

**Novel electro-magnetic
phenomena:**

one-way-waveguides

and

wireless power transfer

Unidirectional backscattering-immune topological electromagnetic states

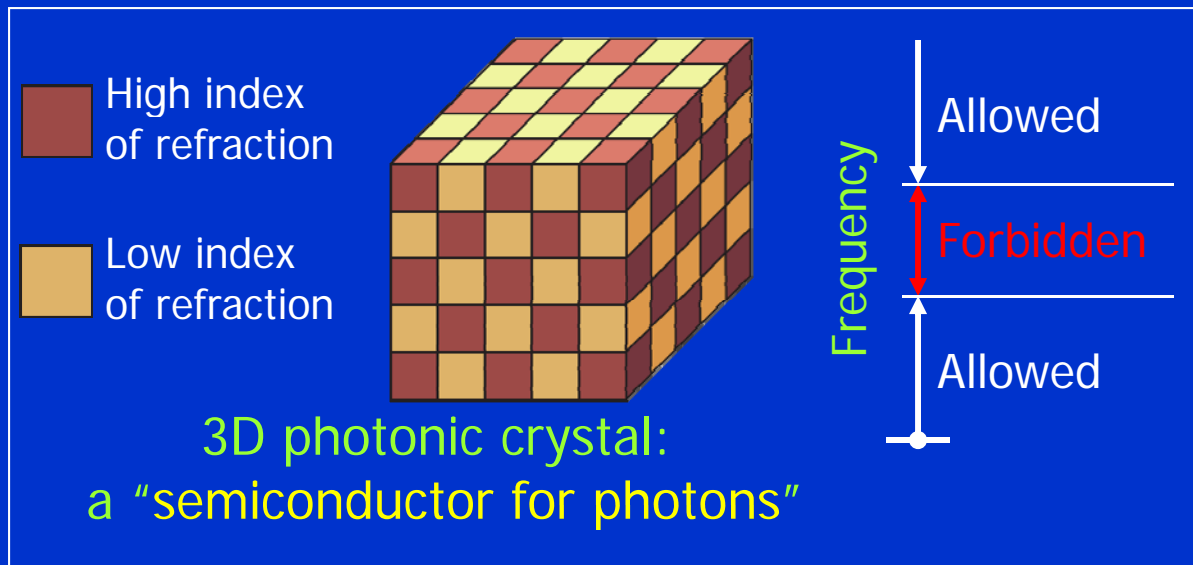
Dr. Zheng Wang
Dr. Yidong Chong
Prof. John Joannopoulos
Prof. Marin Soljačić



Massachusetts Institute of Technology

Metamaterial:

optical properties determined from
its nano-structure
(rather than its composition)

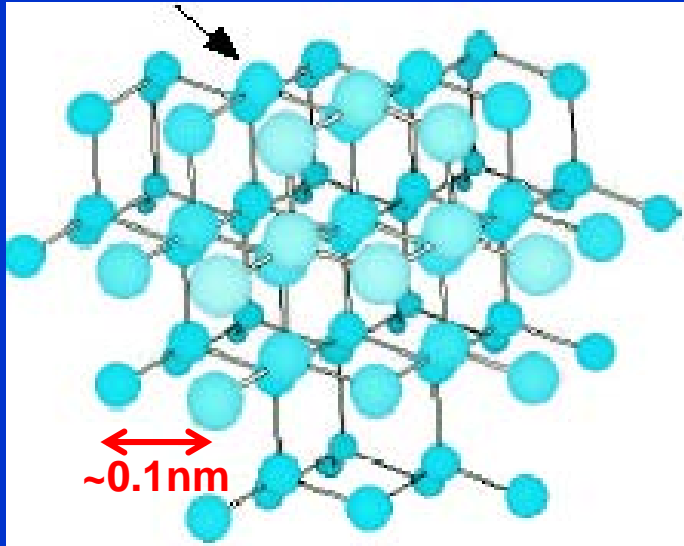


Yablonovitch (1987)
John (1987)

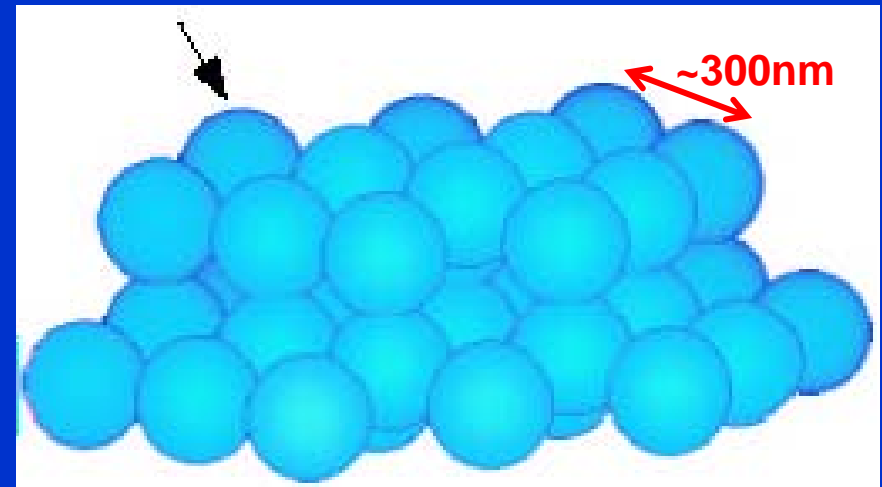
Electronic and Photonic Crystals

Periodic Medium

atoms in diamond structure

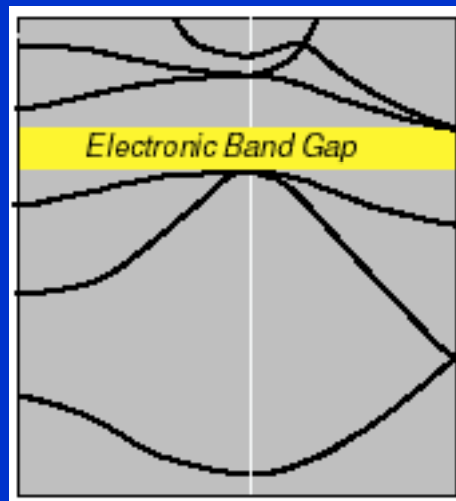


dielectric spheres, diamond lattice



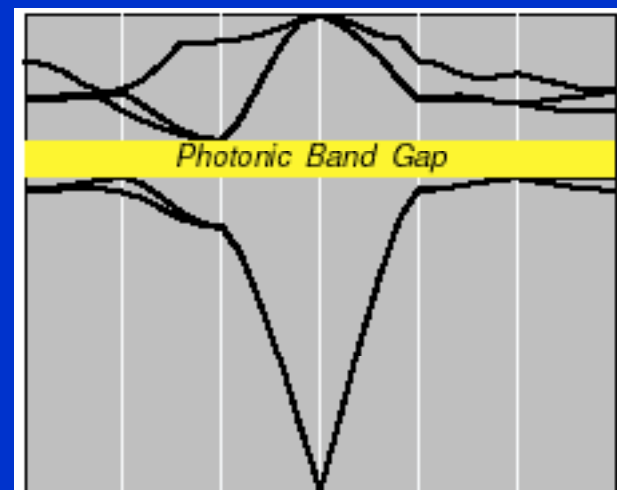
Band Diagram

electron energy



wavevector

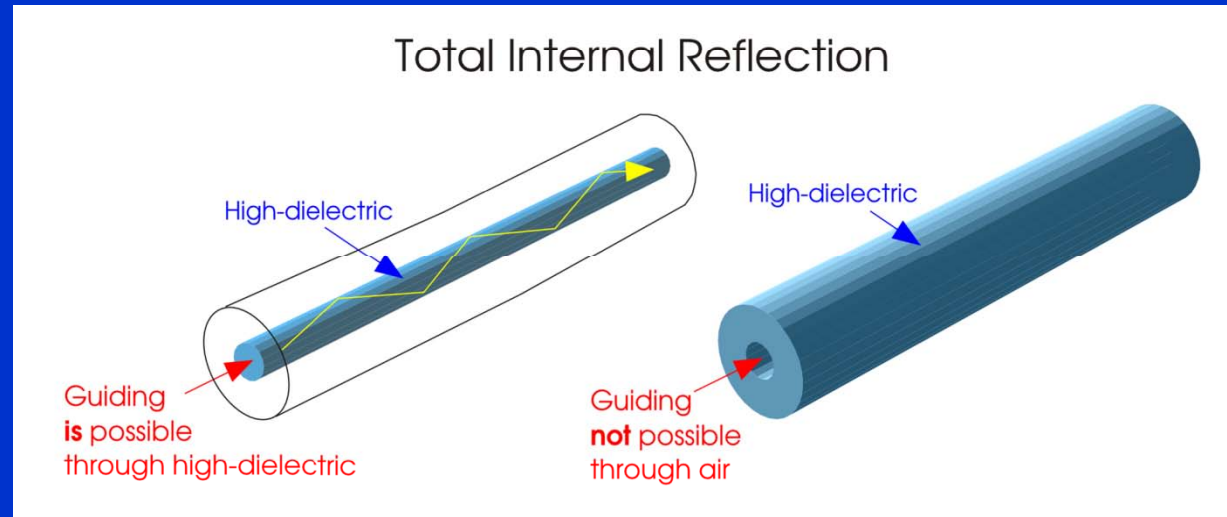
photon frequency



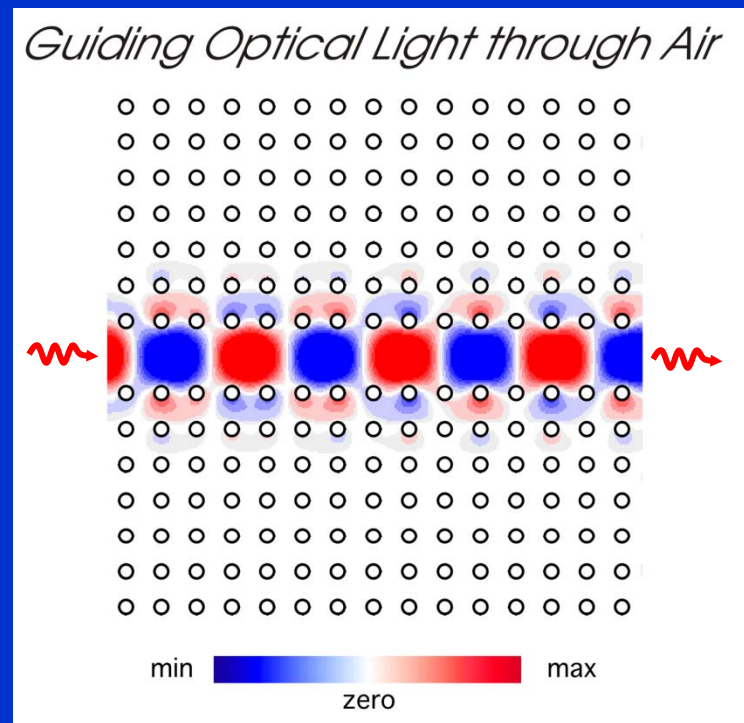
wavevector

Optical waveguides

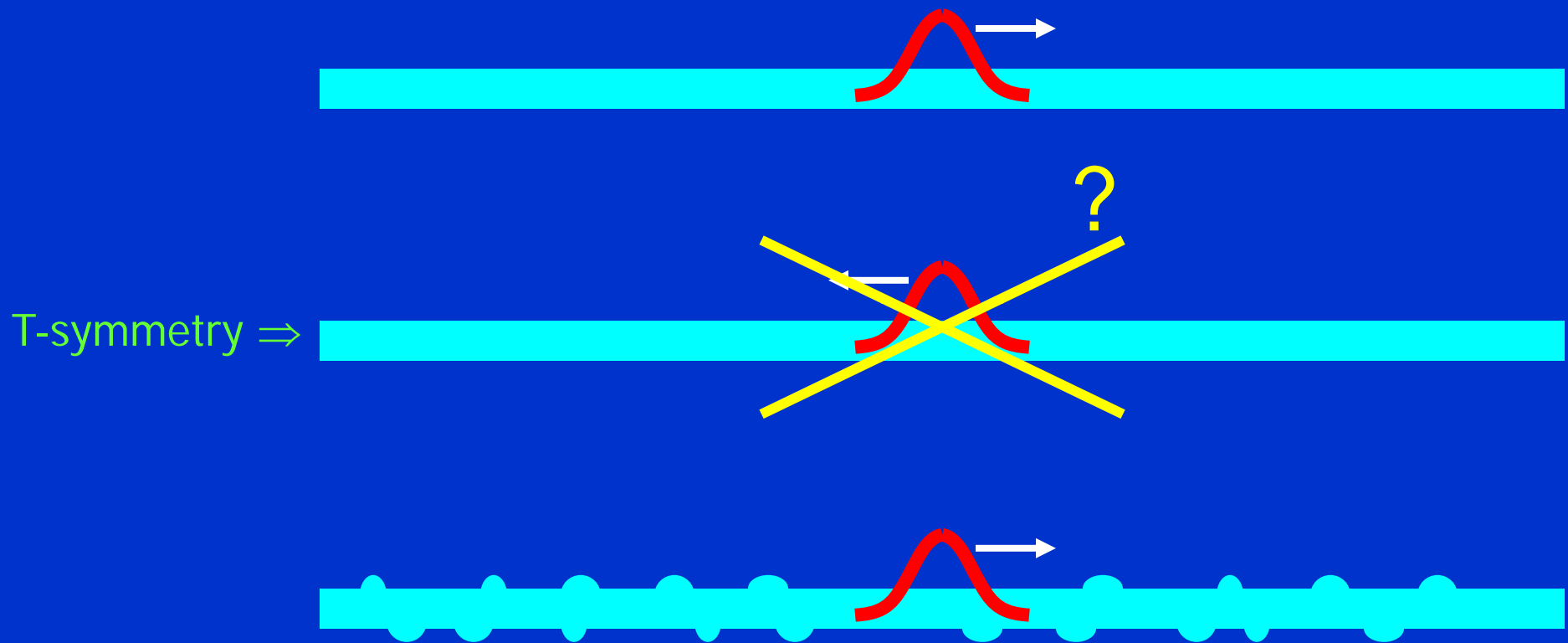
conventional waveguides



photonic crystal waveguides



In both conventional and PhC waveguides...



REFLECTIONS: IMMUNE TO DISORDER!

Topologically-nontrivial Electromagnetic States

Integer Quantum Hall Effect : unusual phenomena in a 2D system of **electrons in crystals**, subjected to a perpendicular strong magnetic field

Chiral Edge States (CESs)

- *Unidirectional transport*
- *Dissipationless transport in presence of impurities*

Thouless et al. (1982)

Simon (1983)

Kohmoto (1985)

Haldane (1988)

Hatsugai (1993)

Enabled by:

- nontrivial topology of band structure
- T-reversal symmetry breaking

Can one extend these ideas to E&M States in **photonic crystals**?

Haldane & Raghu, *PRL* **100**, 013904 (2008)

Raghu & Haldane, *PRA* **78**, 033834 (2008)

Wang, Chong, Joannopoulos & Soljačić, *PRL* **100**, 013905 (2008)

How does this work?

Intro to Chern numbers

Chern number of n-th band:

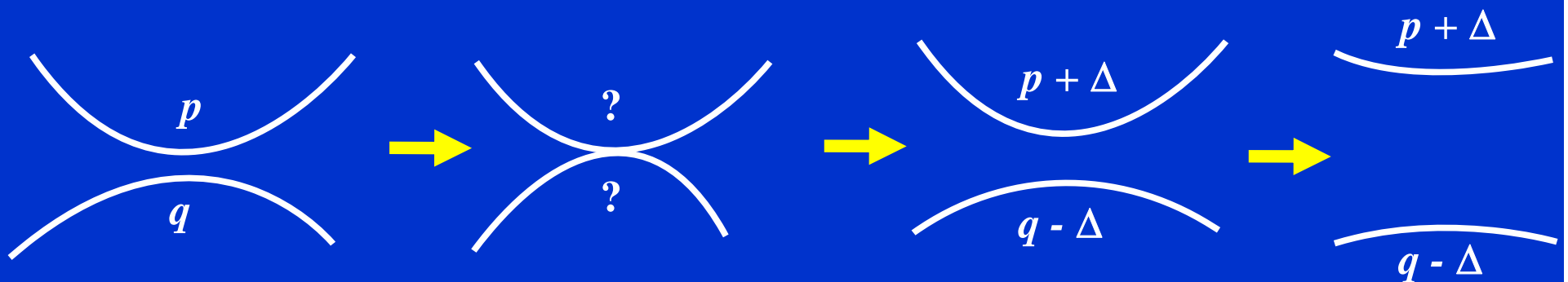
$$C_n = \frac{1}{2\pi i} \int_{BZ} d^2k \left(\frac{\partial \chi_y^n}{\partial k_x} - \frac{\partial \chi_x^n}{\partial k_y} \right)$$

$$\chi^n \equiv i \langle E_{nk} | \nabla_k | E_{nk} \rangle$$

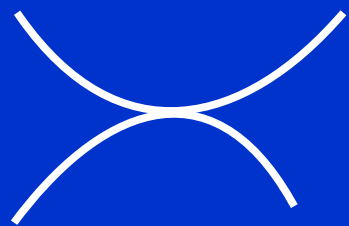
c_n : integer \Rightarrow always changes abruptly

$$\sum_n c_n = 0$$

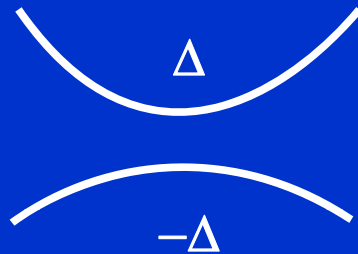
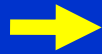
T-symmetric systems $\Rightarrow c_n = 0$



Hatsugai's Relation

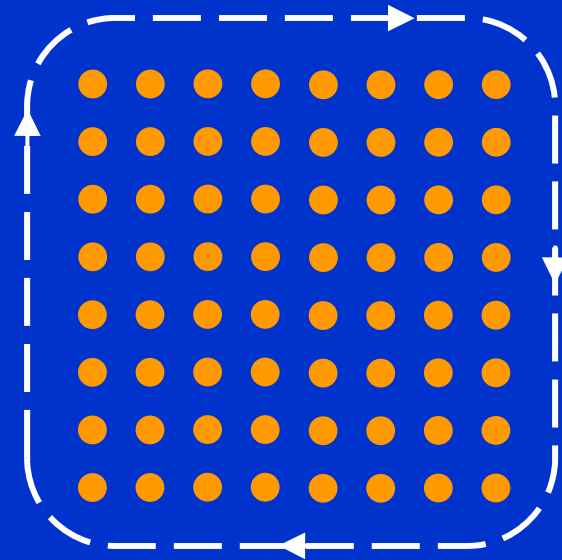


T-symmetric



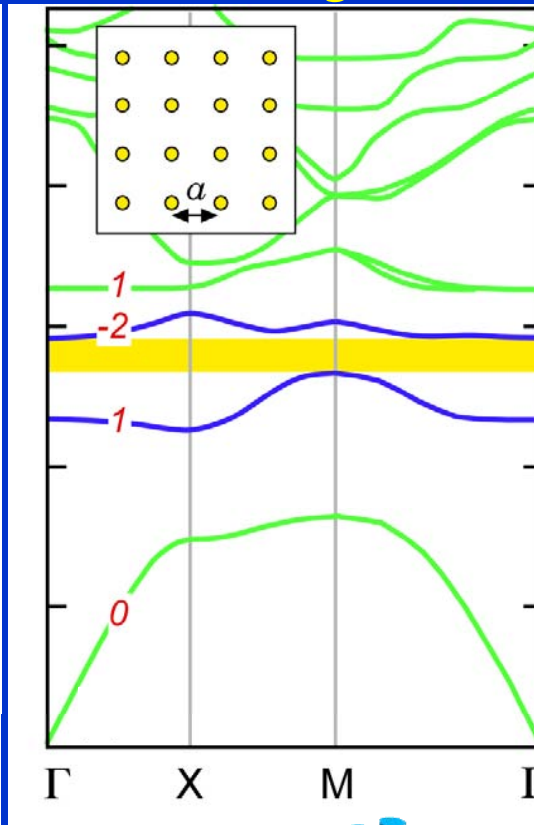
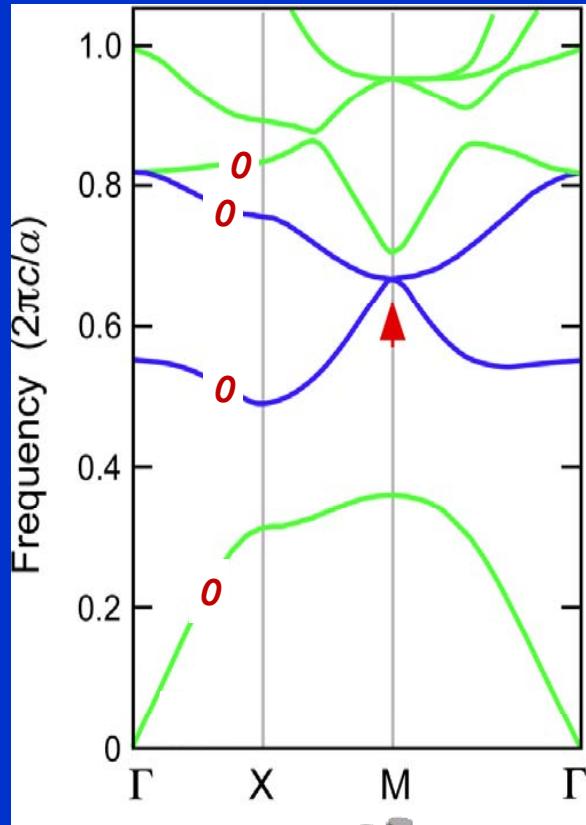
T-broken

$|\Delta|$ one-way edge modes



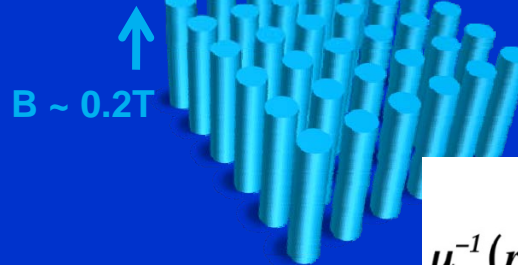
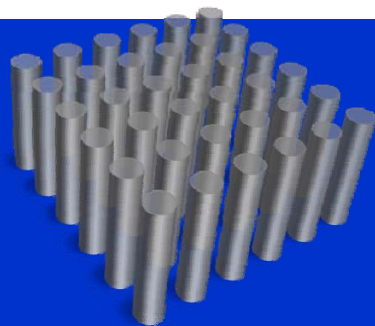
The # of CESs in a gap = $\sum C_n$ over lower bands

Break T-symmetry



← one-way edge states

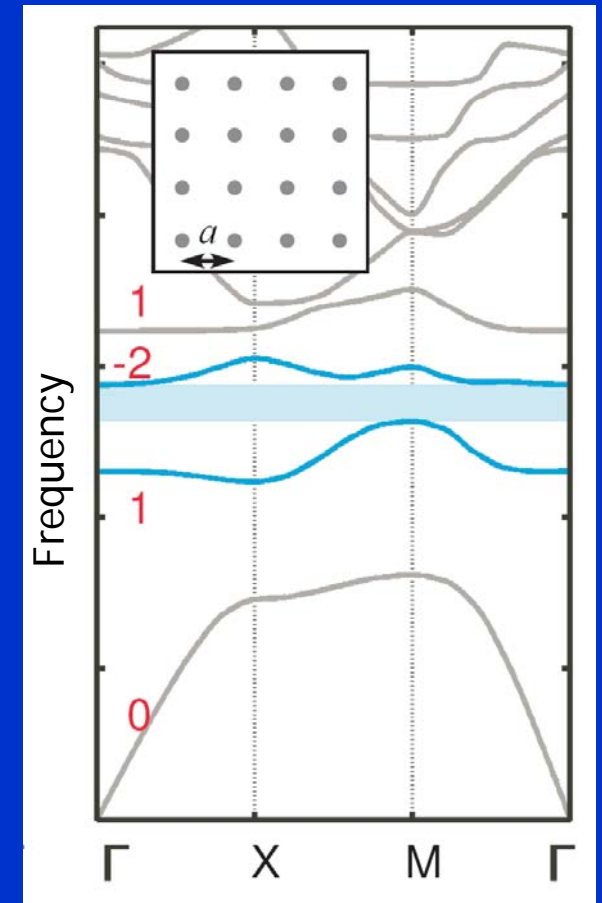
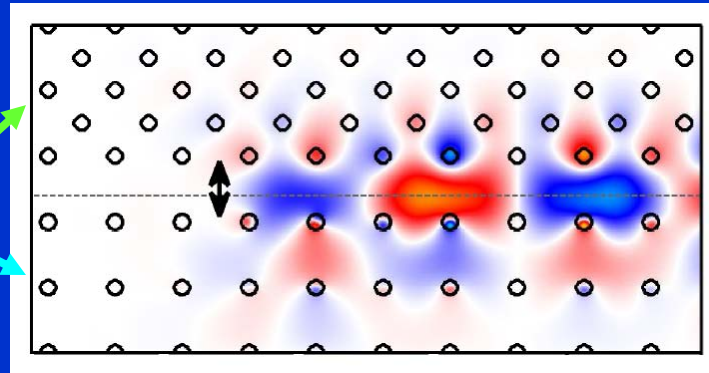
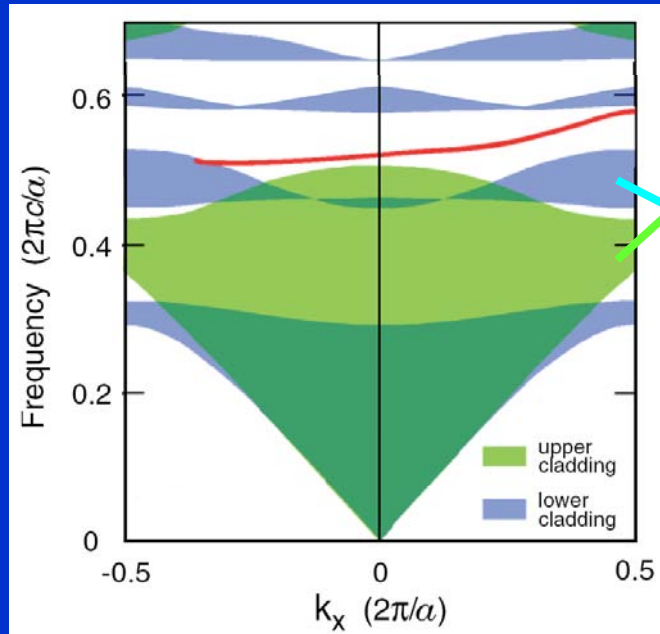
YIG



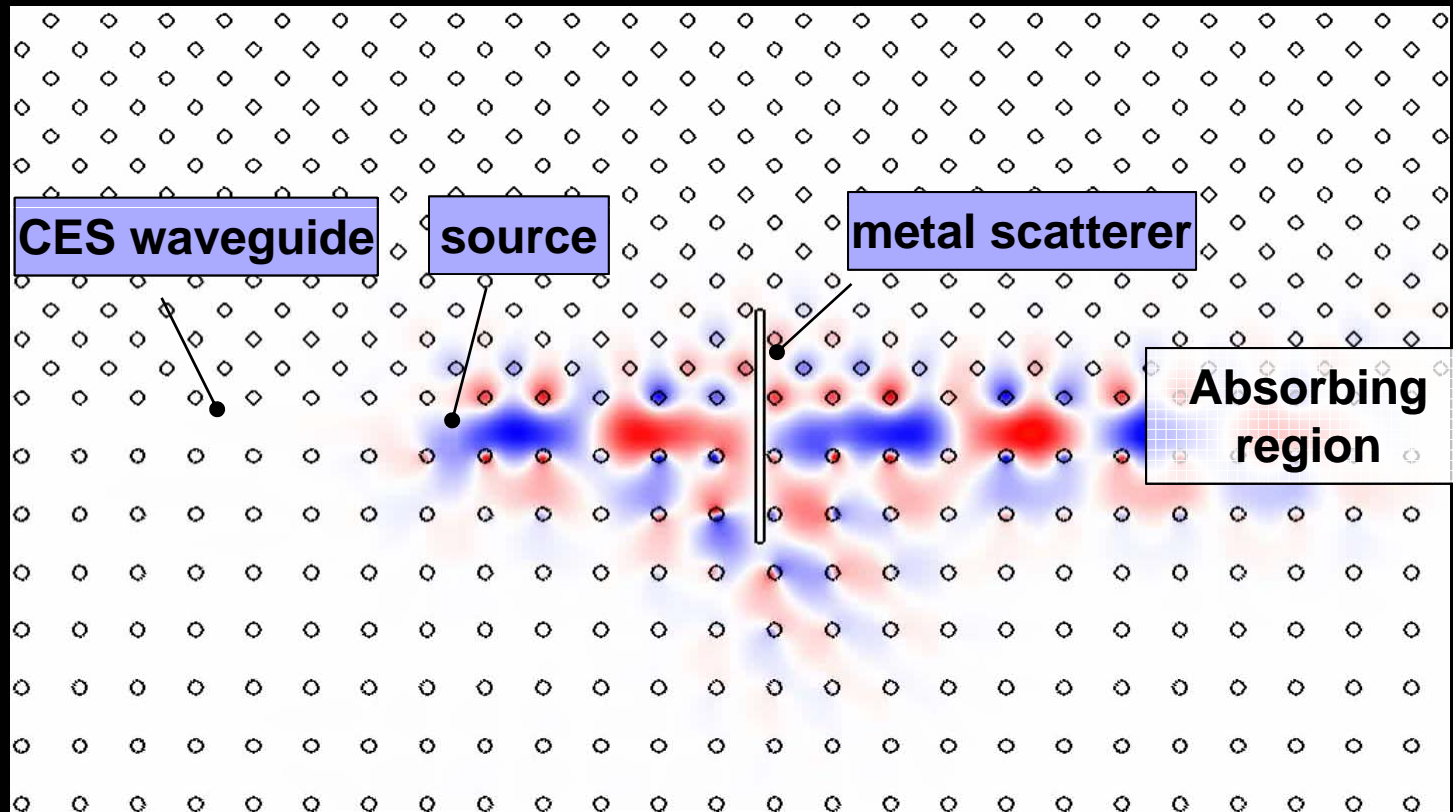
$$\mu^{-1}(r) = \begin{bmatrix} \tilde{\mu}^{-1} & i\eta & 0 \\ -i\eta & \tilde{\mu}^{-1} & 0 \\ 0 & 0 & \mu_0^{-1} \end{bmatrix}$$

increase $\mathbf{H} \rightarrow c_n$ changes discontinuously at degenerate- k points

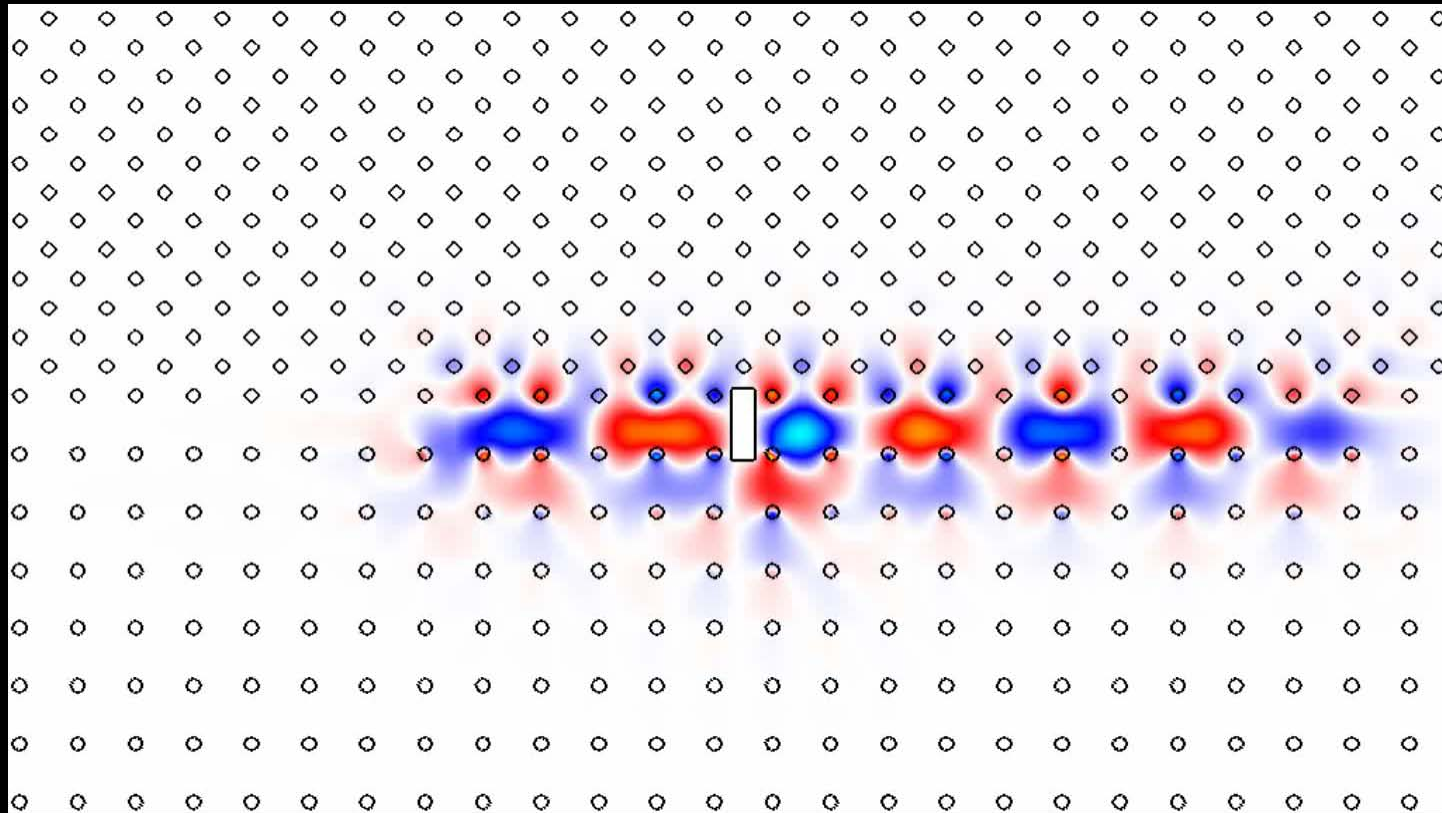
Create one-way edge-states at the PhC boundary



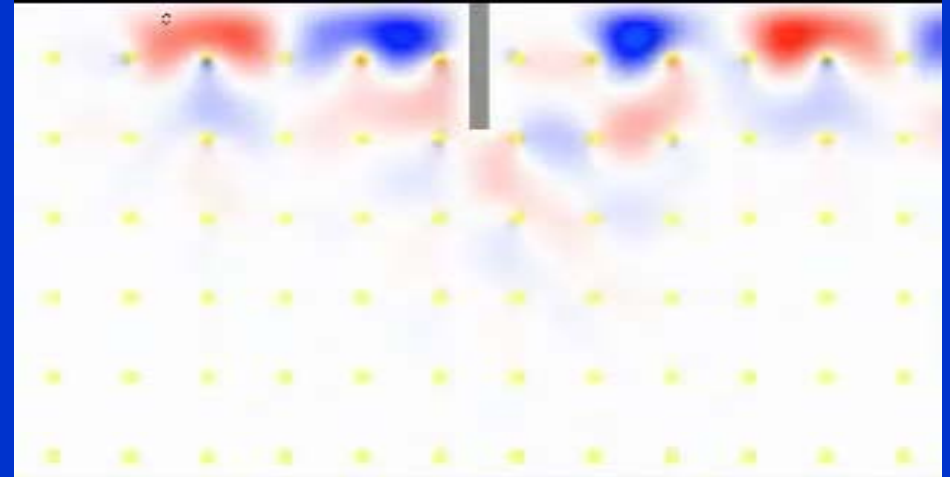
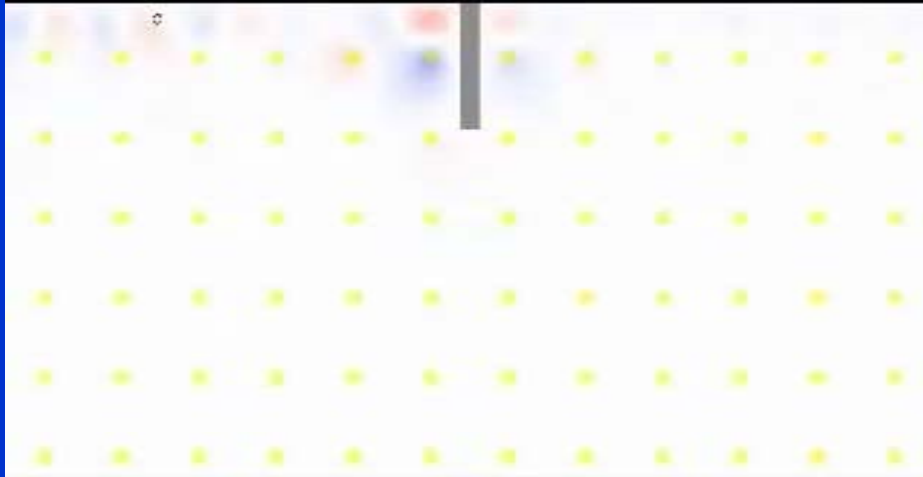
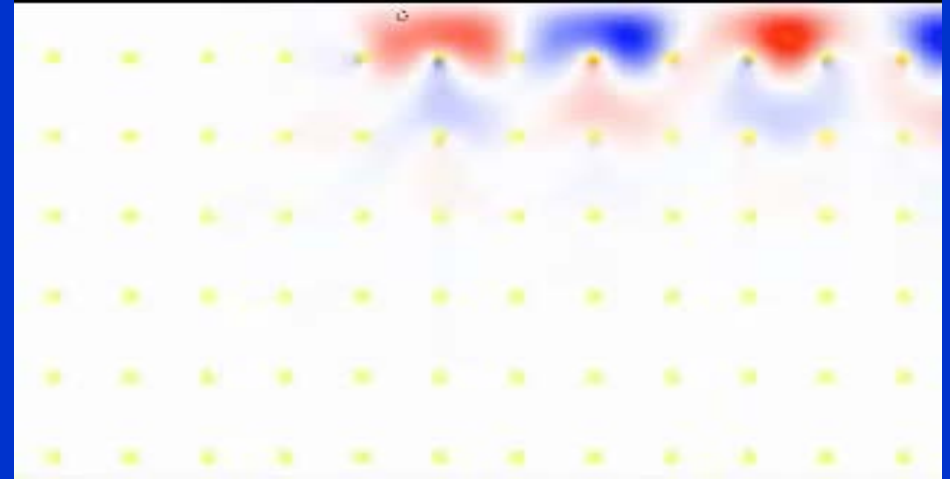
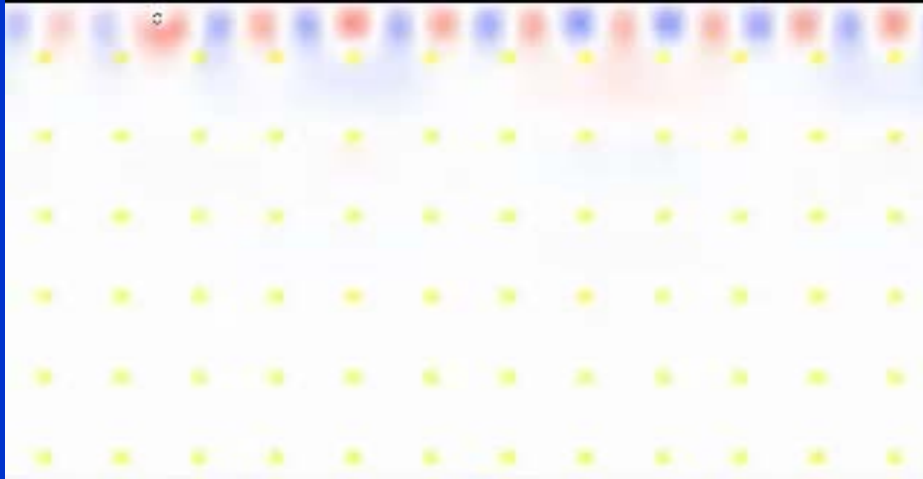
Truly reflectionless!



Truly reflectionless!

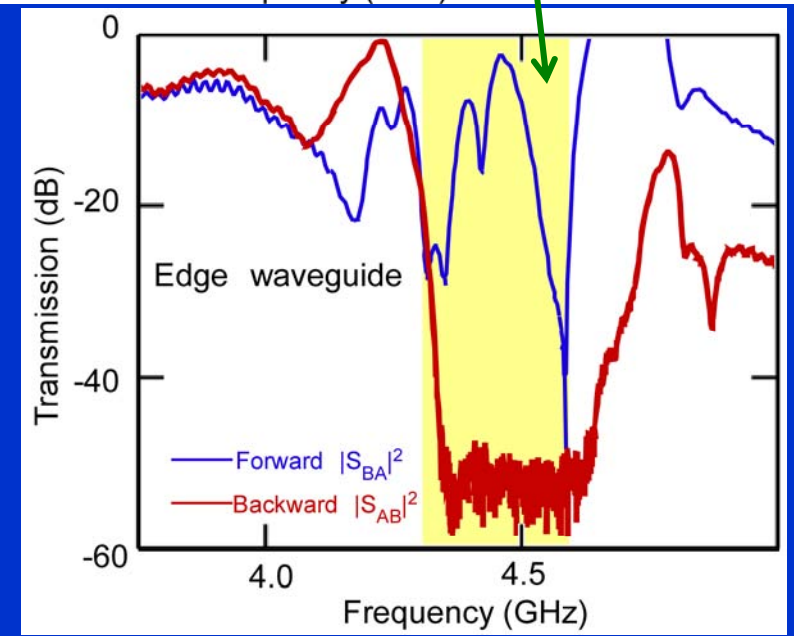
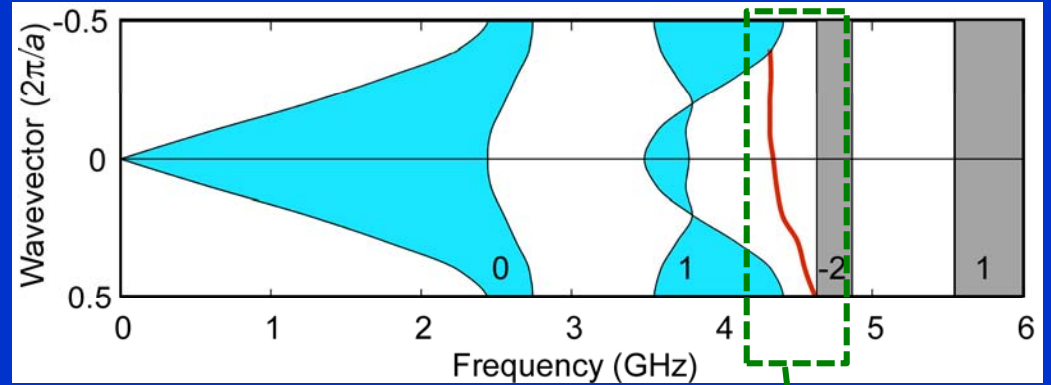
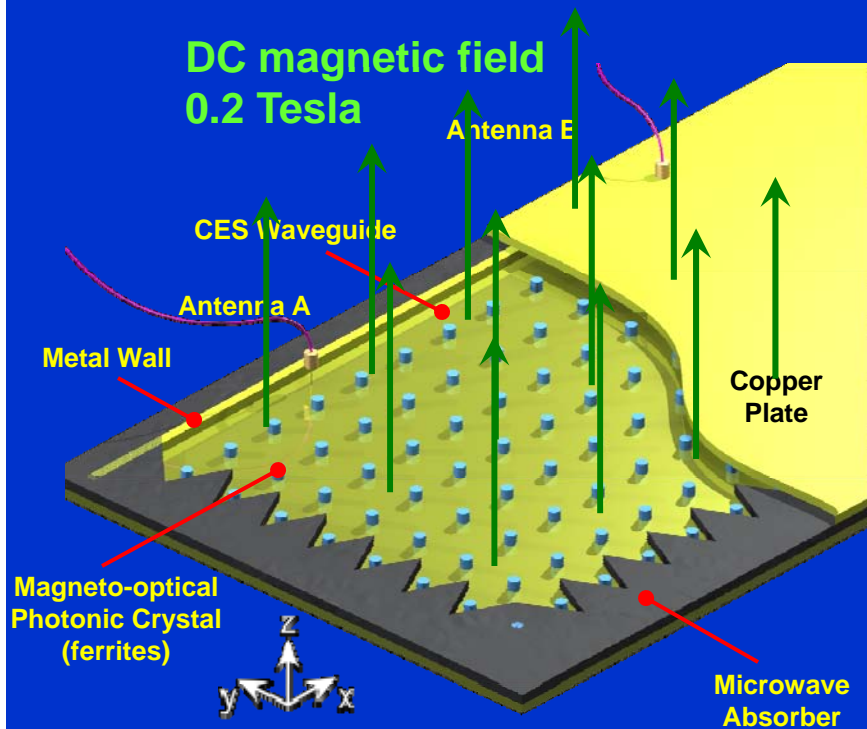


Contrast with conventional waveguides



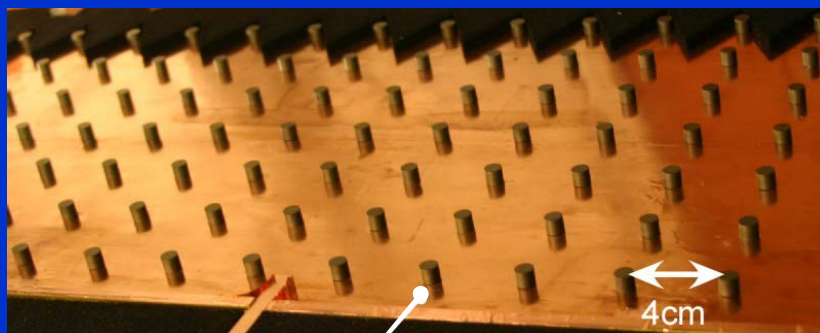
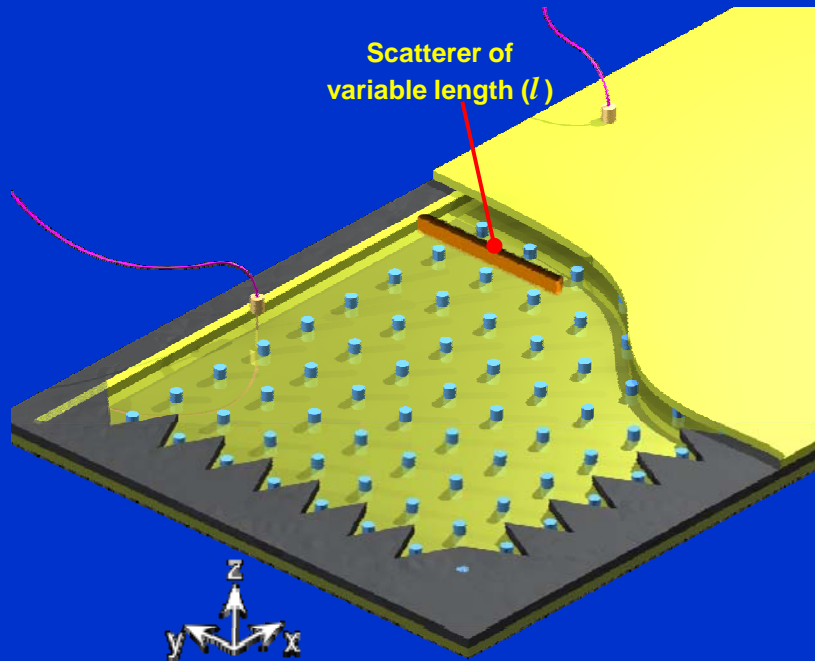
CES waveguide

Observation: *CES*

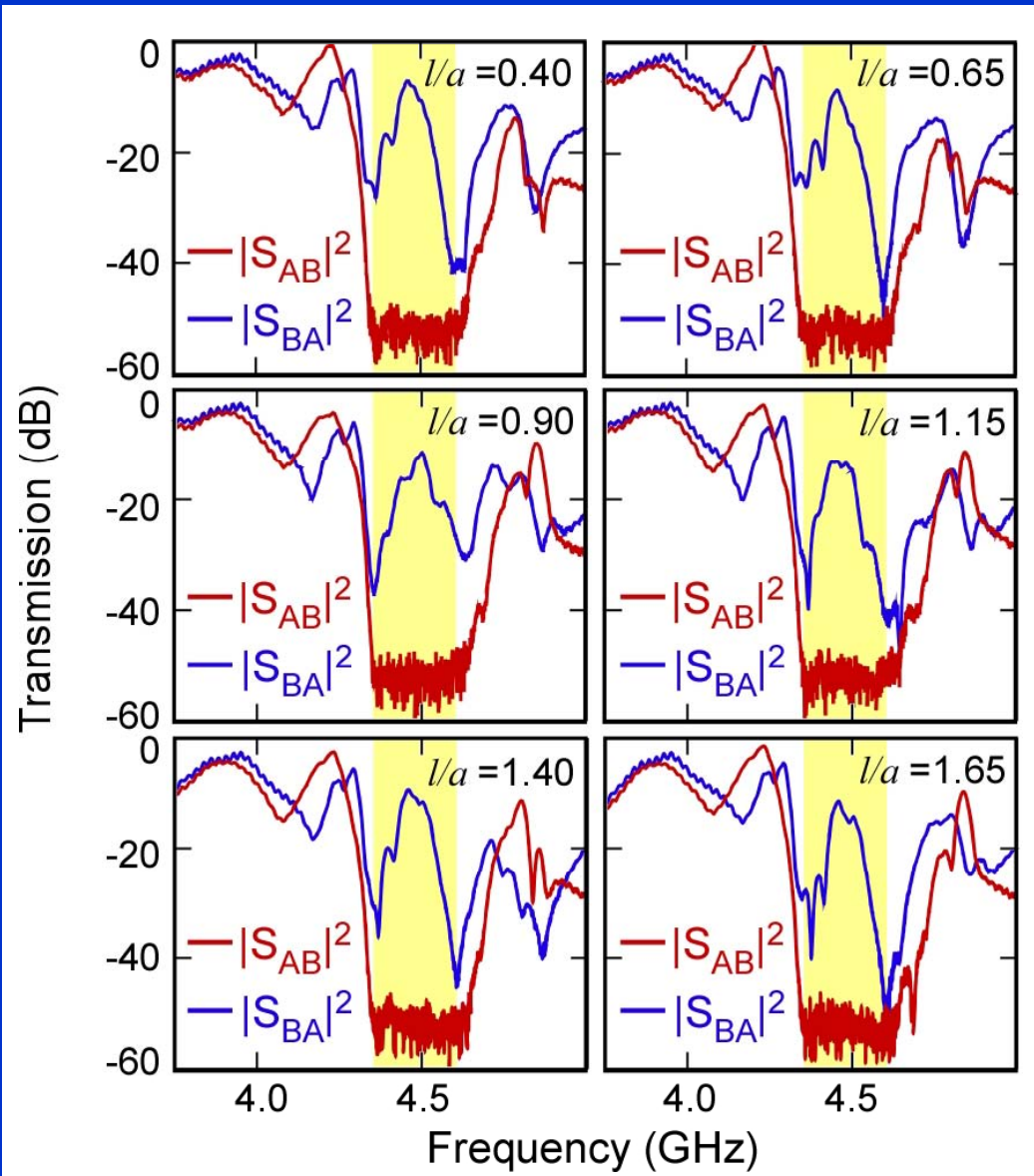


Wang, Chong, Joannopoulos & Soljačić, *Nature* **461**, 772 (2009)

Observation: *backscattering-immunity*



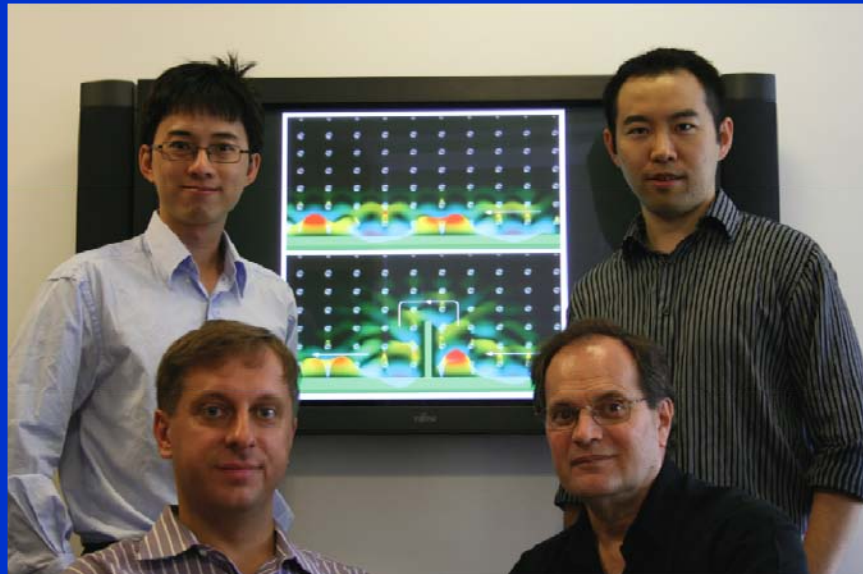
Waveguide



Summary: one-way states

- Chiral Edge States:
 - Unidirectional transport
 - backscattering-immunity
- enabled by:
 - nontrivial topology of band structure
 - T-reversal symmetry breaking
- previously known in quantum Hall effect (electronic system)
- observed for the first time as electromagnetic (photonic) states

Dr. Yidong Chong



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Prof. John Joannopoulos

WiTricity:

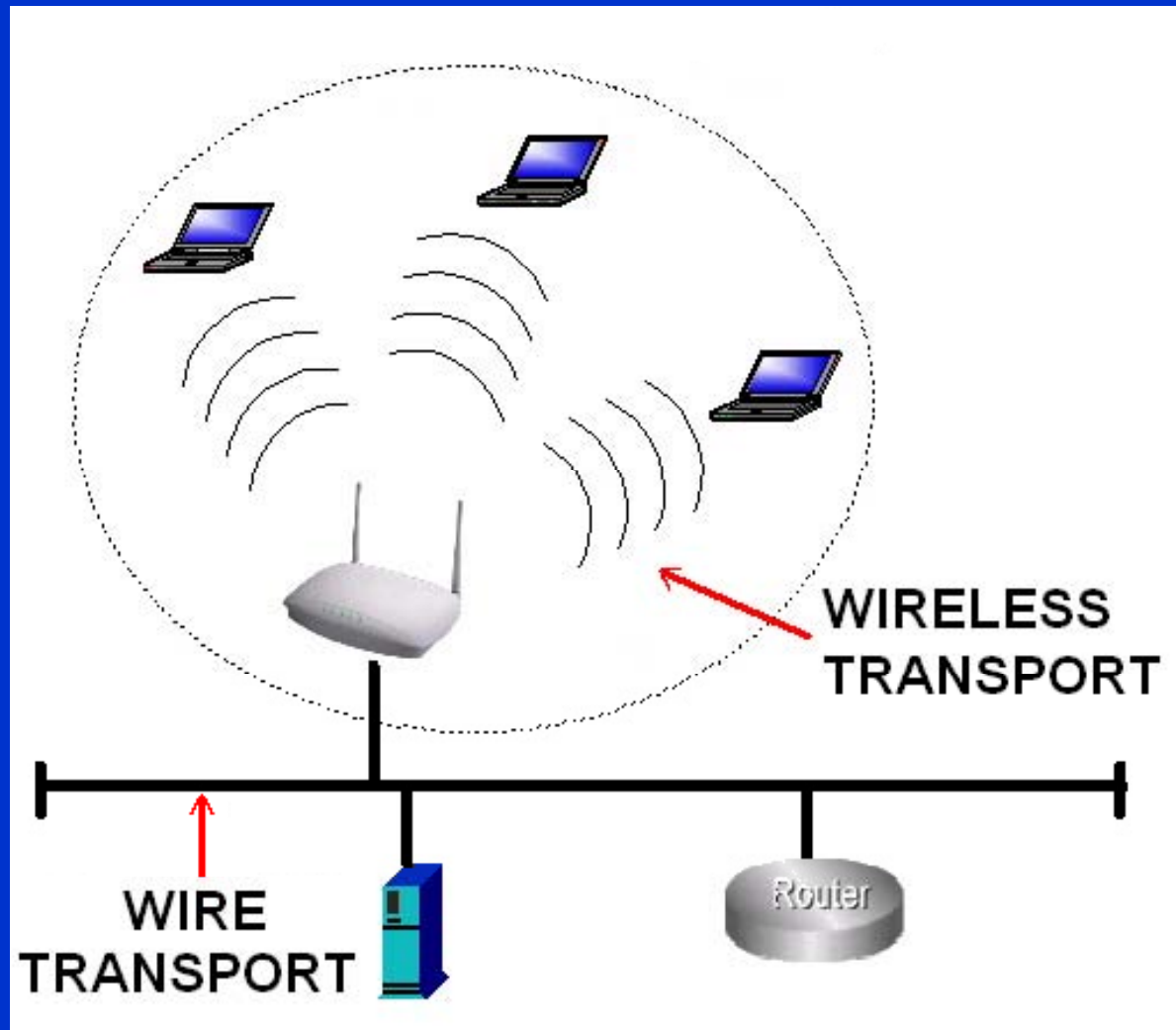
**non-radiative
wireless power transfer**

Motivation



**Tesla tower:
cca. 1904**

Wi-Fi (wireless internet) concept: radiation



Resonant coupling as energy transfer

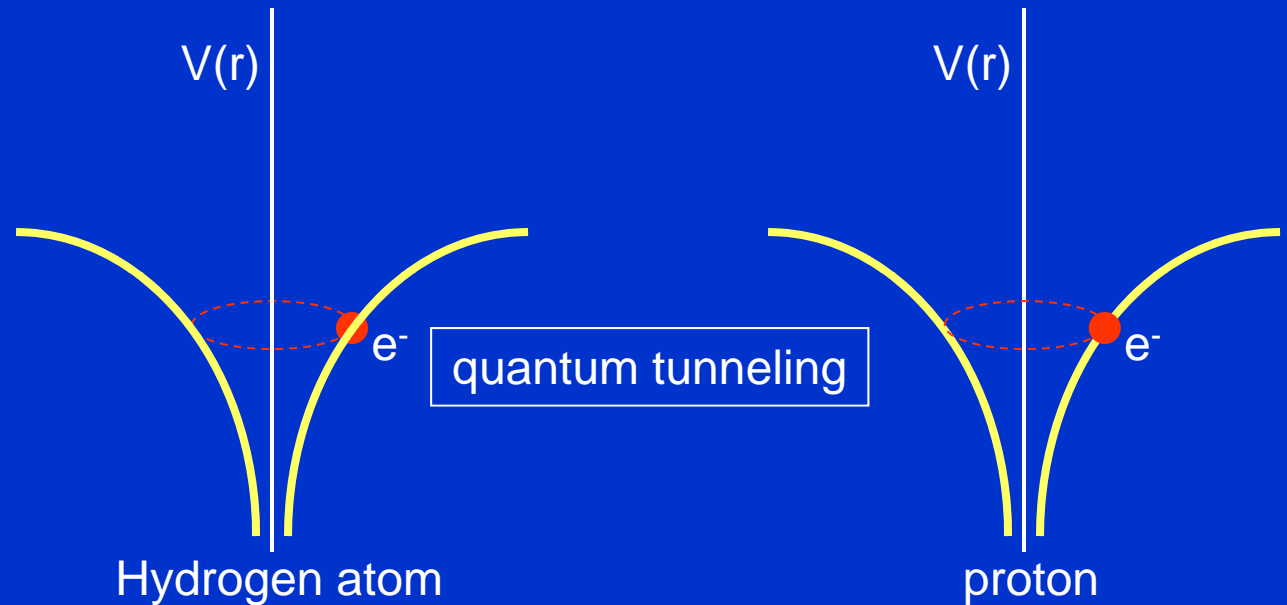
Resonances in quantum mechanics – nonradiative transfer

$$-\frac{\hbar^2}{2m}\nabla^2\psi = E\psi$$

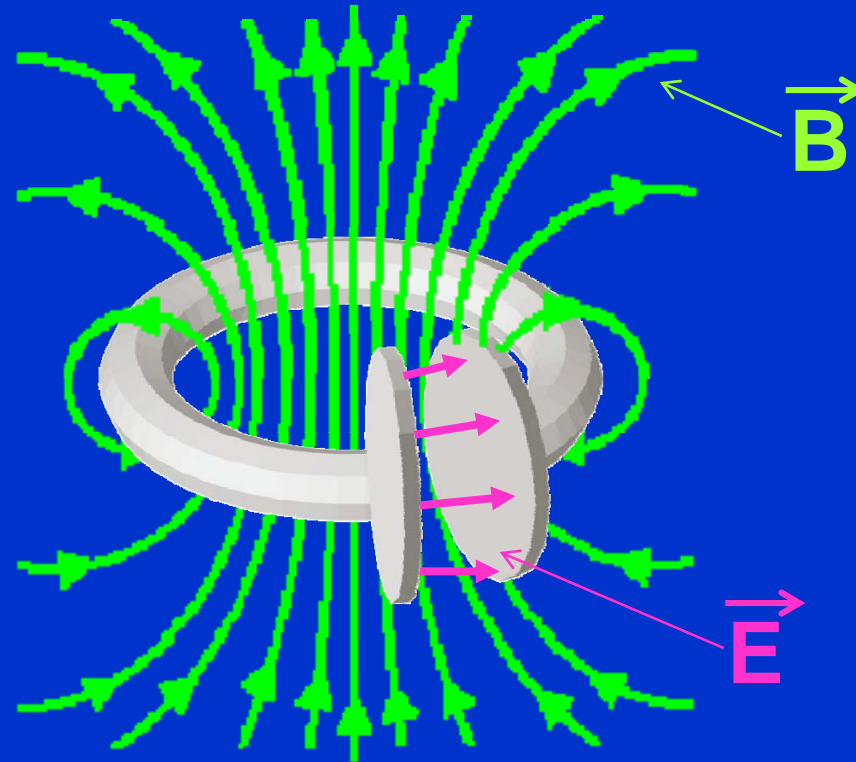
Schrödinger equation

$$-c^2\nabla^2\mathbf{E} = \omega^2\mathbf{E}$$

Maxwell equation



Magnetic resonances



Outside: $U_E \ll U_B$
Most materials: $\mu \sim \mu_{\text{AIR}}$

\Rightarrow weak interaction with B-field!

Examples of “magnetic technology”

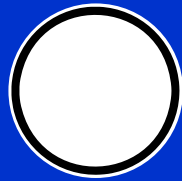


Maglev



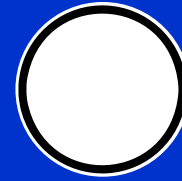
Magnetically levitating bed

Coupled mode theory



resonant object (Source)

$$\frac{da_S}{dt} = -i(\omega - i\Gamma)a_S + i\kappa a_D$$



resonant object (Device)

$$\frac{da_D}{dt} = -i(\omega - i\Gamma)a_D + i\kappa a_S$$

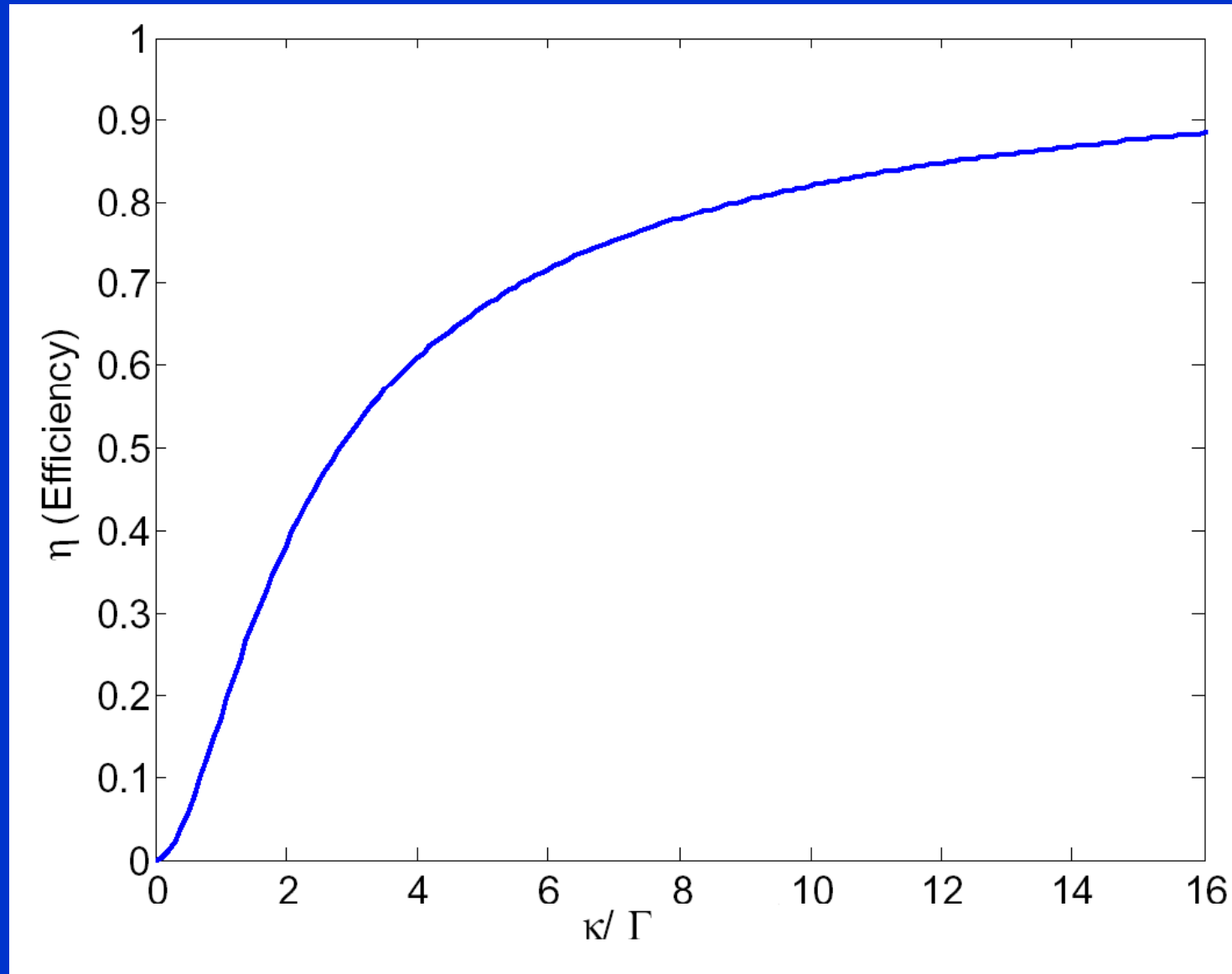
$$Q = \frac{\omega}{2\Gamma}$$

“Strong Coupling”:

$$\kappa/\Gamma \gg 1$$

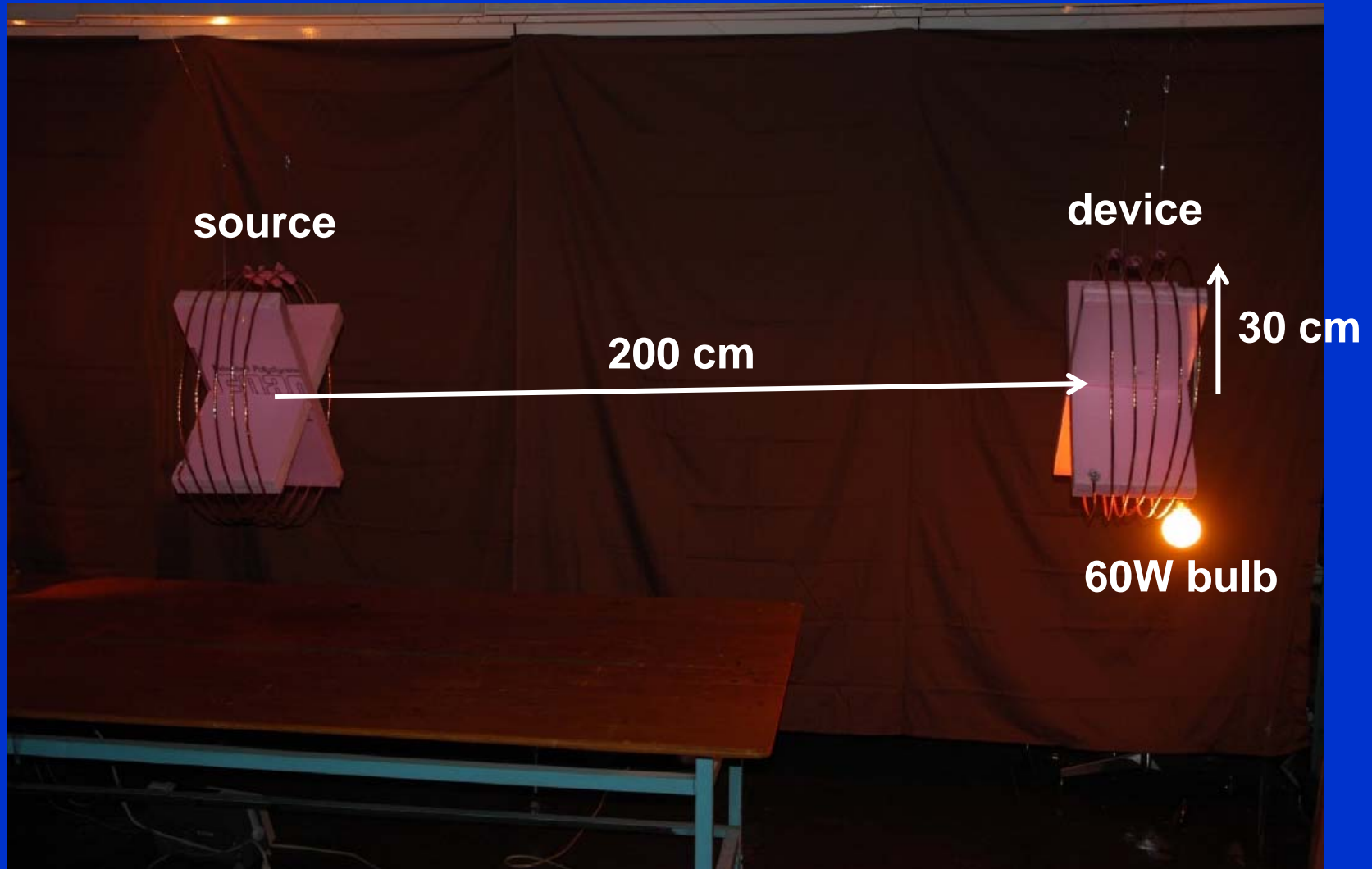
\Rightarrow *efficient* energy transfer

"Strong Coupling" \Rightarrow efficient transfer



Karalis, Joannopoulos & Soljačić, *Annals of Physics* 323, 34 (2008)

Experimental results

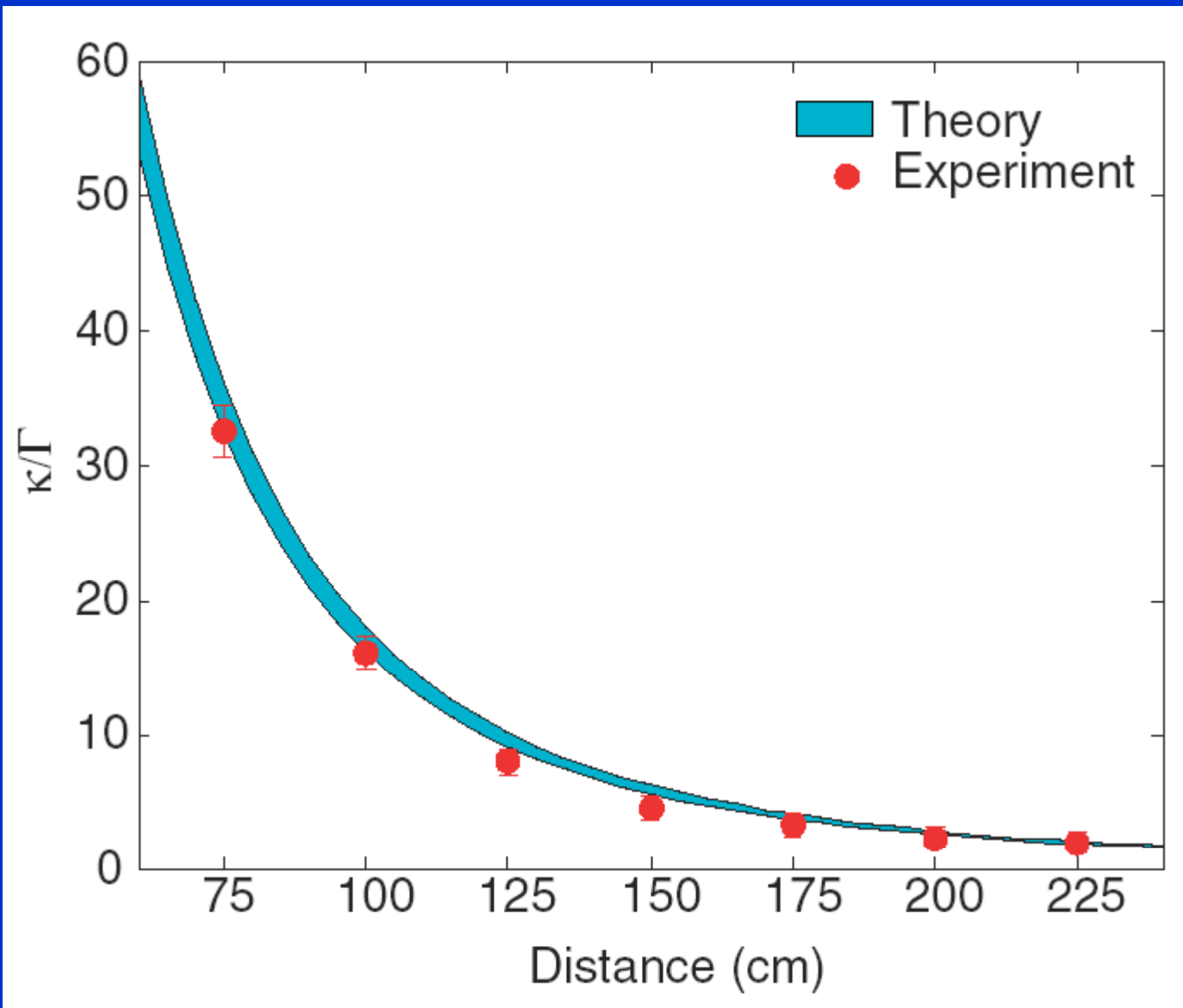


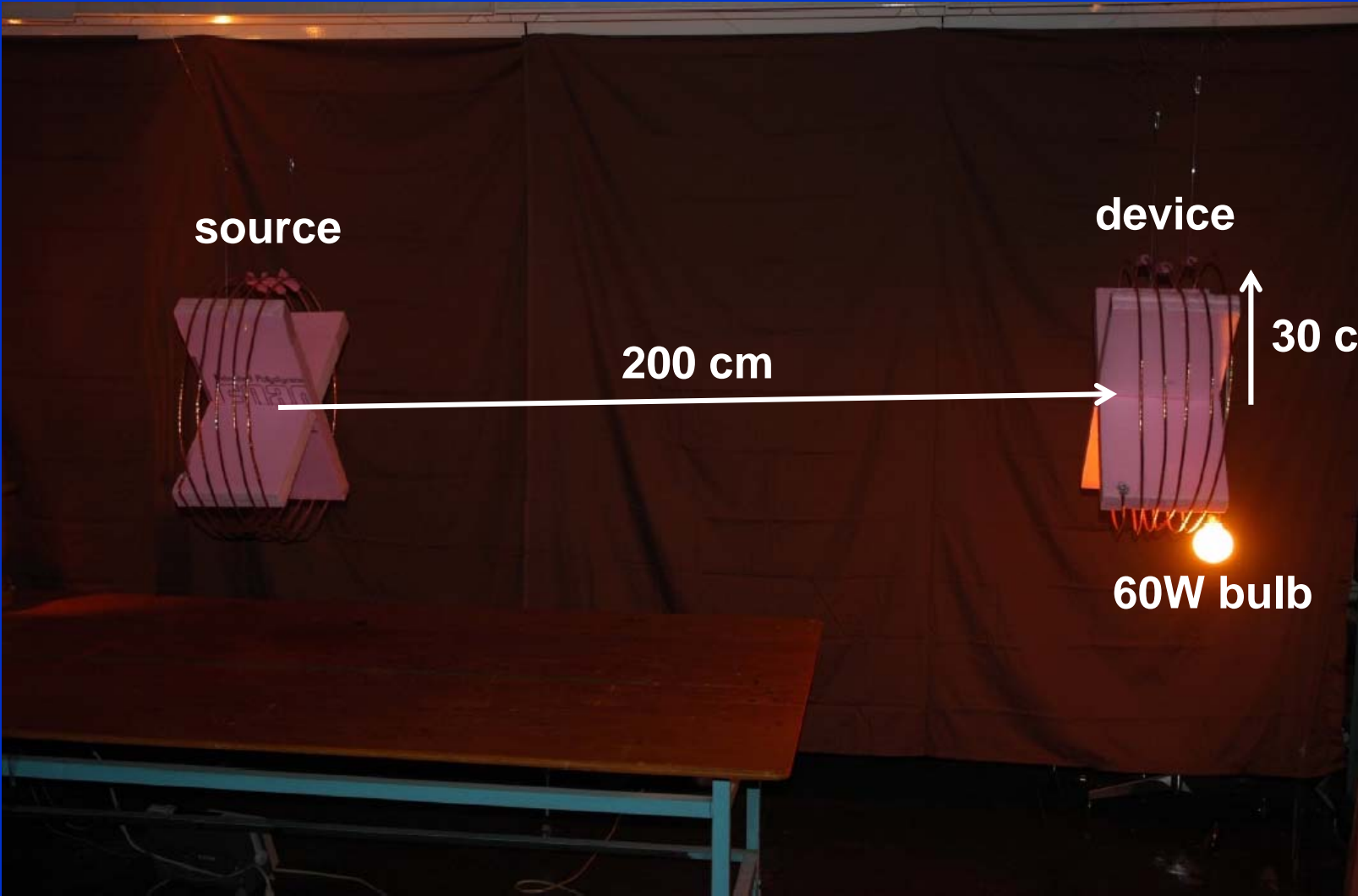
Kurs, Karalis, Moffatt, Joannopoulos, Fisher & Soljačić, *Science* 317, 83 (2007)



same thing, different viewing angle

Experimental proof of strongly-coupled regime





source

device

200 cm

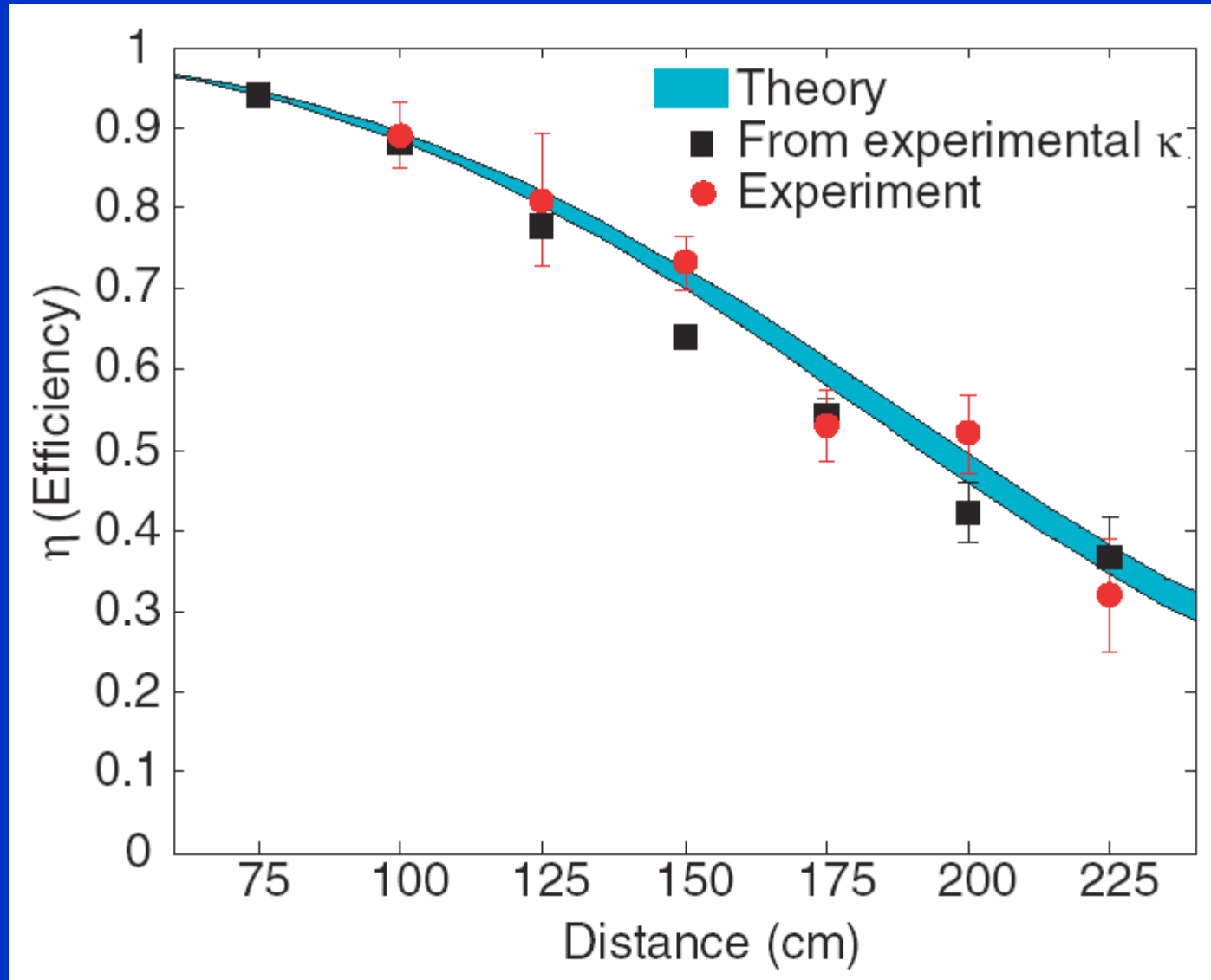
30 cm

60W bulb

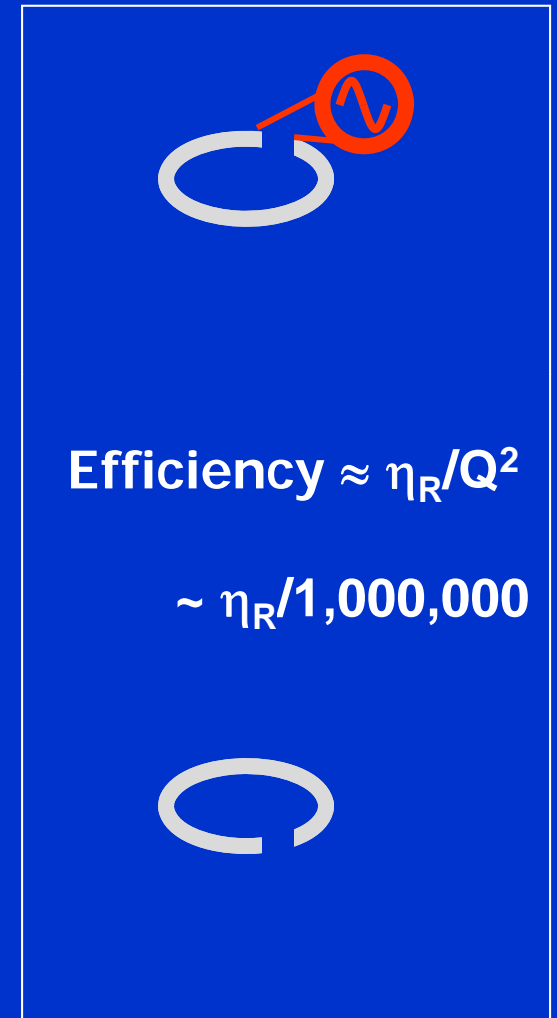
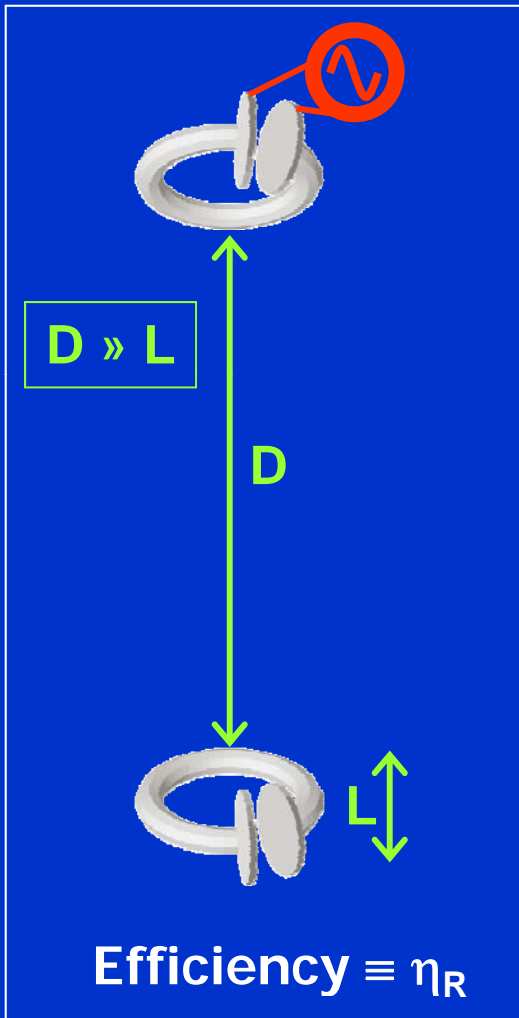
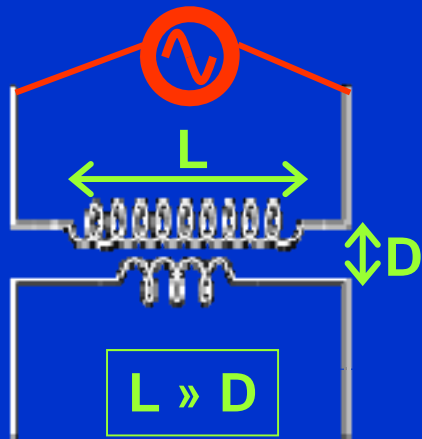
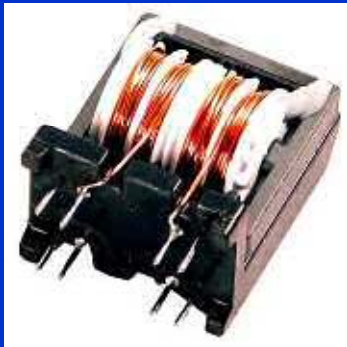
efficiency ~50%

($Q \sim 1000$)

Efficiency vs. distance



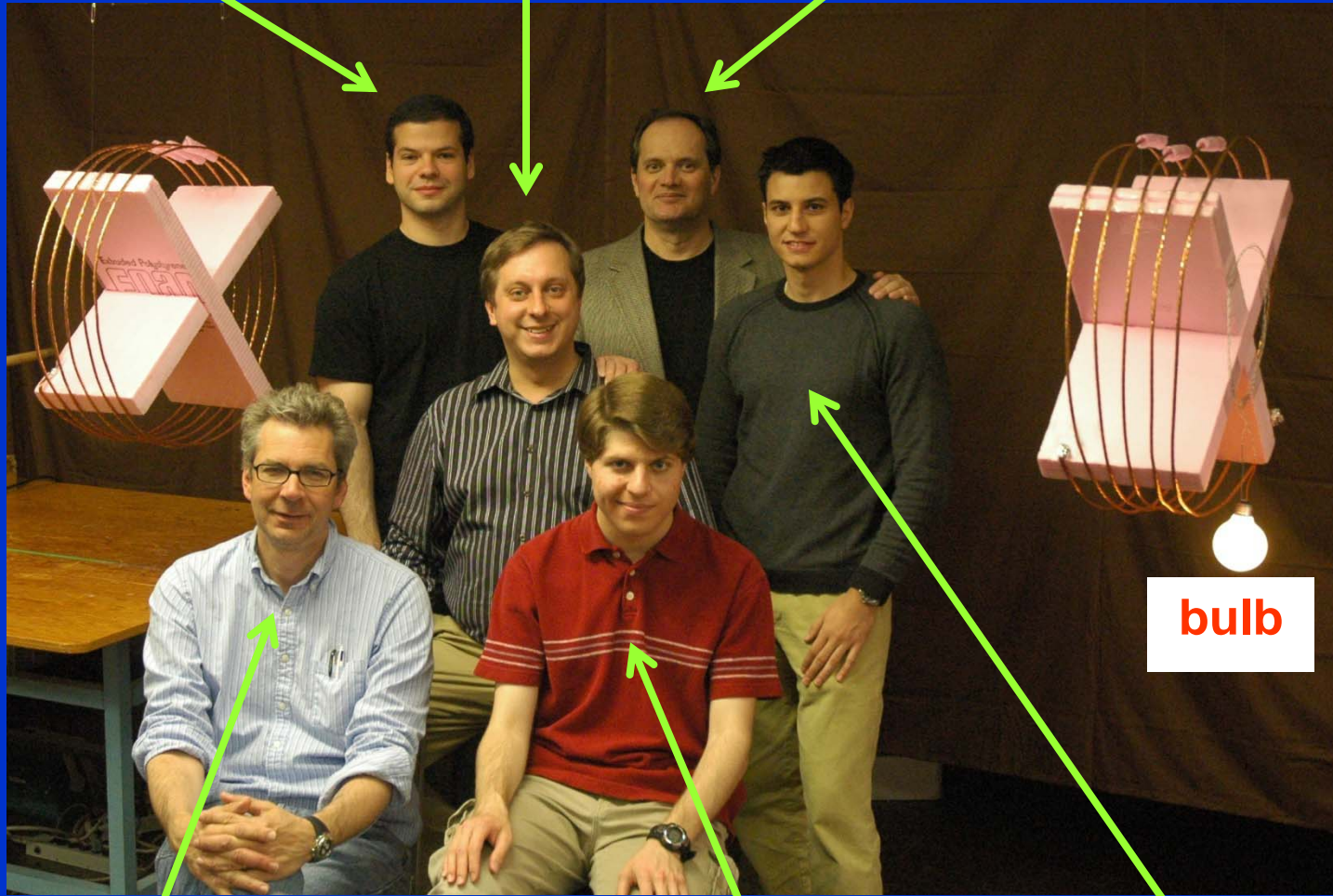
Comparison with inductive coupling



Prof. Marin Soljačić

Andre Kurs

Prof. J.D.Joannopoulos



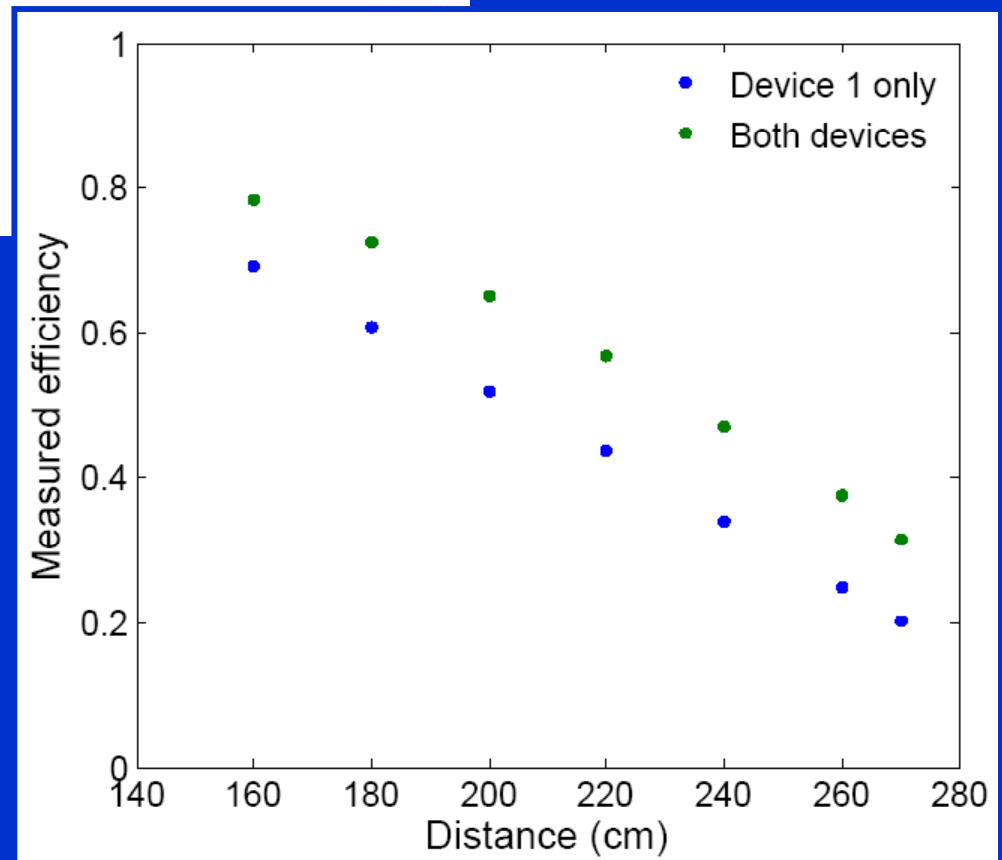
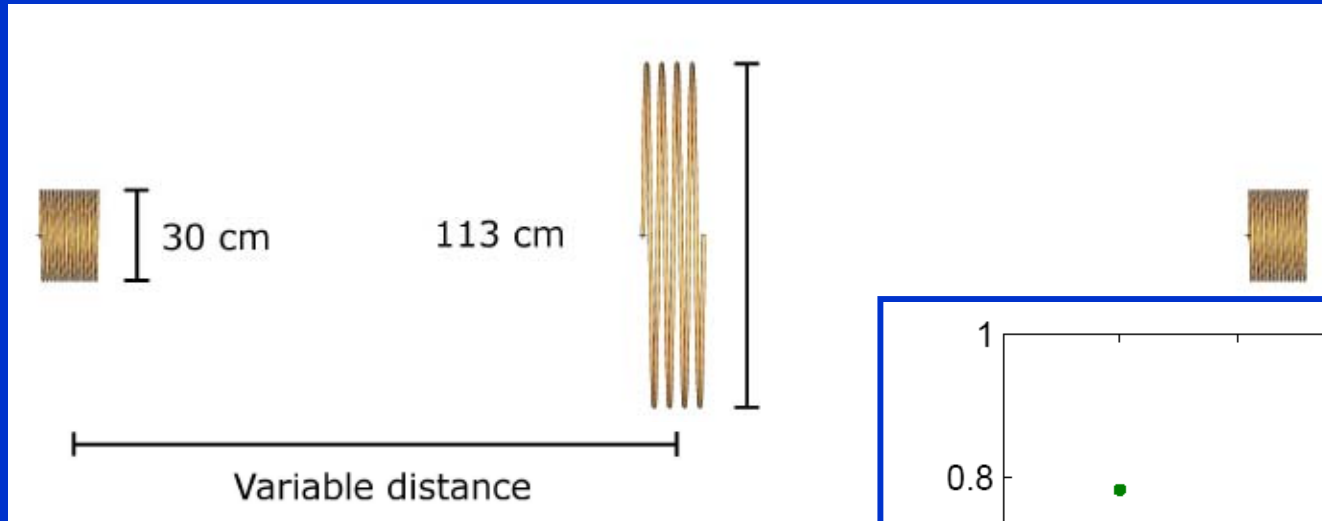
bulb

Prof. Peter Fisher

Robert Moffatt

Dr. Aristeidis Karalis

Experiments with 1 source, 2 devices - different sizes



Some potential applications



Industrial, military, and household robots



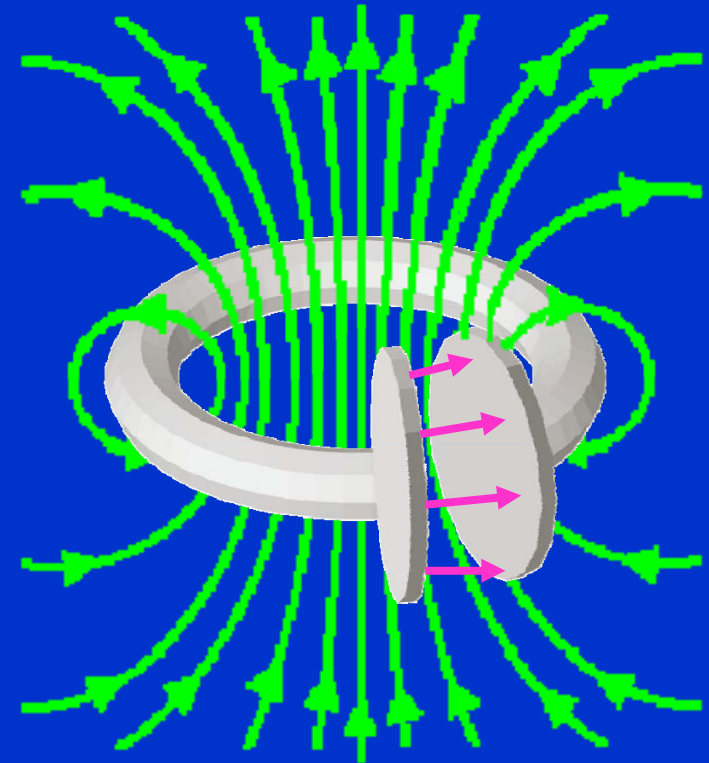
Portable personal electronics



Electric vehicles

Summary: wireless power transfer

- mid-range non-radiative energy transfer scheme based on strongly-coupled resonances
- as a powerful concept, it could enable a wide range of applications



WiTricity TED talk – summer 2009



Eric Giler; *CEO, WiTricity Corporation*