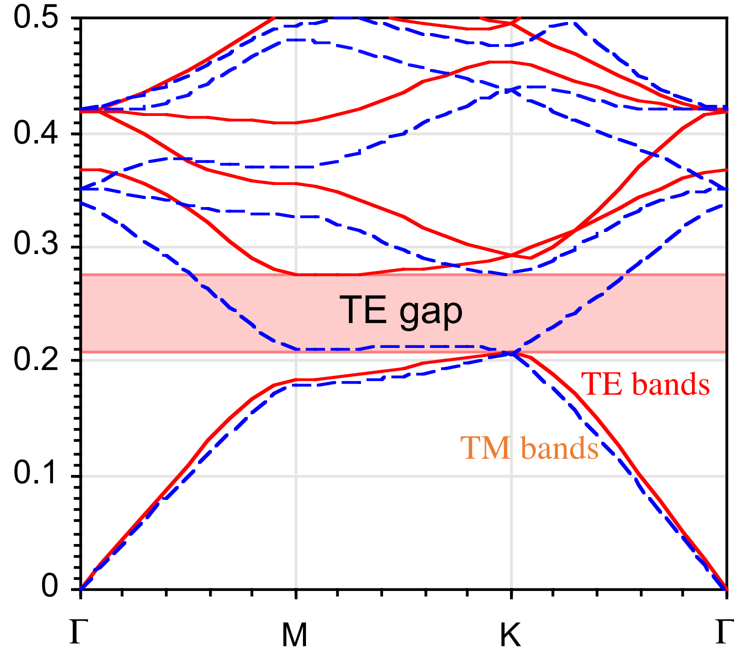
To get strong confinement & gaps,
want **E** mostly parallel to interfaces

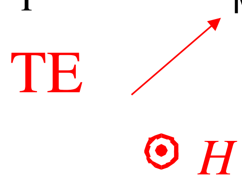
TM: $\parallel$  TE: $\perp$ 

2d photonic crystal: TE gap, ε=12:1



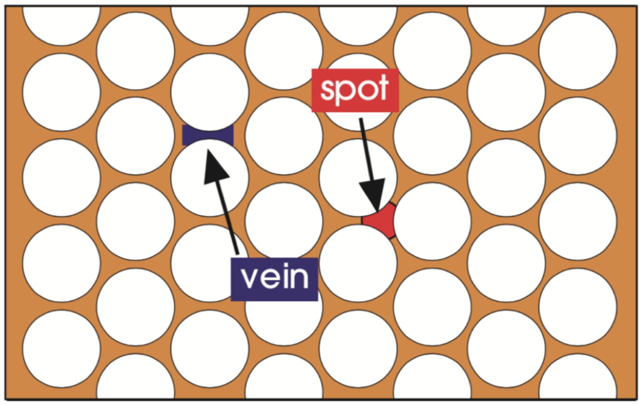






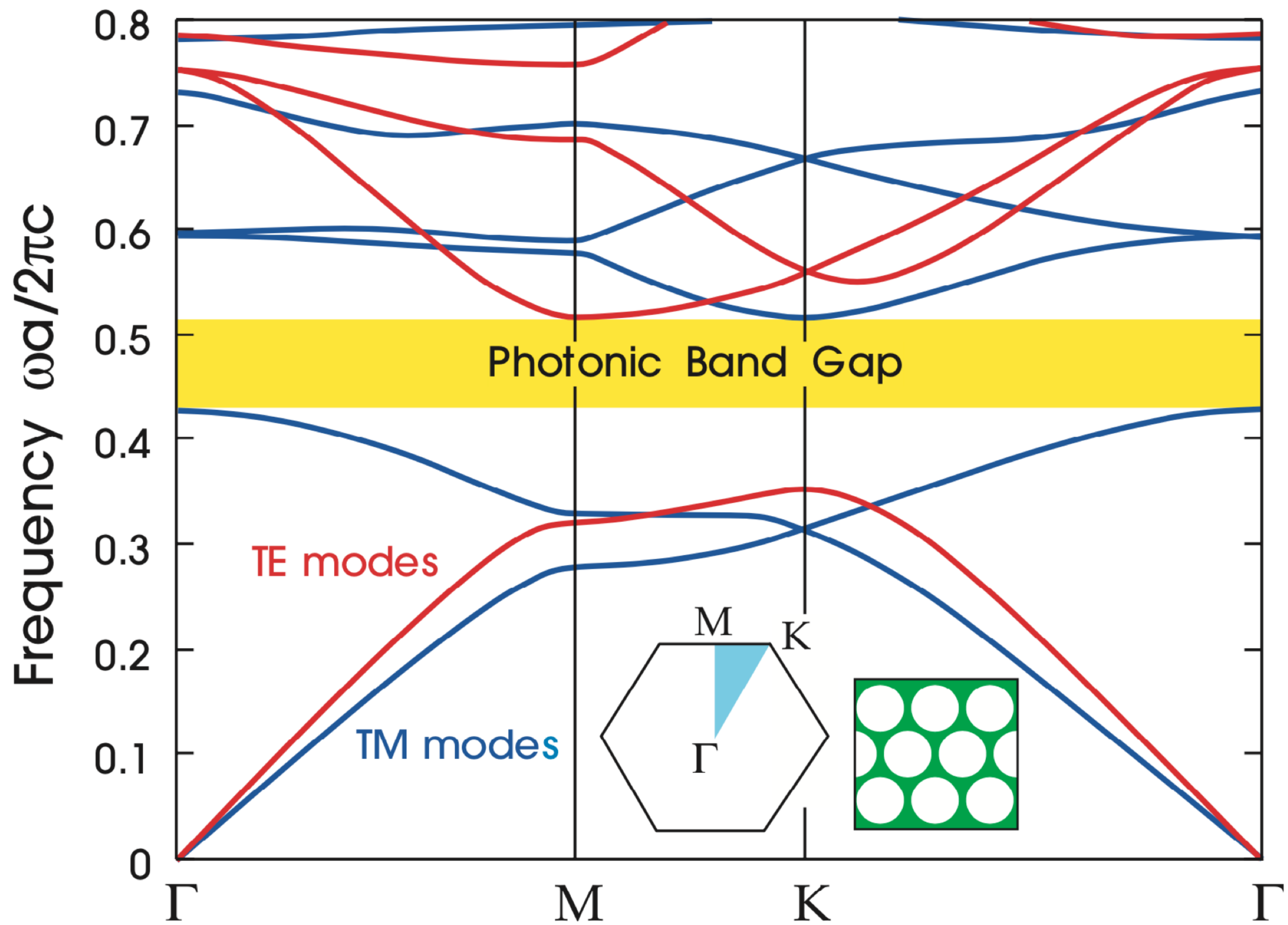
gap for n > ~1.4:1

“Complete” (TE+TM) gap in 2d

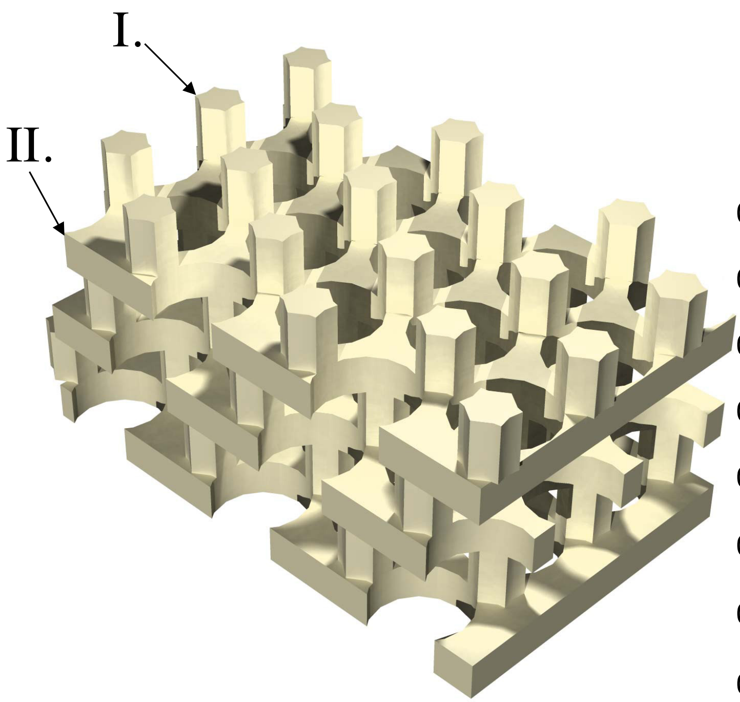


Spots: big enough for lowest TM bands
to concentrate (gap with 3rd band)

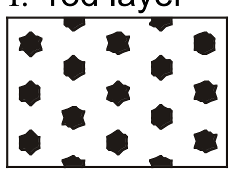
Veins: lowest TE band circles around holes



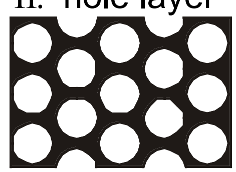
3d photonic crystal: complete gap , ε=12:1

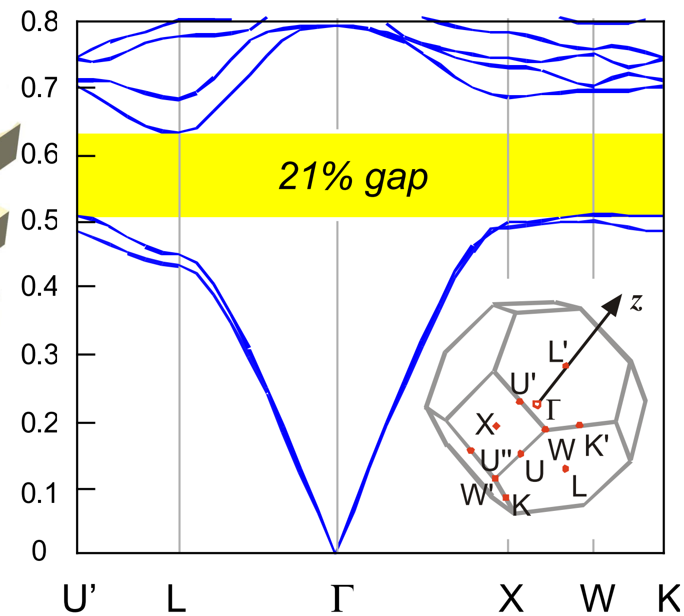


I: rod layer



II: hole layer



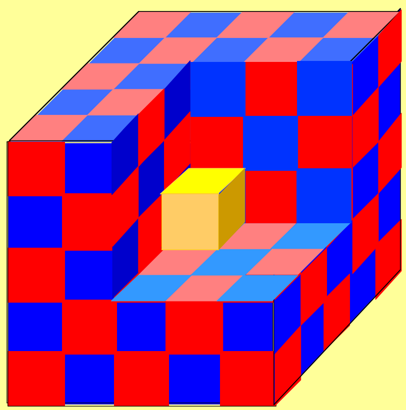


gap for n > ~2:1

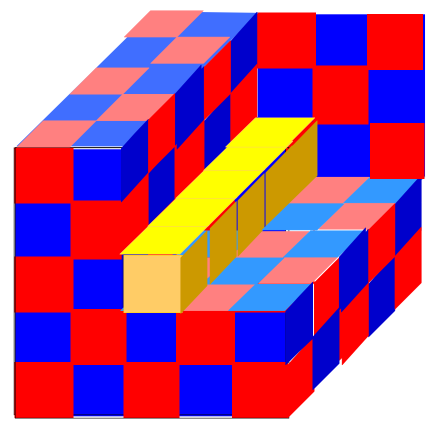
[S. G. Johnson *et al*., *Appl. Phys. Lett*. **77**, 3490 (2000)]

Intentional "defects" are good

microcavities



waveguides ("wires")



Resonance

an oscillating mode trapped for a long time in some volume
(of light, sound, …)

lifetime $\tau >> 2\pi/\omega_0$

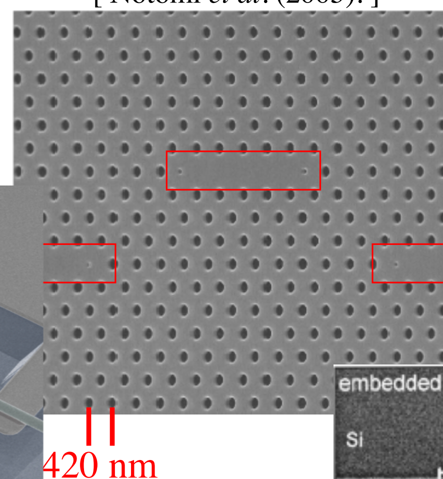
frequency ω_0

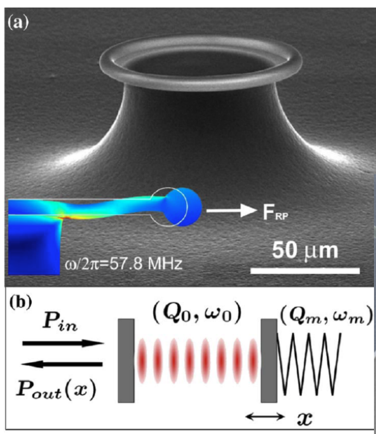
quality factor $Q = \omega_0\tau/2$

energy ~ $e^{-\omega_0 t/Q}$

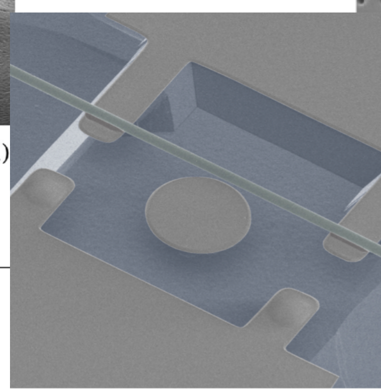
modal volume V

[Notomi *et al*. (2005).]



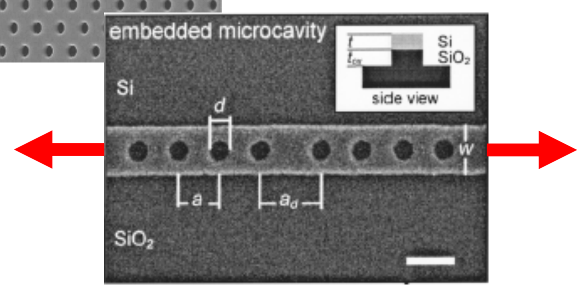


[Schliesser et al., *PRL* **97**, 243905 (2006)]



[Eichenfield et al. *Nature Photonics* **1**, 416 (2007)]

[C.-W. Wong, *APL* **84**, 1242 (2004).]



Why Resonance?

an oscillating mode trapped for a long time in some volume

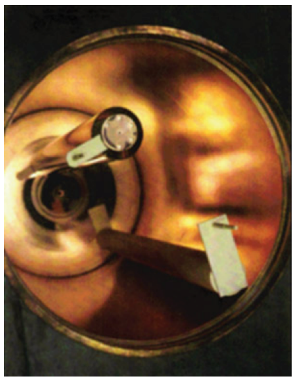
- long time = narrow bandwidth … filters (WDM, etc.)
  — $1/Q$ = fractional bandwidth

- resonant processes allow one to "impedance match" hard-to-couple inputs/outputs

- long time, small V … enhanced wave/matter interaction
  — lasers, nonlinear optics, opto-mechanical coupling, sensors, LEDs, thermal sources, …

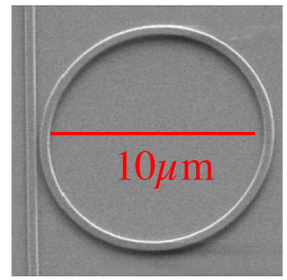
How Resonance?

need mechanism to trap light for long time



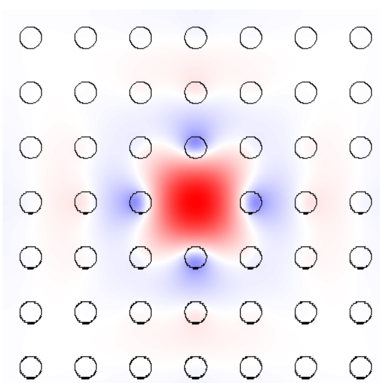
[llnl.gov]

metallic cavities:
good for microwave,
dissipative for infrared

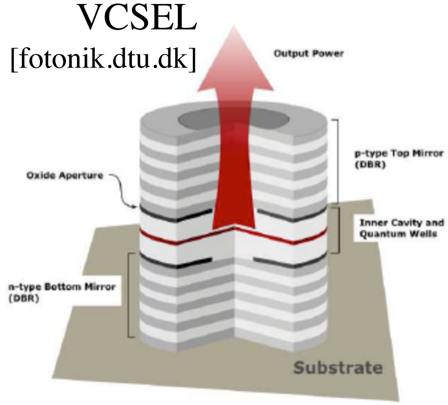


[Xu & Lipson (2005)]

ring/disc/sphere resonators:
a waveguide bent in circle,
bending loss ~ exp(–radius)

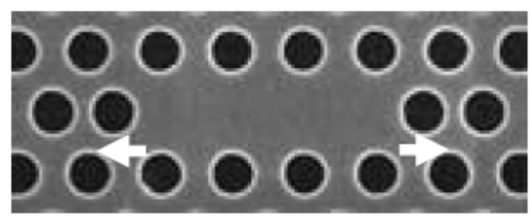


VCSEL
[fotonik.dtu.dk]



photonic bandgaps
(complete or partial
+ index-guiding)

[Akahane, *Nature* **425**, 944 (2003)]

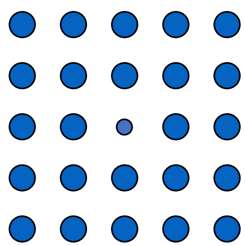


(planar Si slab)

Why do defects in crystals
trap resonant modes?

What do the modes look like?

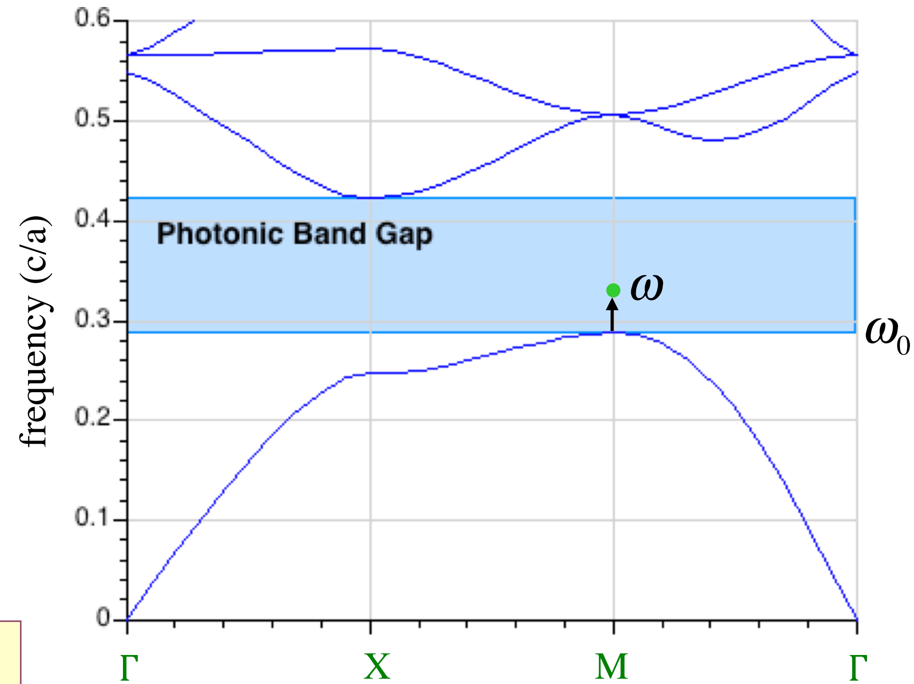
Single-Mode Cavity

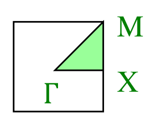


A *point defect*
can push up
a single mode
from the band edge

$$\text{field decay} \sim \sqrt{\frac{\omega - \omega_0}{\text{curvature}}}$$

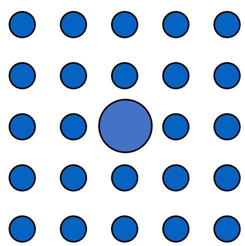
Bulk Crystal Band Diagram





(k not conserved)

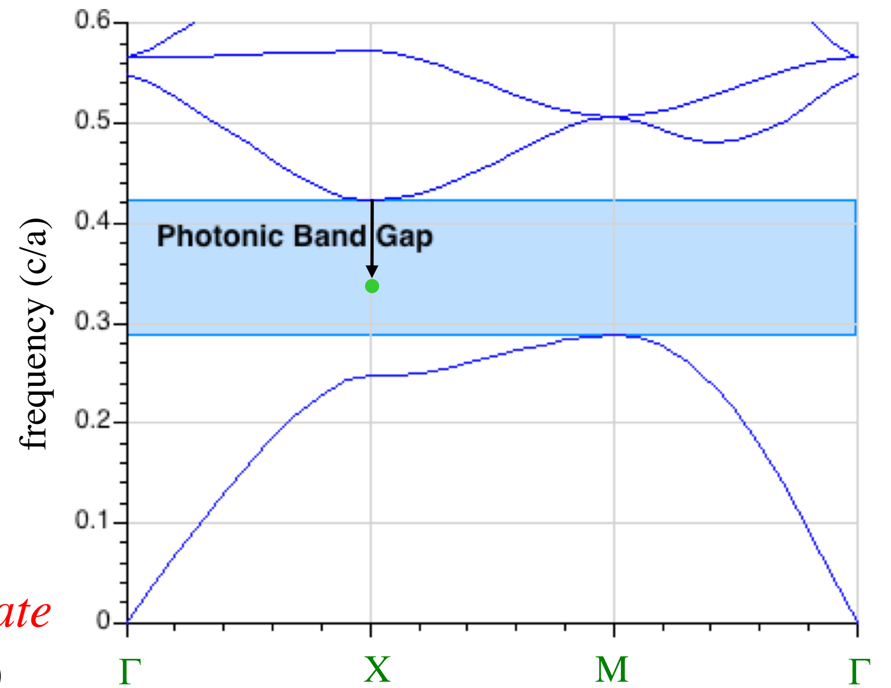
“Single”-Mode Cavity

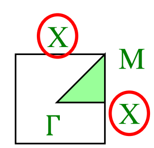


A *point defect* can pull down a “single” mode

…here, doubly-*degenerate* (*two* states at *same* ω)

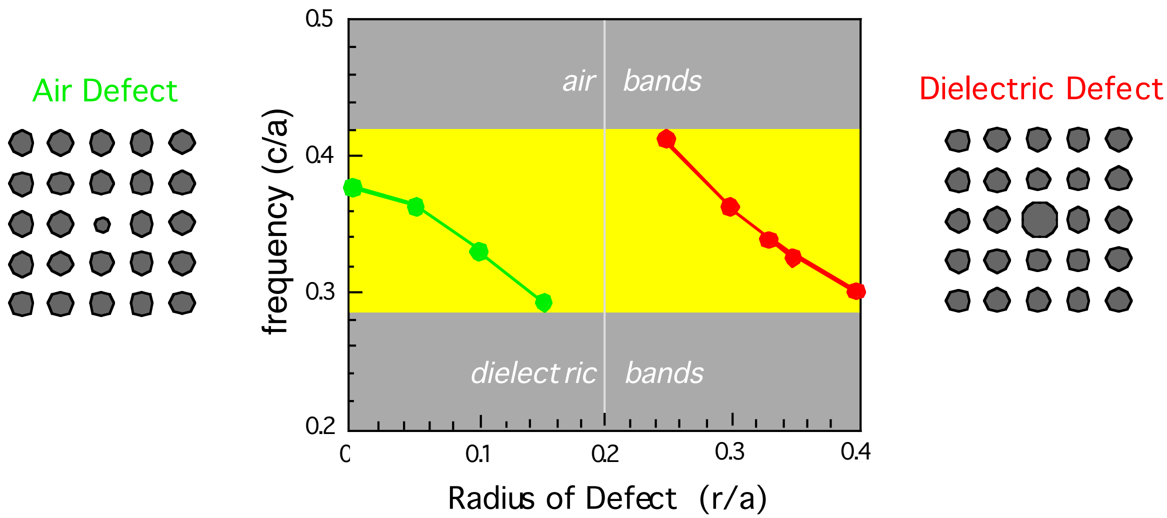
Bulk Crystal Band Diagram



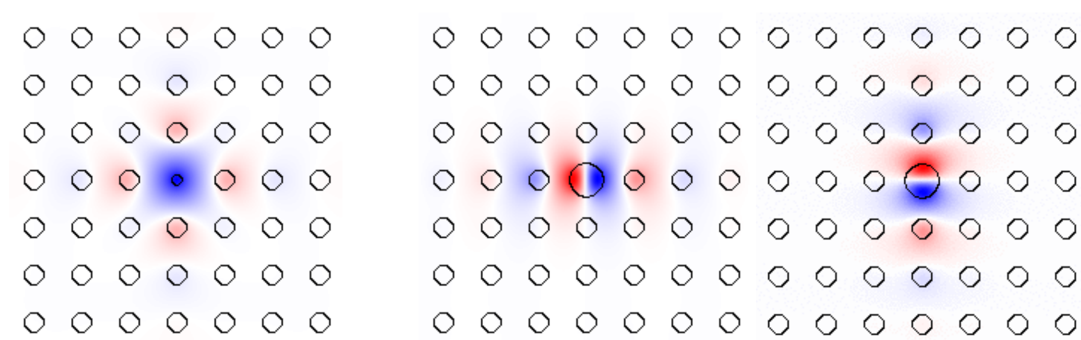


(k not conserved)

Tunable Cavity Modes



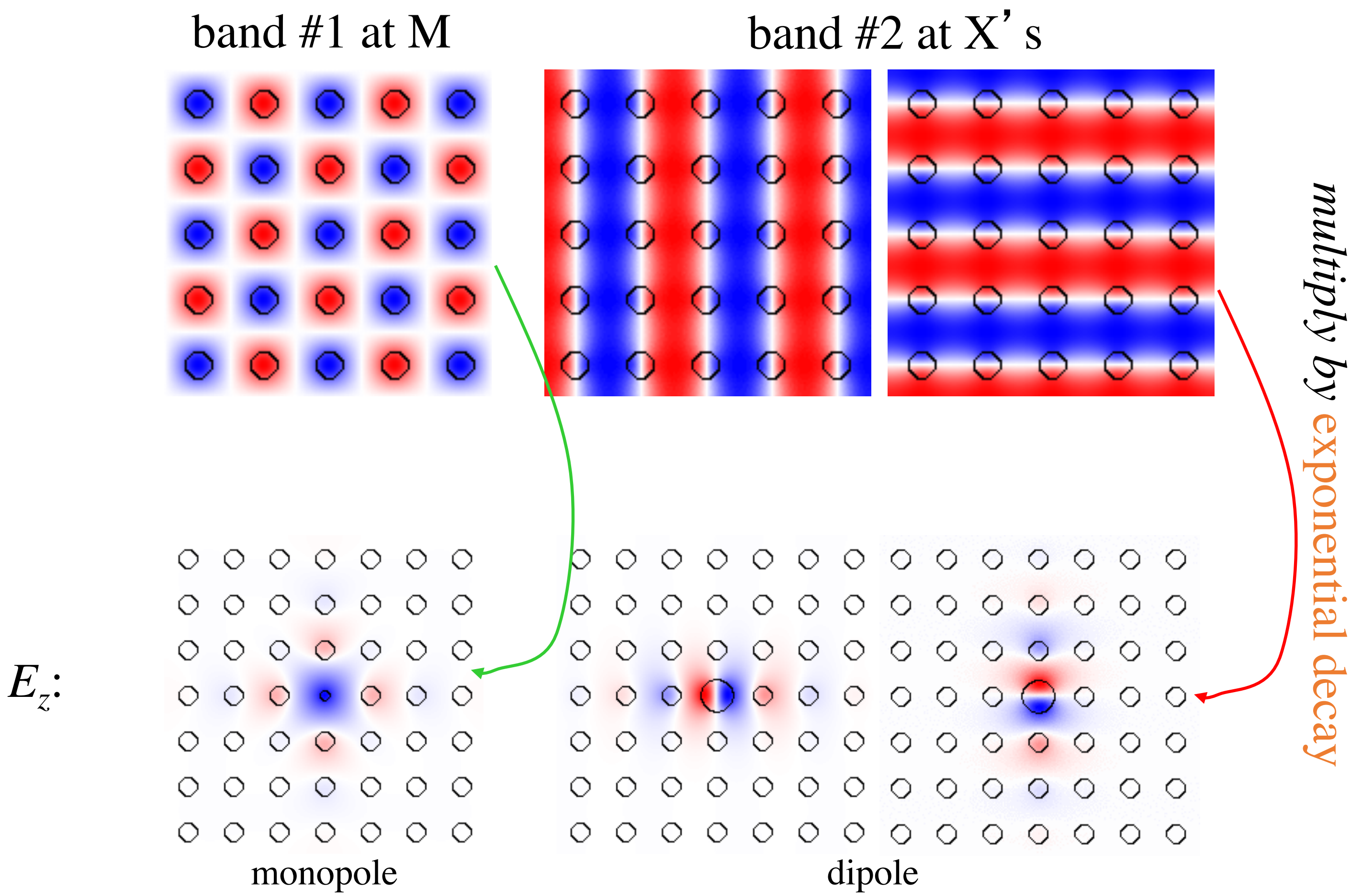
E_z:



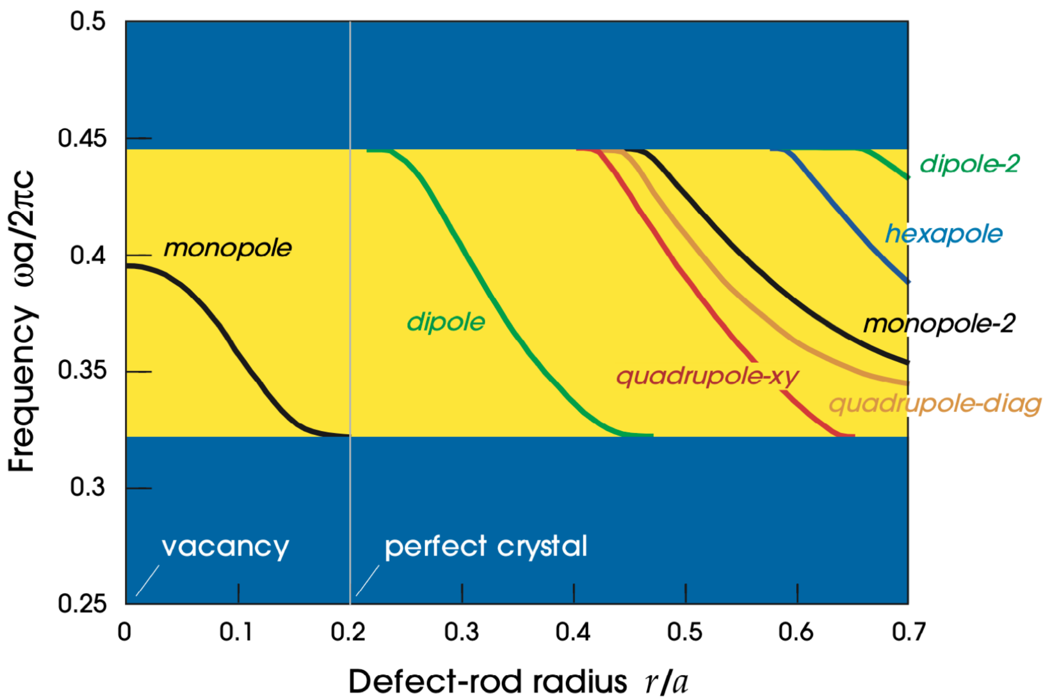
monopole

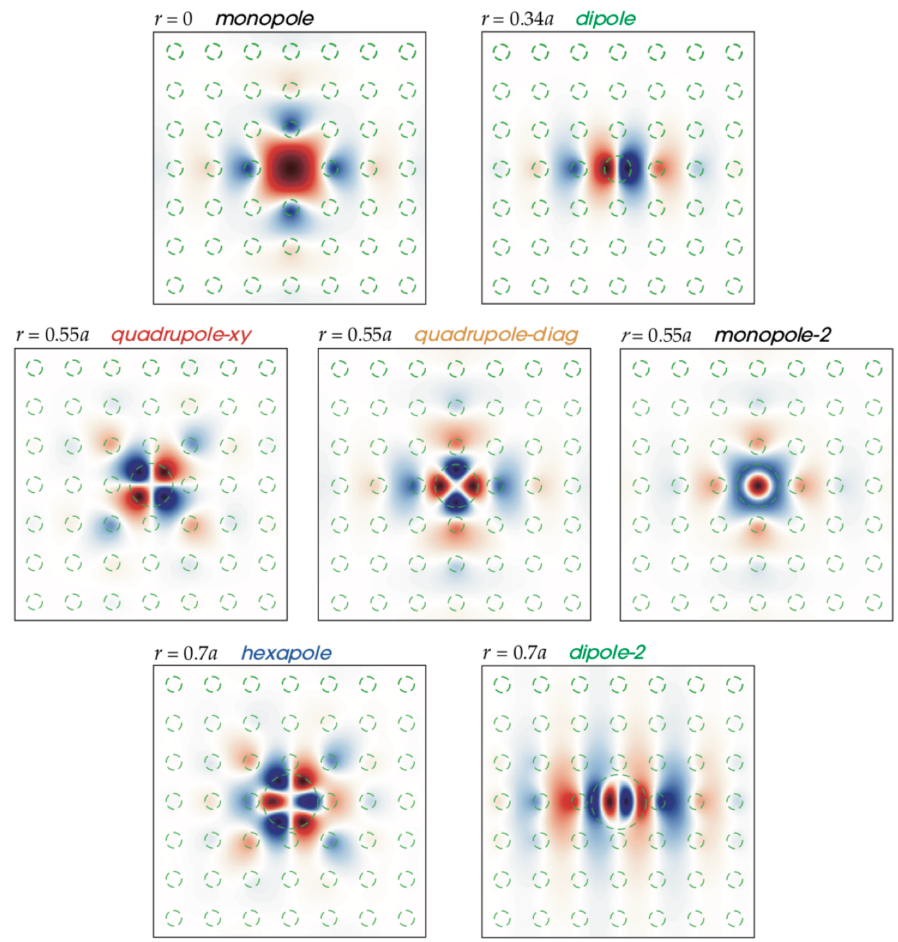
dipole

Tunable Cavity Modes



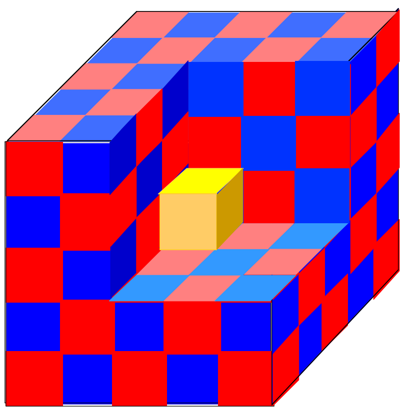
More defect modes (4 out of 5 C_{4v} irreps here)



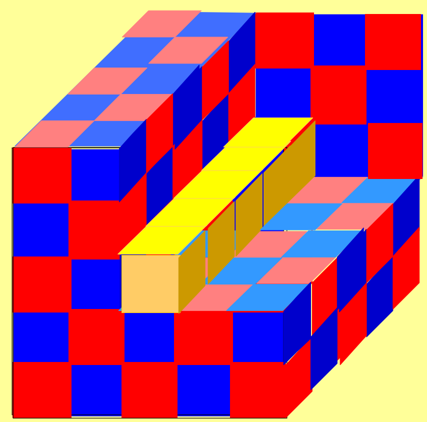


Intentional “defects” are good

microcavities

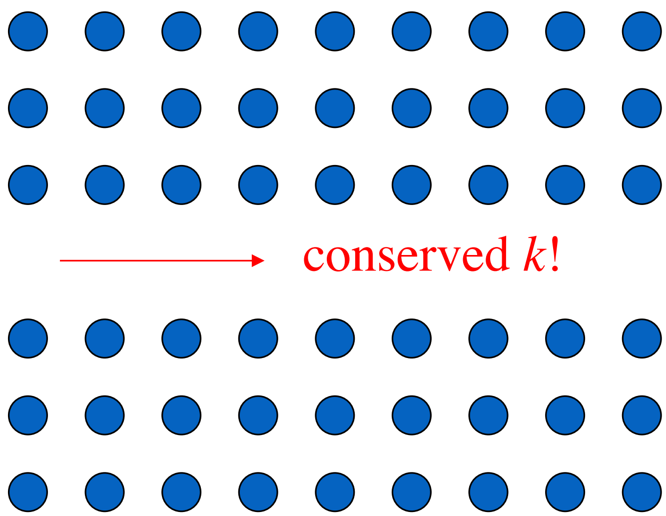


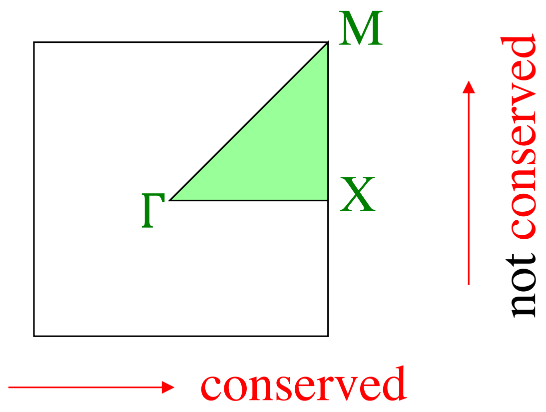
waveguides (“wires”)



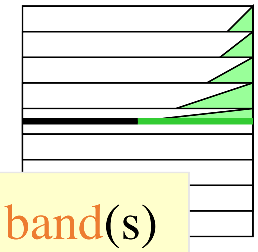
Projected Band Diagrams

1d periodicity



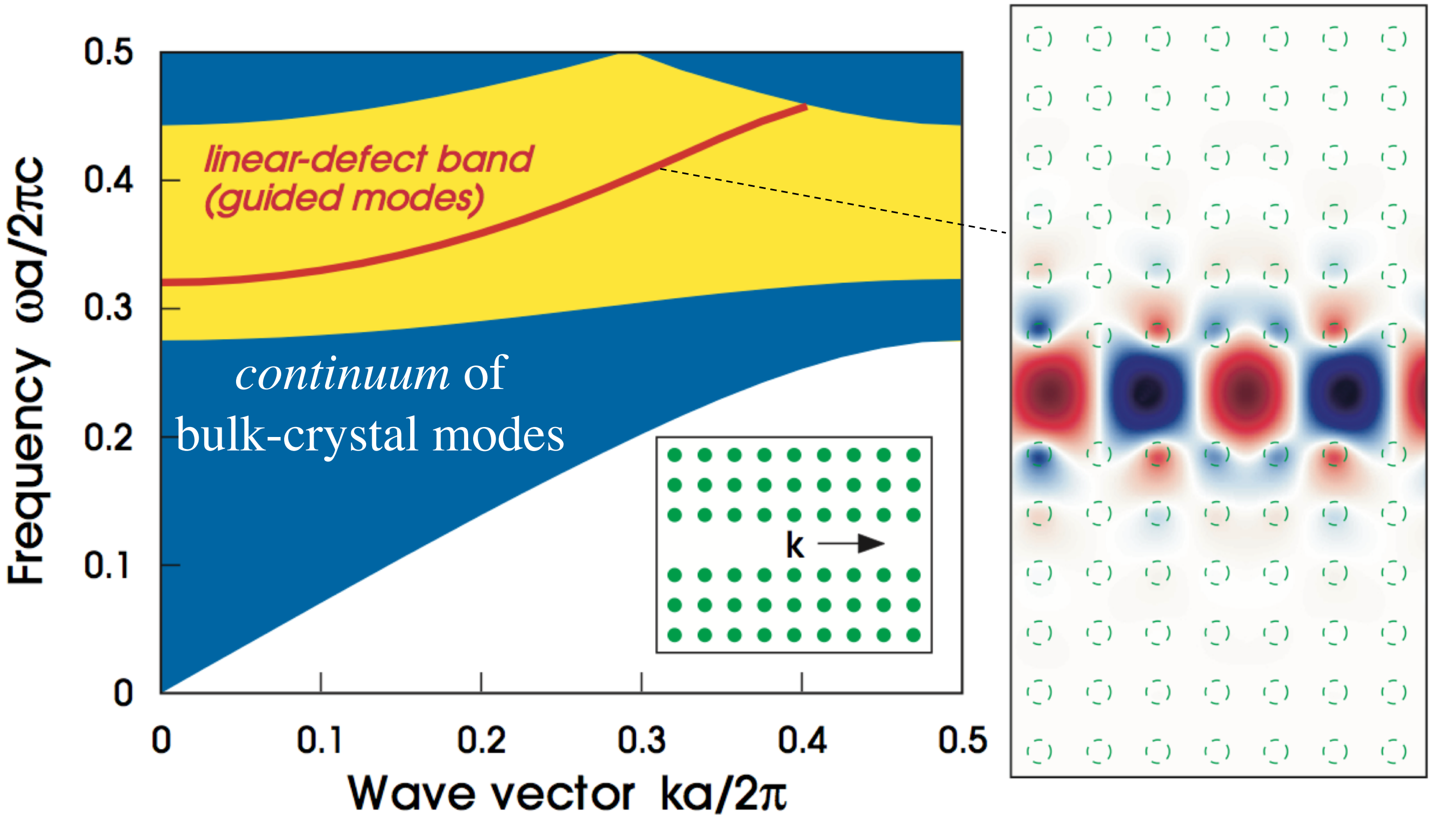


So, plot ω vs. k_x only…project Brillouin zone onto Γ–X:



gives continuum of bulk states + discrete guided band(s)

Air-waveguide Band Diagram



any state in the gap cannot couple to bulk crystal ⇒ localized

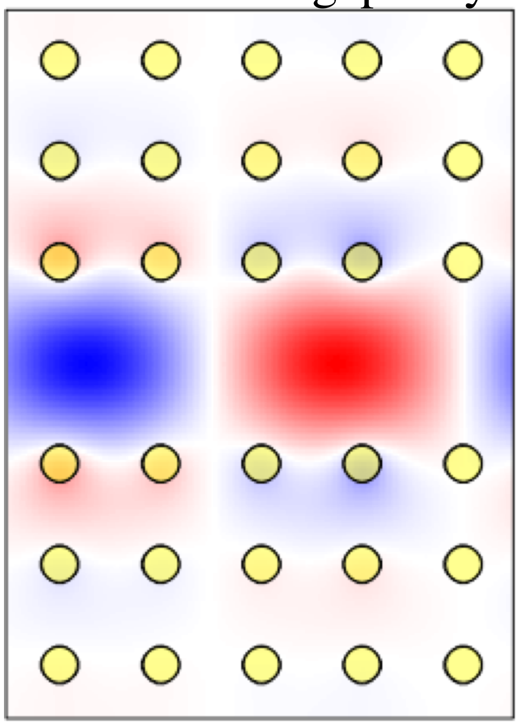
(Waveguides don't really need a *complete* gap)

Fabry-Perot waveguide:

This is exploited *e.g*. for photonic-crystal fibers…

Guiding Light in Air!

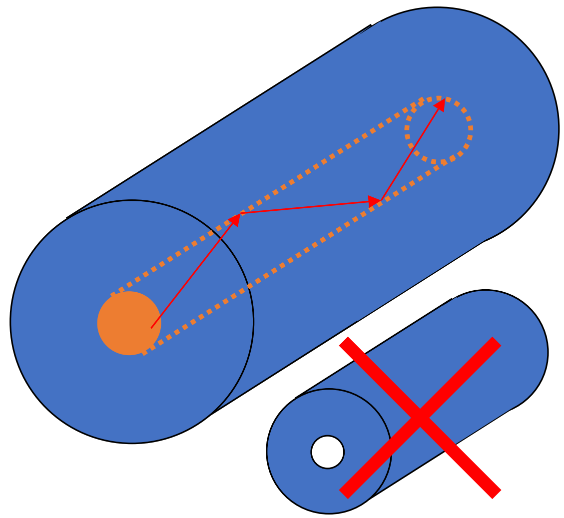
mechanism is gap only



vs. standard optical fiber:

"total internal reflection"

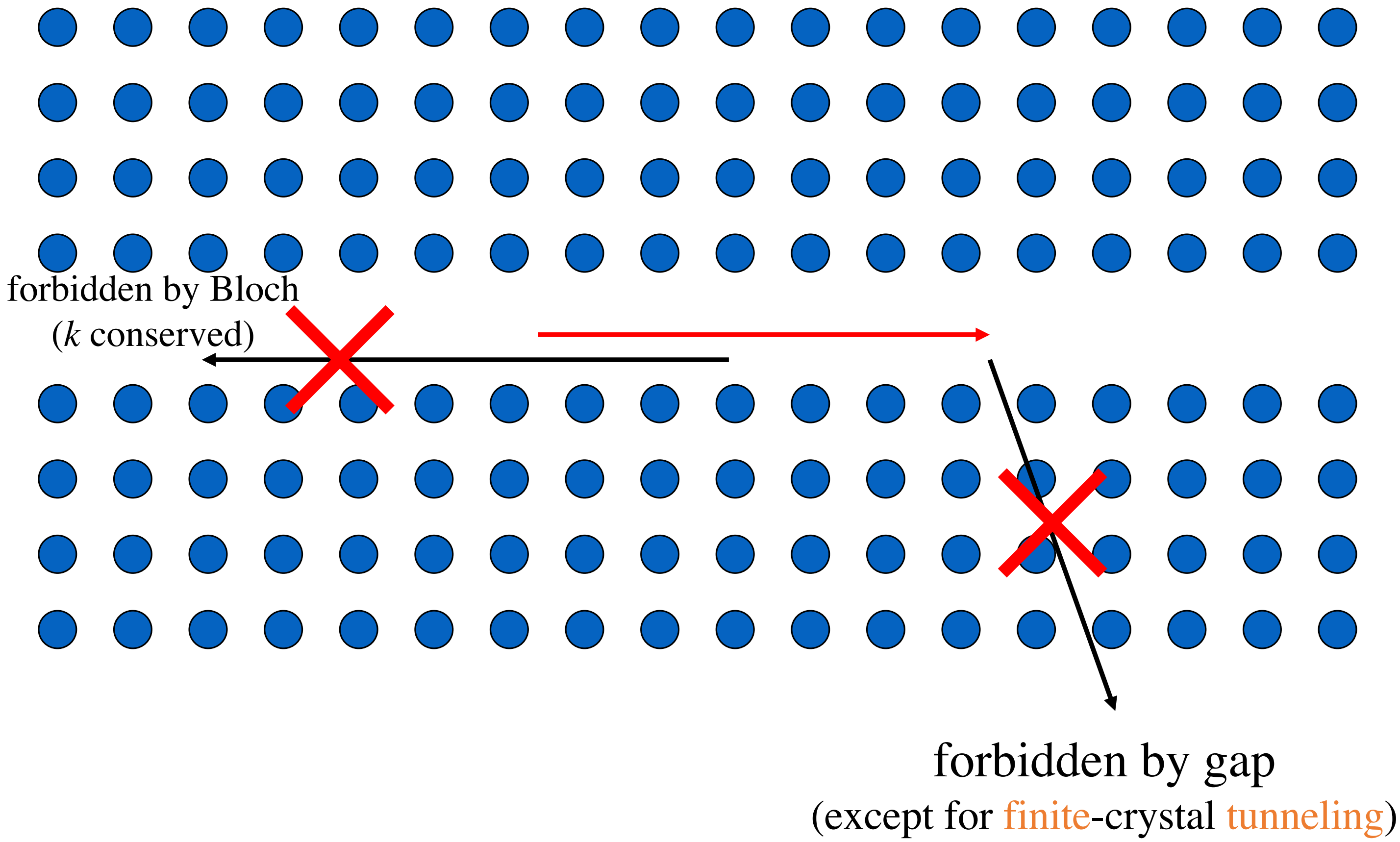
— requires *higher*-index core



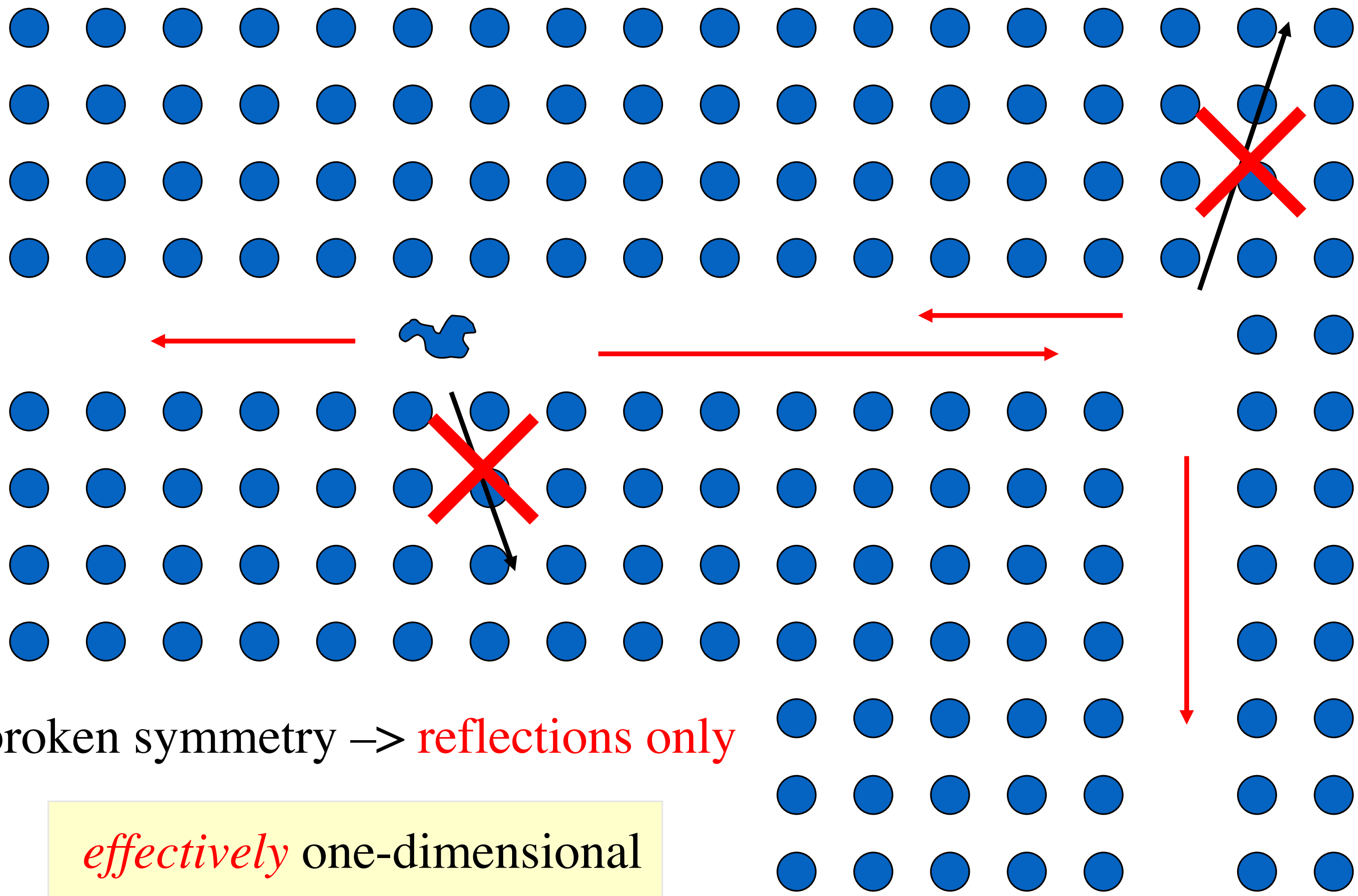
no hollow core!

hollow = lower absorption, lower nonlinearities, higher power

Review: Why no scattering?



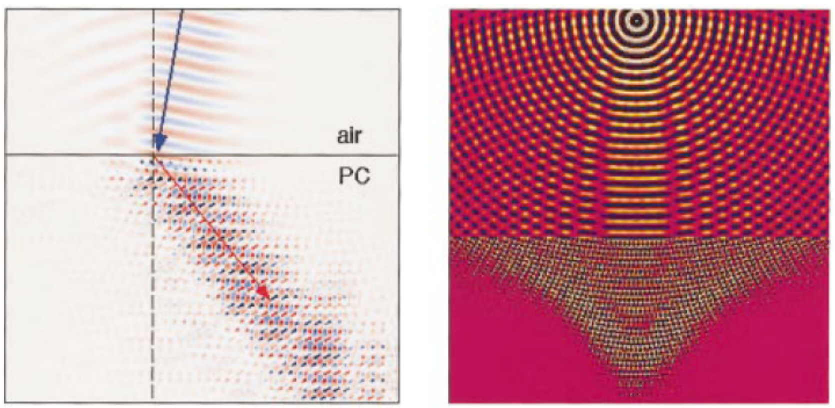
Benefits of a complete gap…



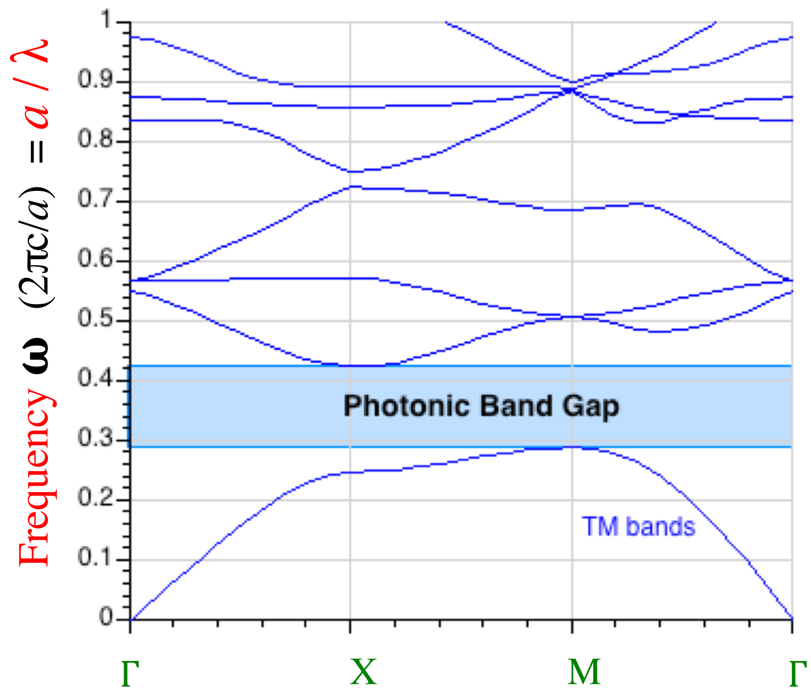
broken symmetry –> reflections only

effectively one-dimensional

Band diagrams: Poor tool to understand refraction/reflection at interfaces



[M. Notomi, *PRB* **62**, 10696 (2000).]



At an interface, only ω and surface-parallel **k** are conserved.

— we need *all the solutions* at a given ω, not the different ω's at a given **k**.

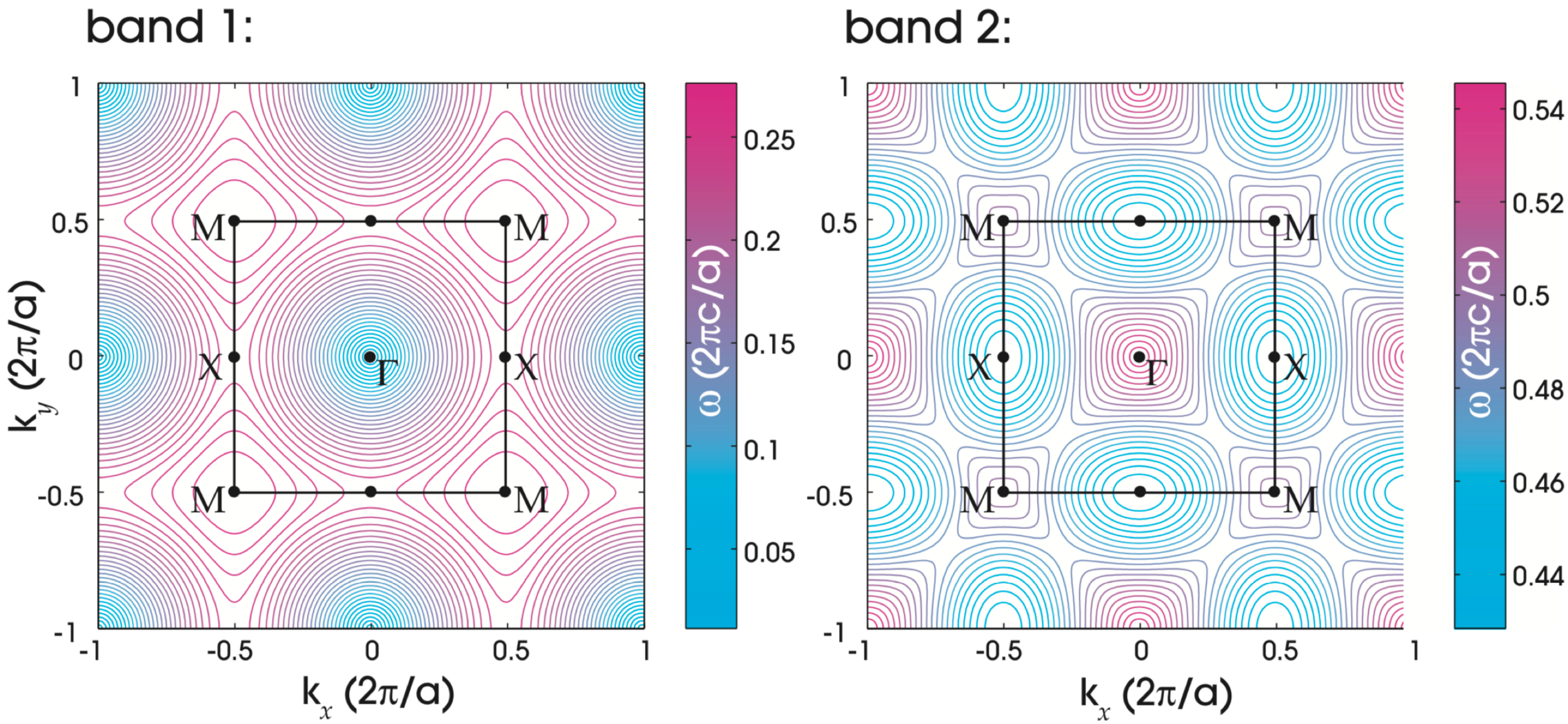
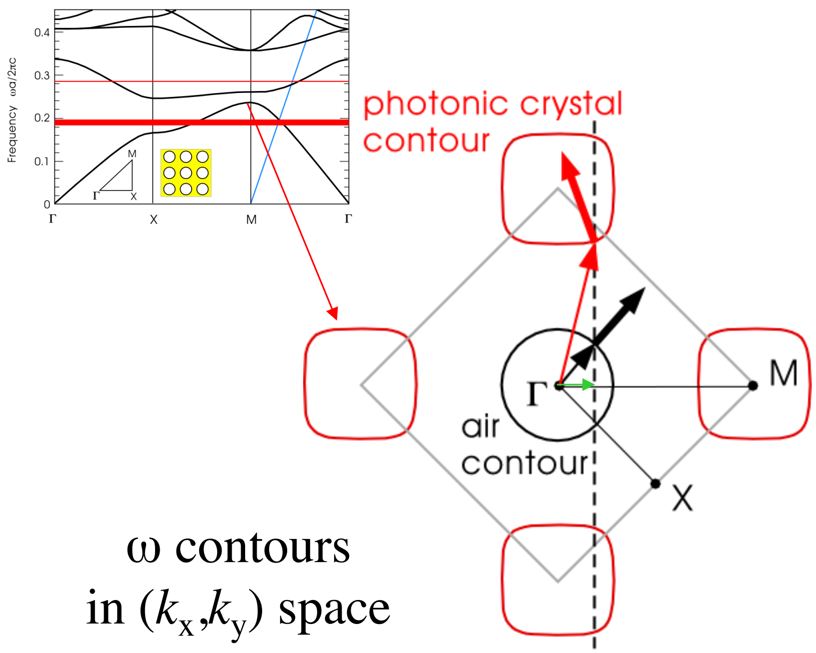


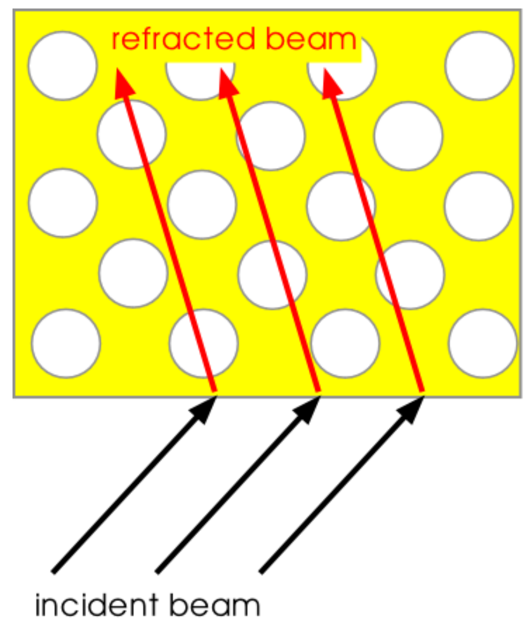
Figure 15: Isofrequency diagrams: contour plots of $\omega(k_x, k_y)$ for the first two TM bands of a square lattice of radius $0.2a$ dielectric rods ($\varepsilon = 11.4$) in air. The first Brillouin zone is shown as black squares.

Refraction and wavevector diagrams

[Luo *et al*, *PRB* **65**, 2001104 (2002).]



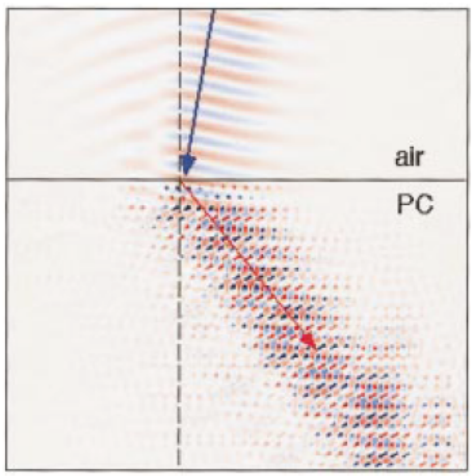
ω contours in (k_x, k_y) space



→ $k_{||}$ is conserved

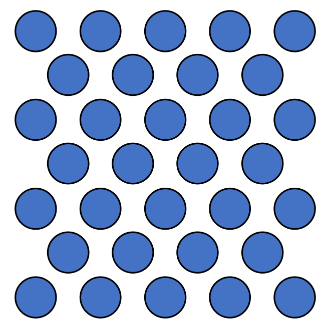
Negative-refractive
all-dielectric photonic crystals

negative refraction



focussing

(2d rods in air, TE)



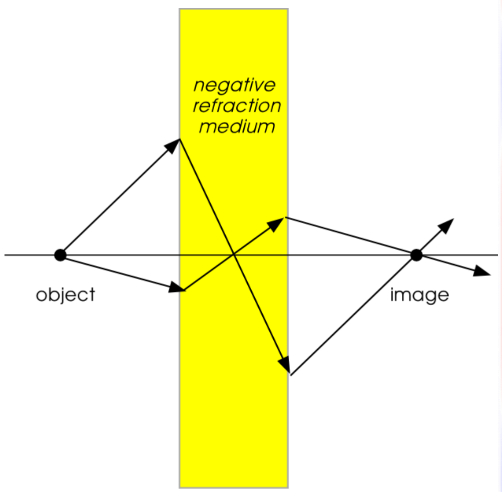
[M. Notomi, *PRB* **62**, 10696 (2000).]

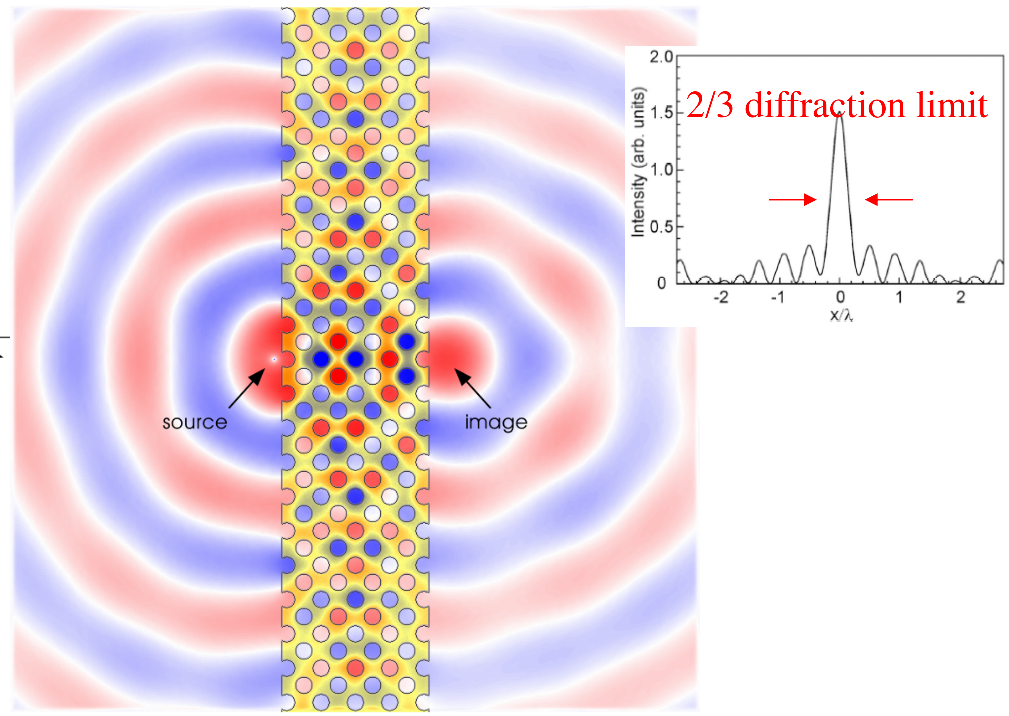
not metamaterials: wavelength ~ a,

no homogeneous material can reproduce *all* behaviors

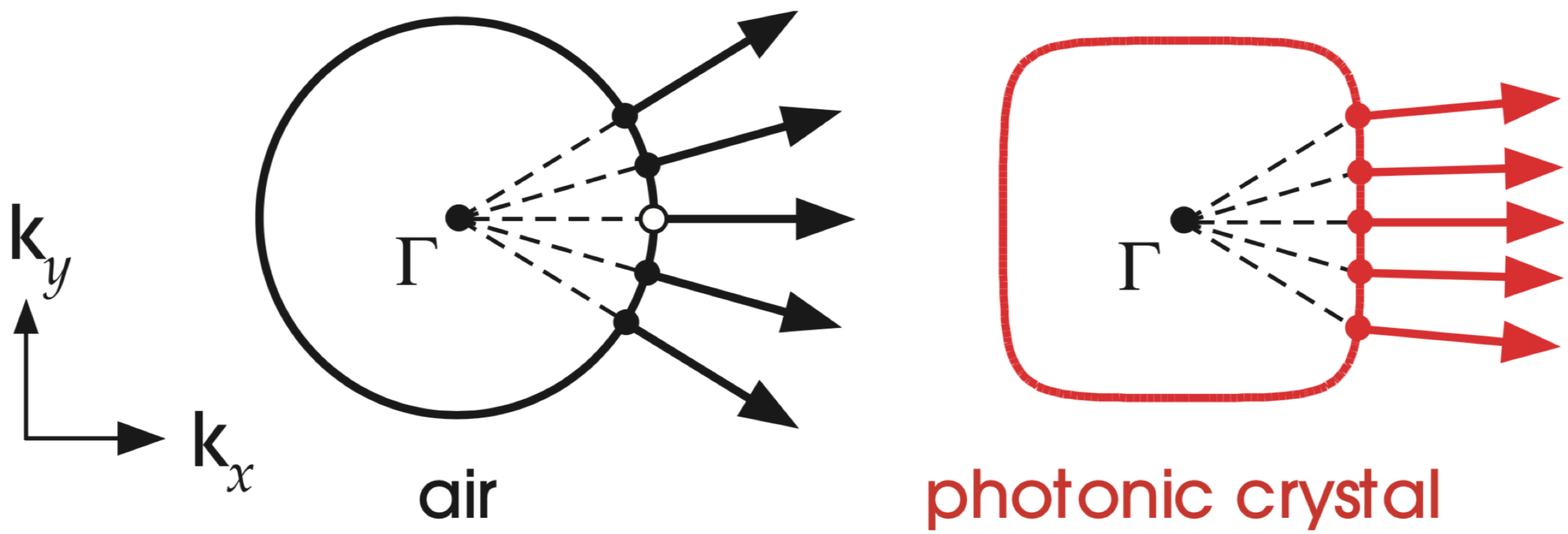
“Superlensing” with Photonic Crystals

[Luo *et al*, *PRB* **68**, 045115 (2003).]





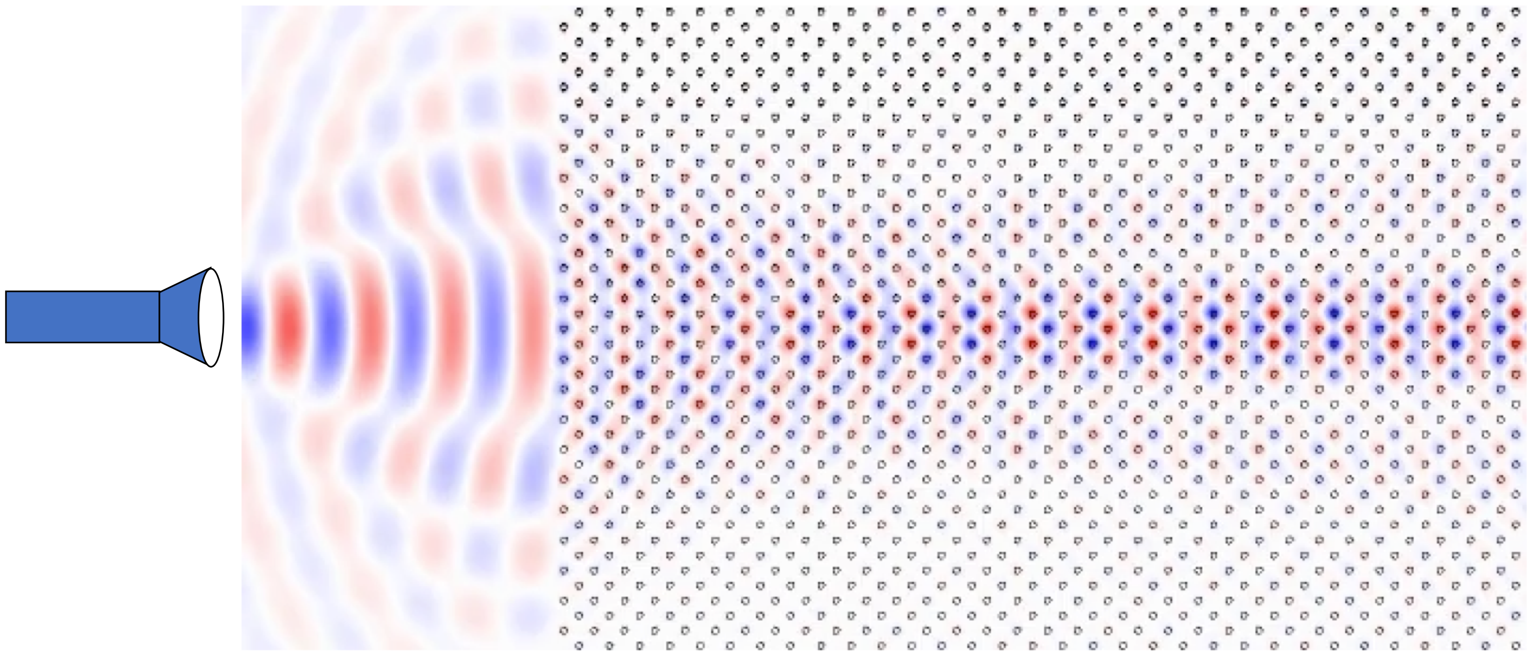
Supercollimation



A Gaussian (etc.) beam propagating in the *x* direction consists of many k_y components at the same ω. In a homogeneous medium, each k_y component travels in a different direction (group velocity). The beam therefore spreads (diffracts).

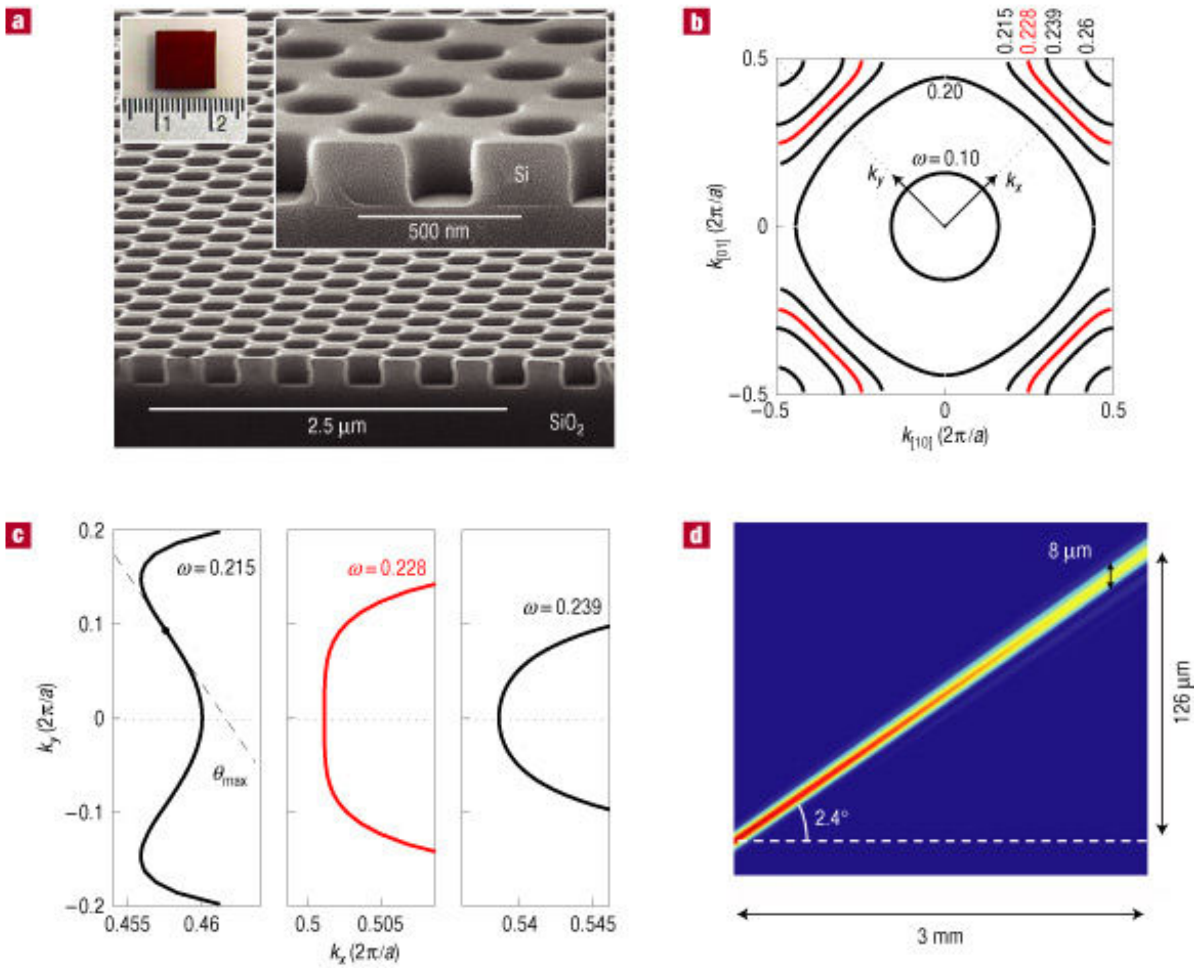
In a photonic crystal, the ω contour can be very "flat" so beam spreading is minimized: all the k_y components travel in almost the same direction. Supercollimation!

Supercollimation on the computer:



the light forms one or more *coherent "Bloch beams"*
that propagate *without scattering*
… and almost *without diffraction* (*supercollimation*)

Experimental supercollimation



Rakich et al., "Achieving centimetre-scale supercollimation in a large-area two-dimensional photonic crystal," *Nature Materials* **5**, 93–96 (2006).

Experimental supercollimation at λ≈1.5μm

Rakich et al., "Achieving centimetre-scale supercollimation in a large-area two-dimensional photonic crystal," *Nature Materials* **5**, 93–96 (2006).

Theory:

Experiment (measured vertical scattering from disorder)

Theory, including disorder: