Light, sound, and topology

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since 2009

now 4 divisions (three experiment, one theory)

new building Oct 2016

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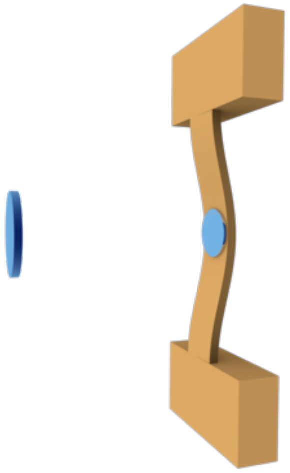
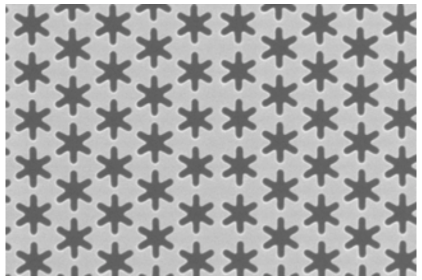
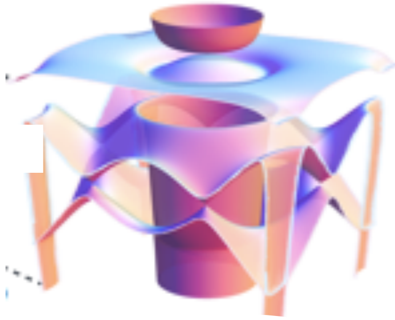


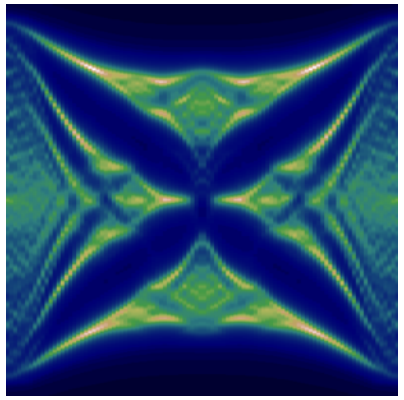
Cavity Optomechanics



Optomechanical Arrays



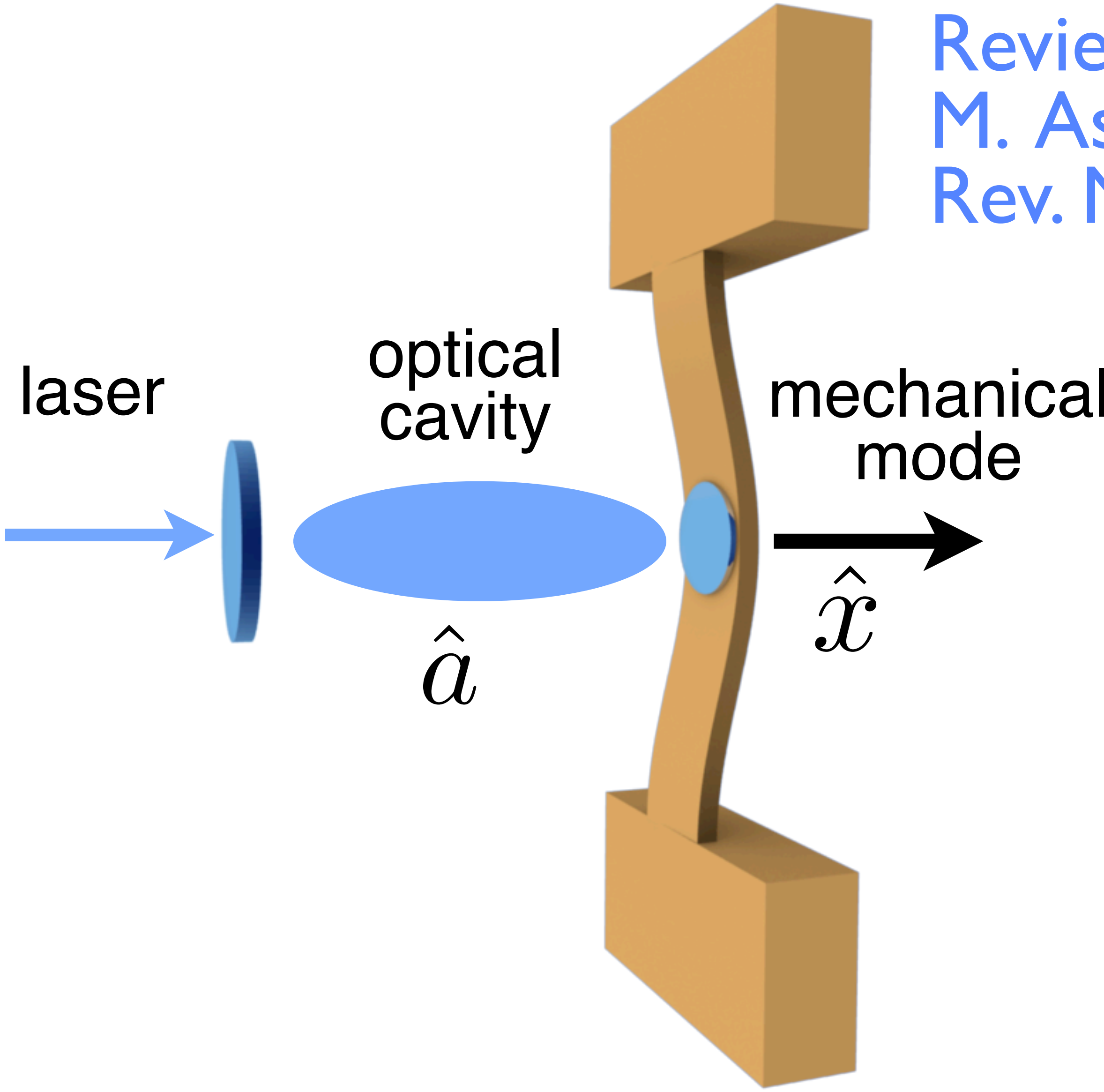
Topological Phases of Sound (and Light)



Artificial magnetic fields for photons

Optomechanical Hamiltonian

Review "Cavity Optomechanics":
M. Aspelmeyer, T. Kippenberg, FM
Rev. Mod. Phys. **86**, 1391 (2014)



$$\hat{H} = \hbar\omega_{\mathrm{cav}} \cdot (1 - \hat{x}/L)\hat{a}^\dagger\hat{a} + \hbar\Omega\hat{b}^\dagger\hat{b} + \ldots$$

$$\hat{x} = x_{\mathrm{ZPF}}(\hat{b} + \hat{b}^\dagger)$$

$$x_{\mathrm{ZPF}} = \sqrt{\hbar/2m\Omega}$$

Optomechanical Hamiltonian

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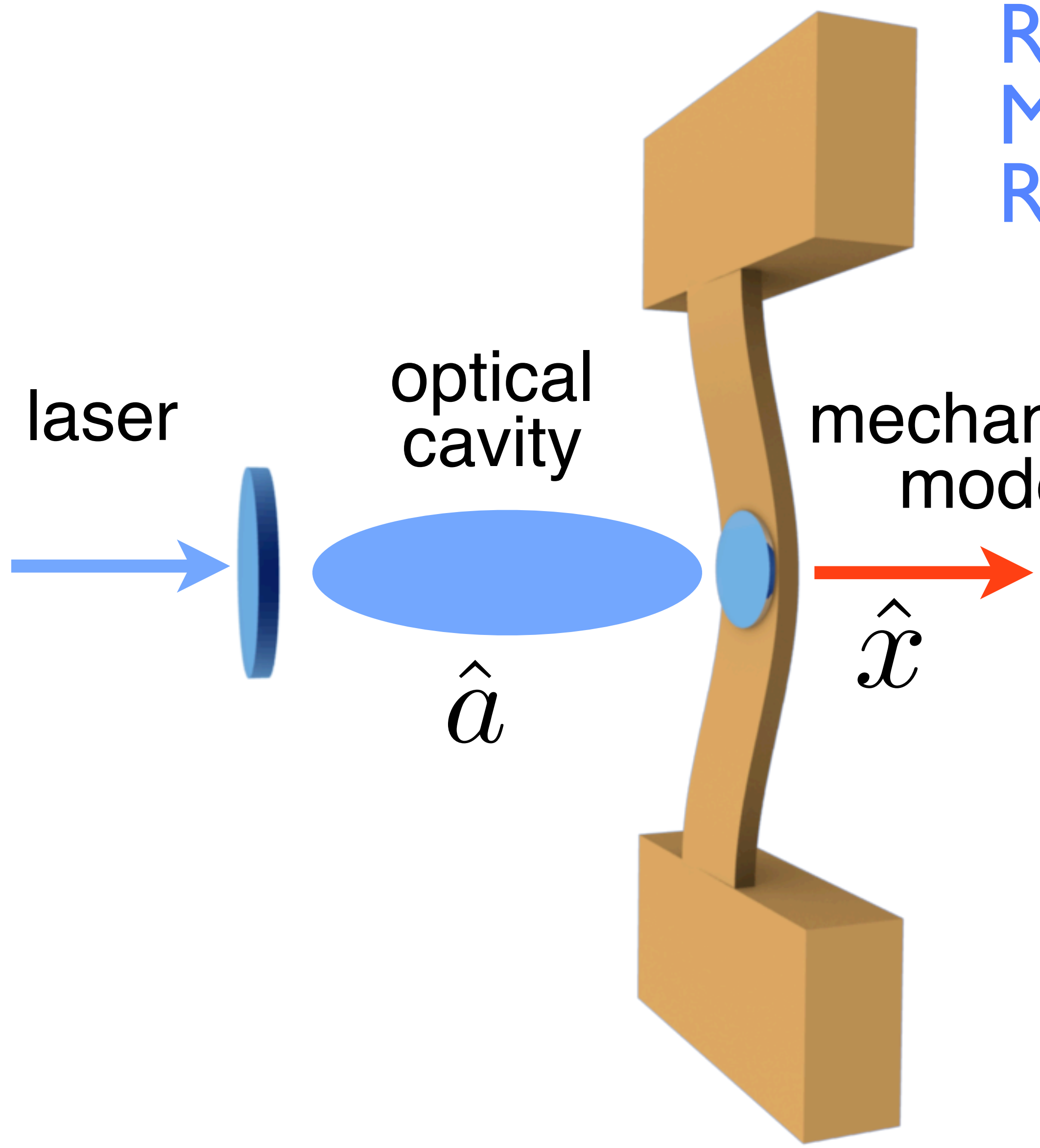


$$g_0 \sim \mathrm{Hz} - \mathrm{MHz}$$

$$\hat{H} = -(\Delta + g_0(\hat{b} + \hat{b}^\dagger))\hat{a}^\dagger\hat{a} + \Omega\hat{b}^\dagger\hat{b} + \ldots$$

laser detuning

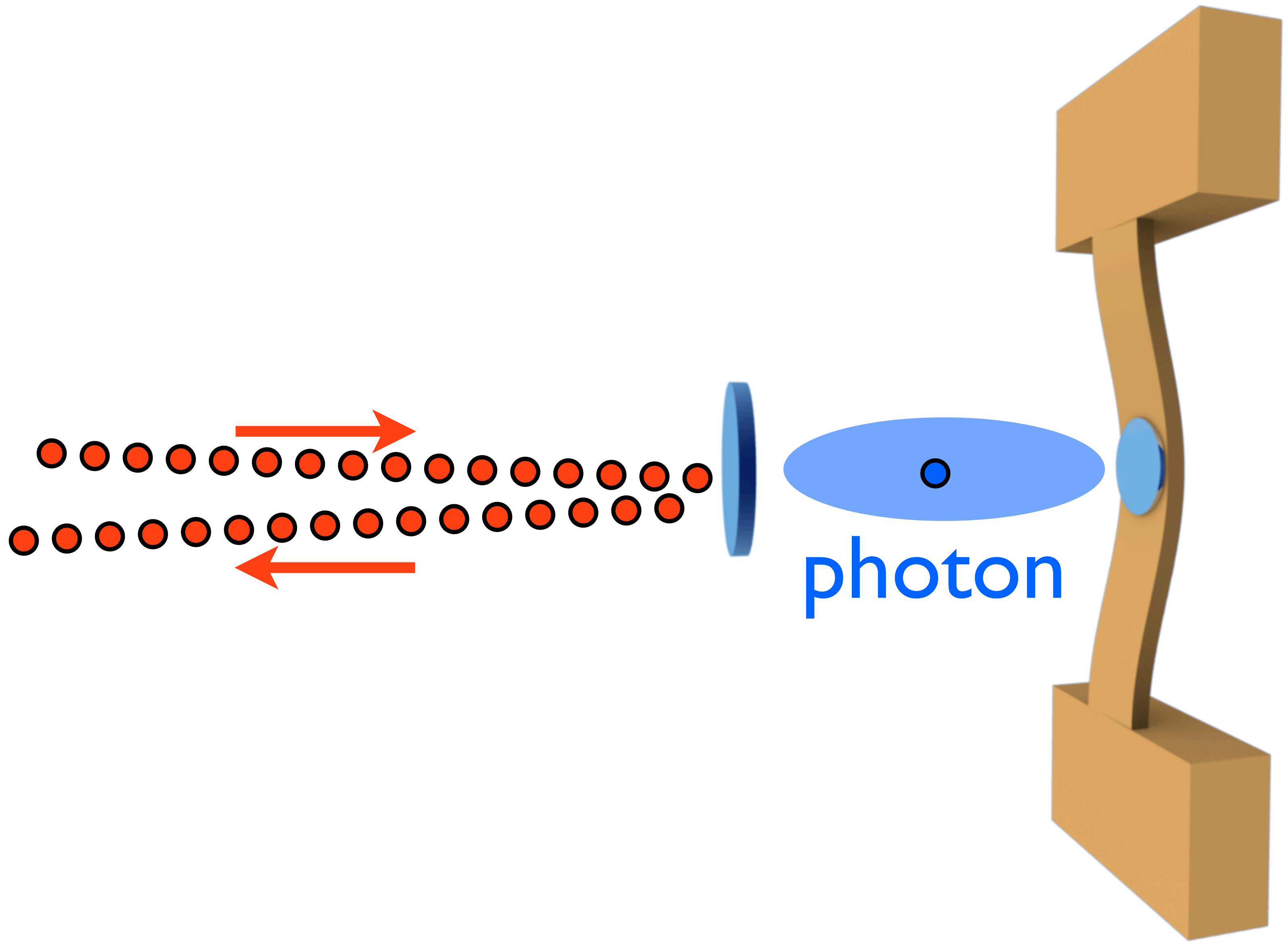
optomech. coupling

$$\Delta = \omega_L - \omega_{\mathrm{cav}}$$

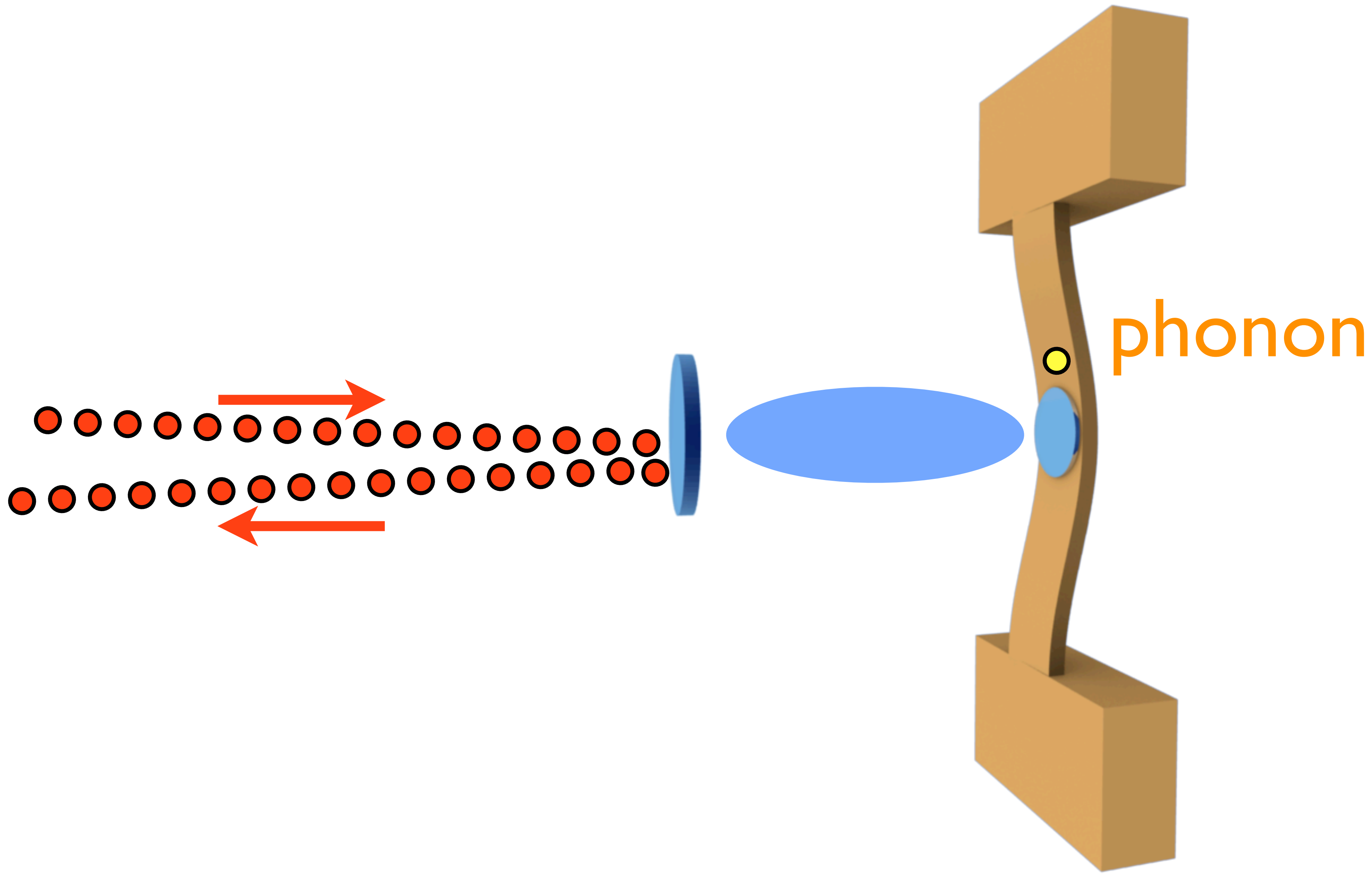
$$\hat{x} = x_{\mathrm{ZPF}}(\hat{b} + \hat{b}^\dagger)$$

$$x_{\mathrm{ZPF}} = \sqrt{\hbar/2m\Omega}$$

Converting photons into phonons



Converting photons into phonons



“Linearized” Optomechanical Hamiltonian

$$\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$$

$$\hat{a} = \alpha + \delta\hat{a}$$

$$\hbar g_0 (\alpha \delta\hat{a}^\dagger + \alpha^* \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

“laser-enhanced optomechanical coupling”: $g = g_0 \alpha$

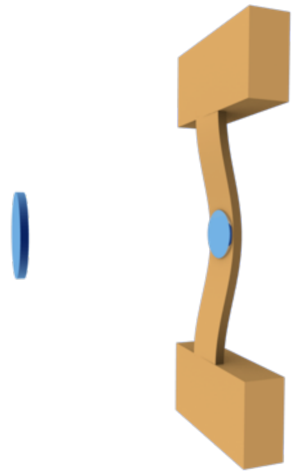
$g_0 \sim \mathrm{Hz} - \mathrm{MHz}$

bare optomechanical coupling (geometry, etc.: fixed!)

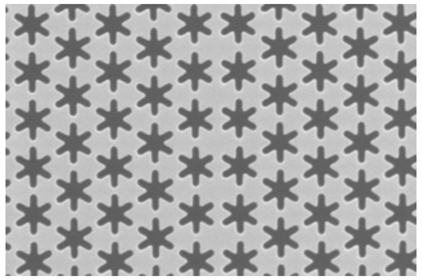
α

laser-driven cavity amplitude

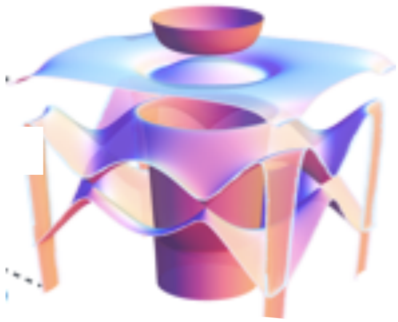
tuneable! **phase**!



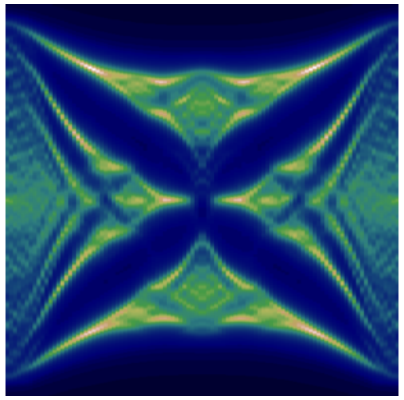
Cavity Optomechanics



Optomechanical Arrays

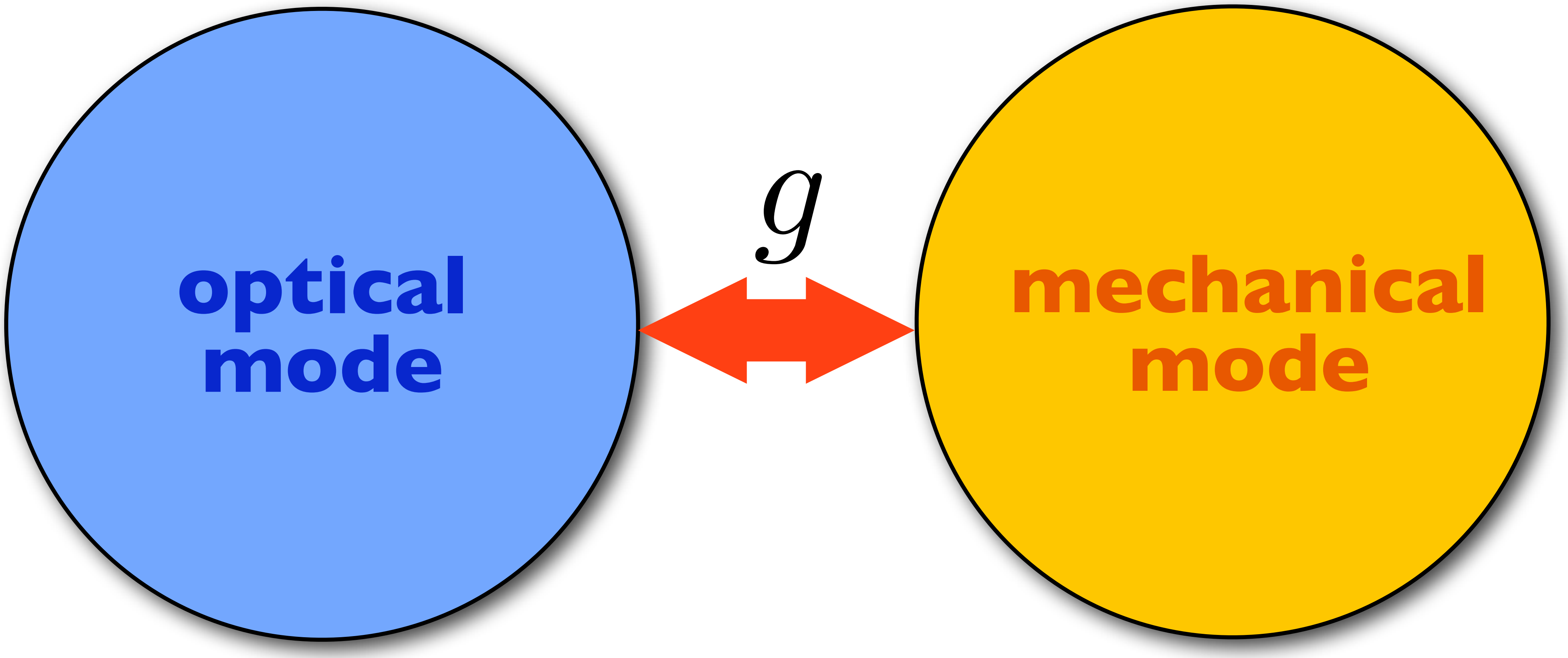


Topological Phases of Sound (and Light)



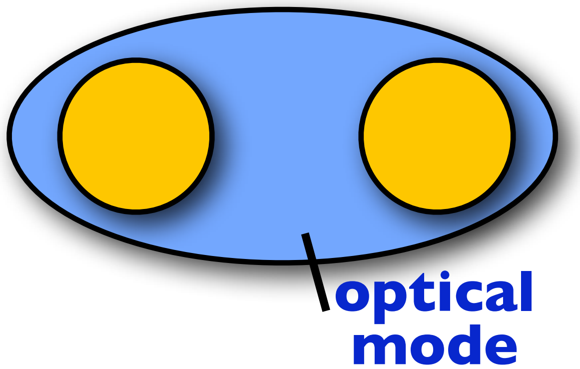
Artificial magnetic fields for photons

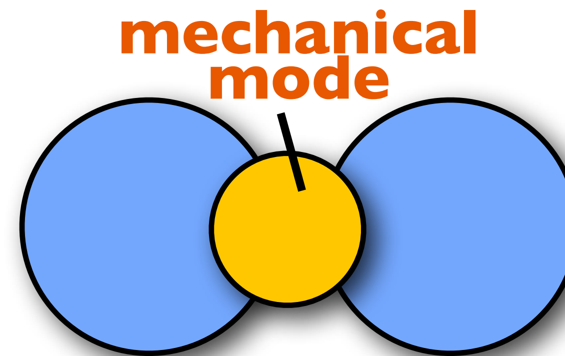
Single-mode optomechanics

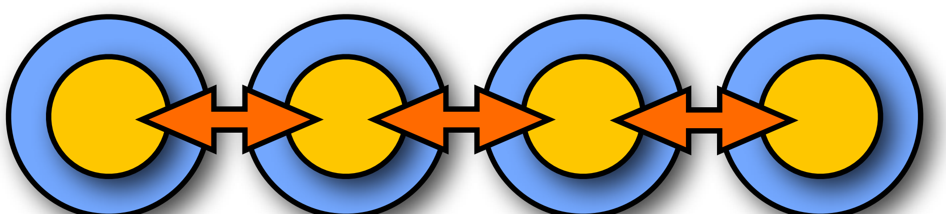


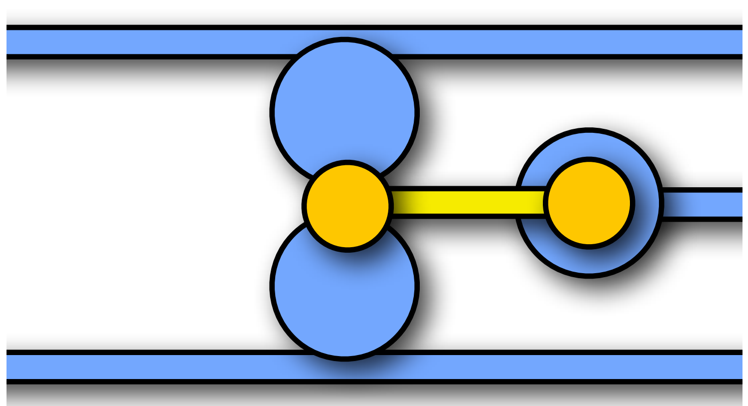
✓displacement sensing
✓cooling
✓strong coupling
✓self-oscillations (limit cycles)

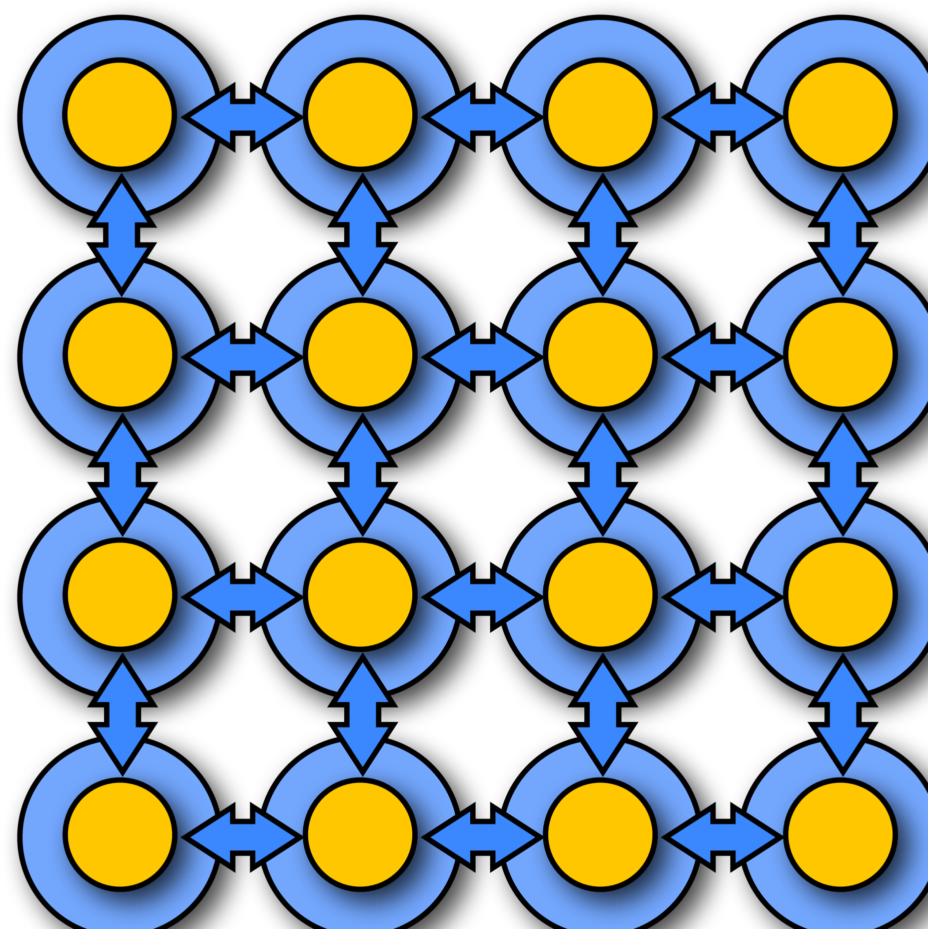
Many modes



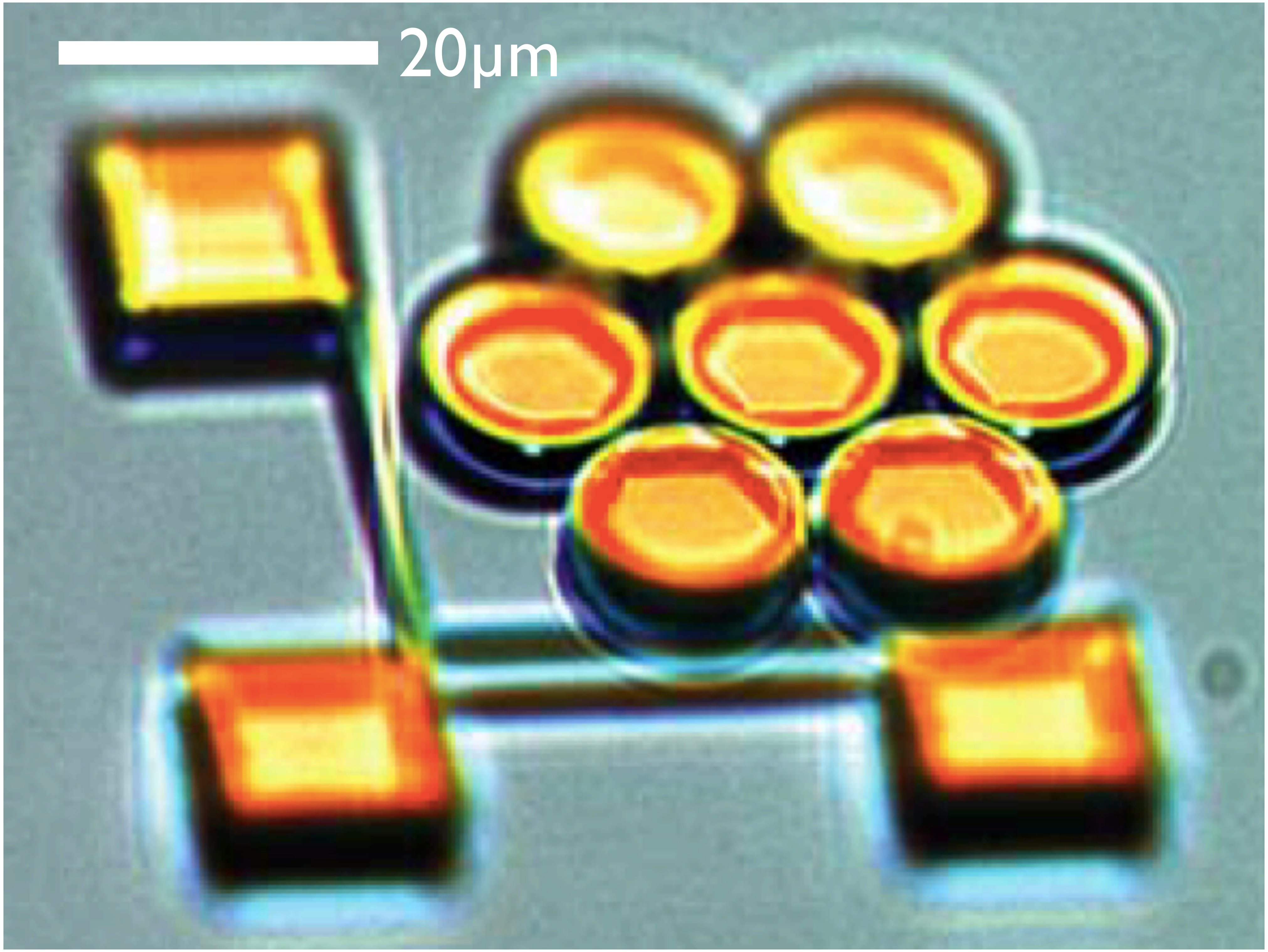








First realizations

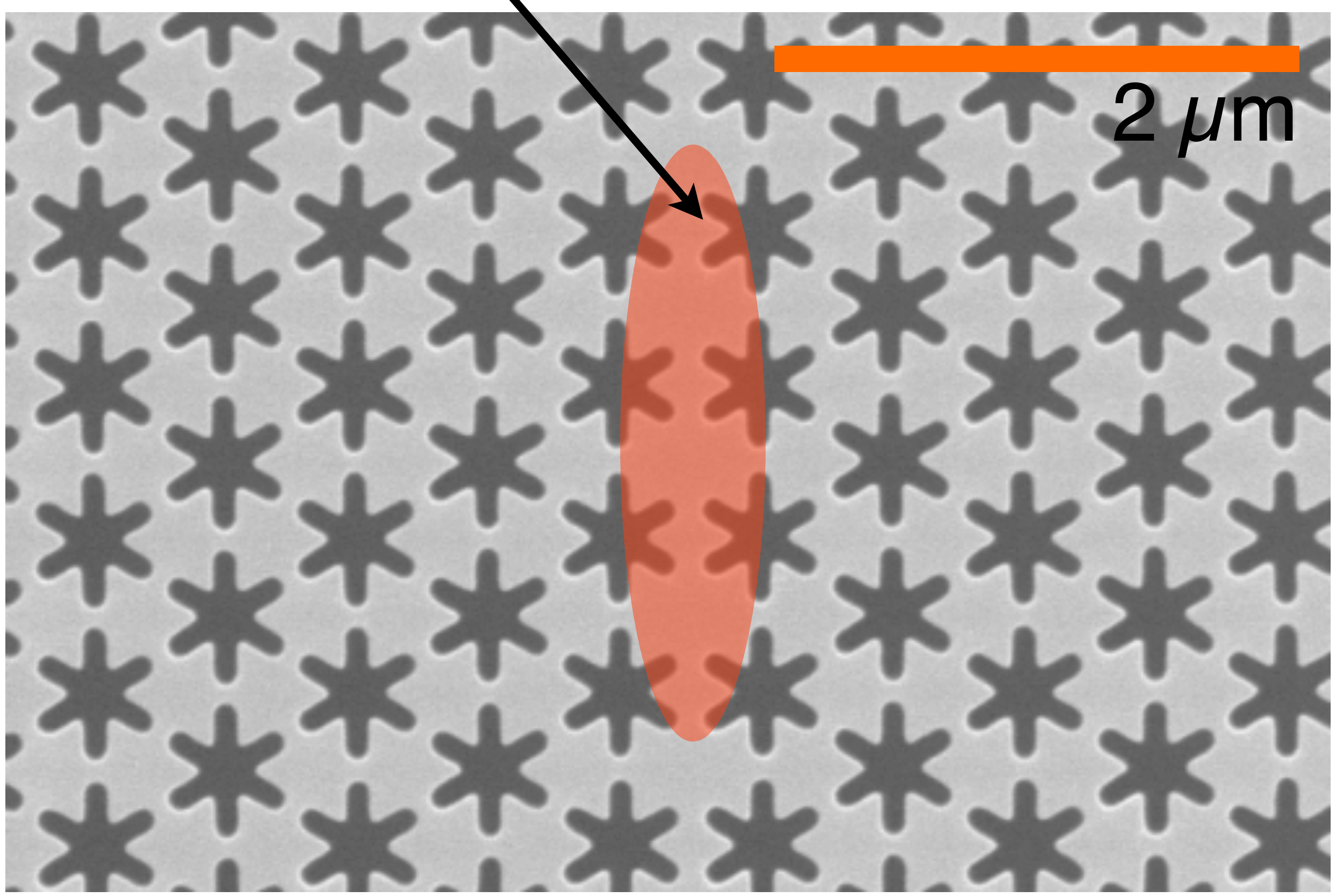


Lipson group, Cornell arXiv:1505.02009 (synchronization)

Optomechanical crystals

= free-standing photonic crystal structures (Painter group)

localized optical and vibrational (GHz) mode



advantages:

tight vibrational confinement:
high frequencies, small mass
(stronger quantum effects)

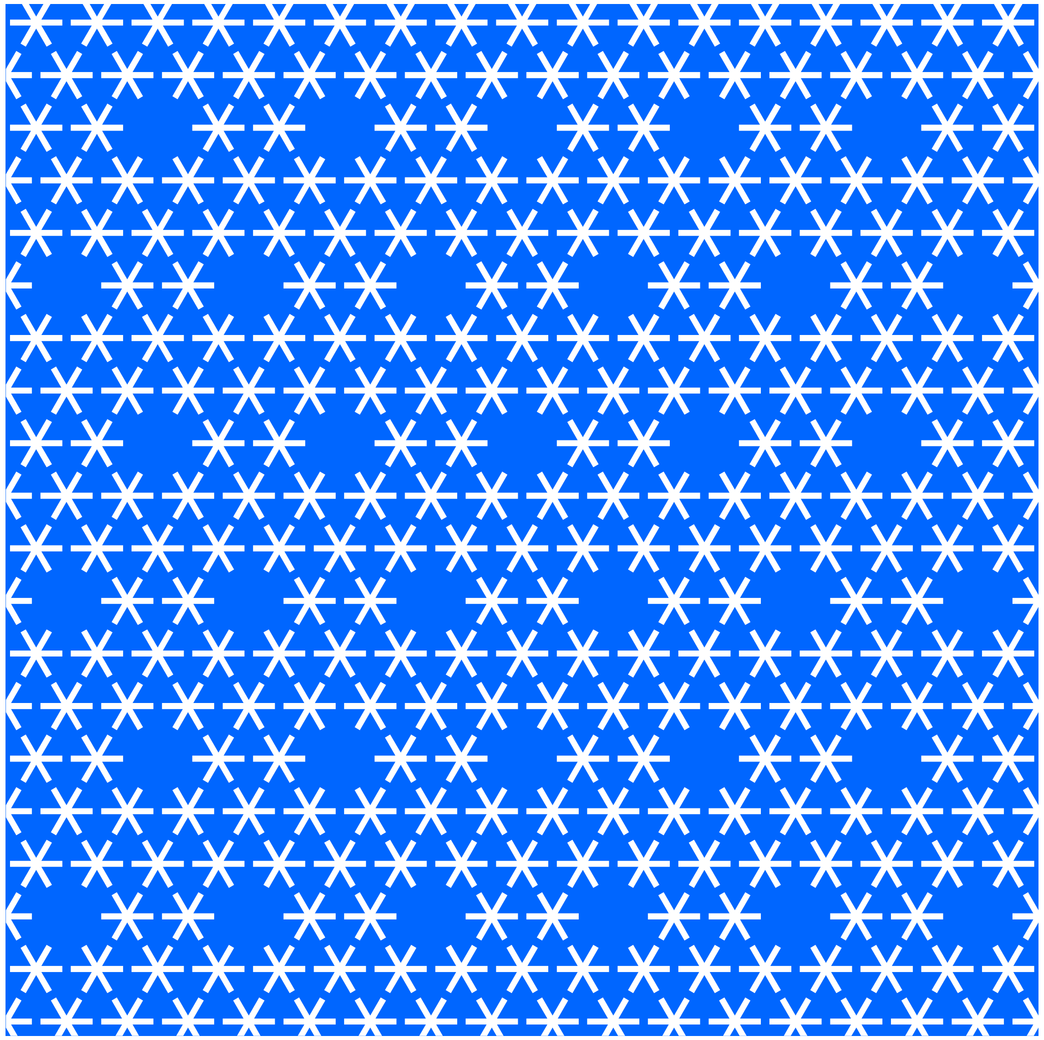
tight optical confinement:
large optomechanical coupling
(100 GHz/nm)

integrated on a chip

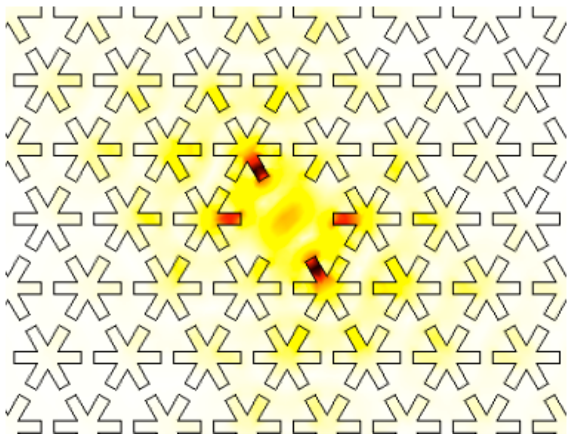
Safavi-Naeini et al PRL 2014
Eichenfield et al Nature 2009

Optomechanical arrays

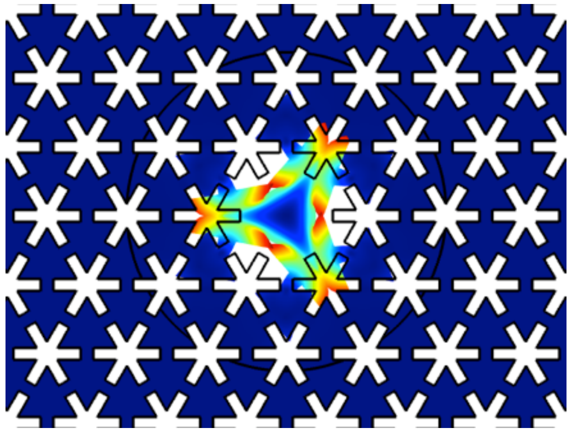
Optomechanical array: Many coupled optomechanical cells

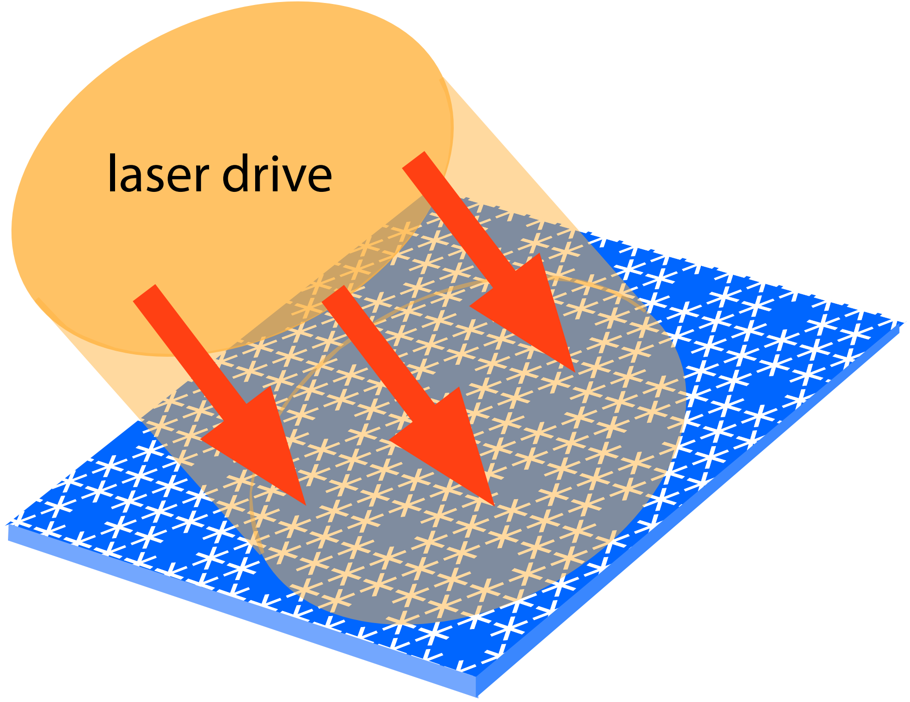


optical mode



mechanical mode

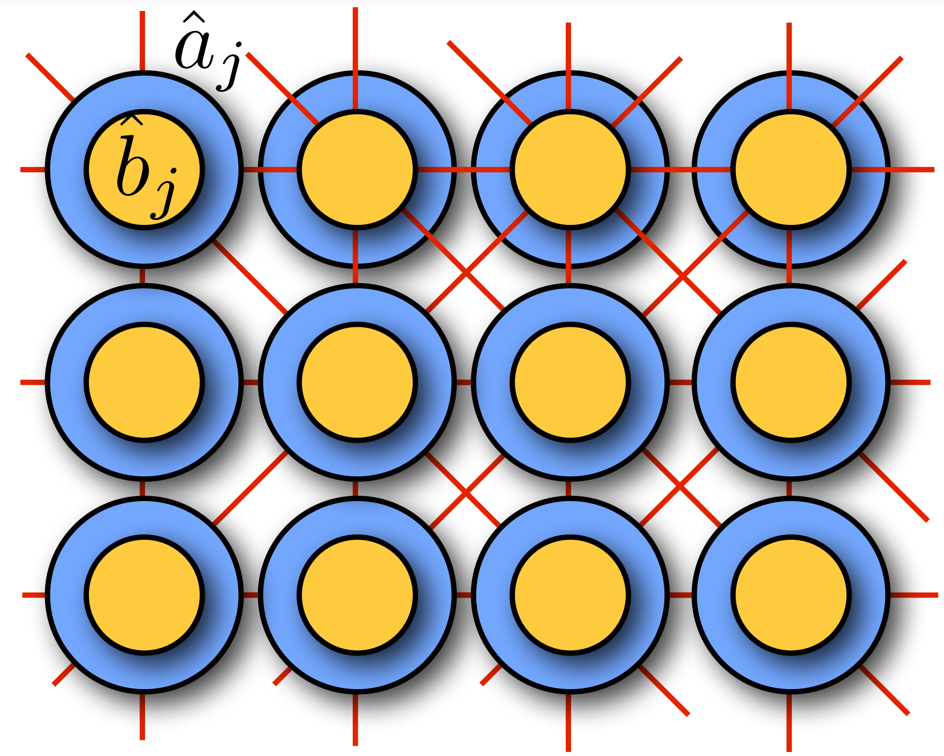




Possible design based on "snowflake" 2D optomechanical crystal (Painter group), here: with suitable defects forming a superlattice (array of cells)

Modeling an optomechanical array

Tight-binding model for photons & phonons hopping and interacting on a lattice



laser detuning

$$\Delta = \omega_L - \omega_{\mathrm{opt}}$$

each cell: optomech. interaction laser drive

$$\hat{H}_{\mathrm{om},j} = -\Delta \hat{a}_j^\dagger \hat{a}_j + \Omega \hat{b}_j^\dagger \hat{b}_j - g_0(\hat{b}_j^\dagger + \hat{b}_j)\hat{a}_j^\dagger \hat{a}_j + \alpha_L(\hat{a}_j^\dagger + \hat{a}_j)$$

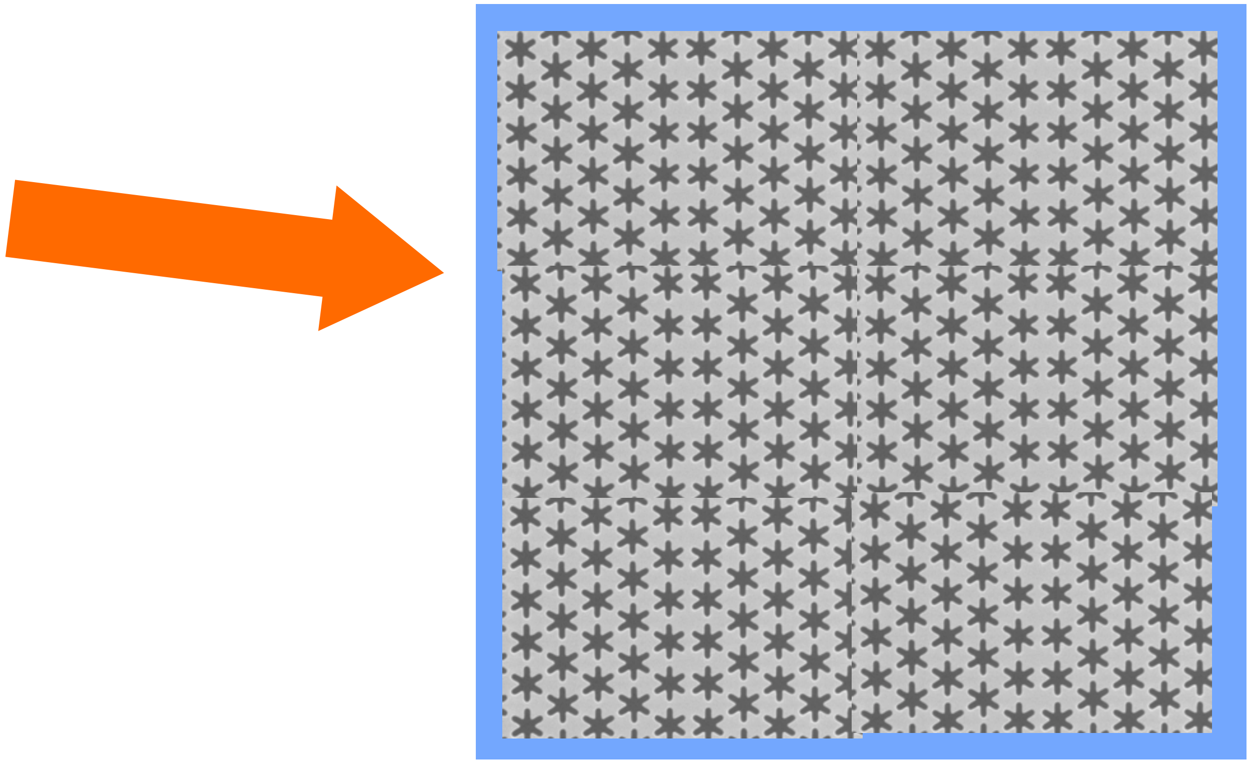
$$\hat{H}_{\mathrm{int}} = - \mathrm{J} \sum_{\langle i,j \rangle} (\hat{a}_i^\dagger \hat{a}_j + \hat{a}_i \hat{a}_j^\dagger) - \mathrm{K} \sum_{\langle i,j \rangle} (\hat{b}_i^\dagger \hat{b}_j + \hat{b}_i \hat{b}_j^\dagger)$$

optical coupling (photon tunneling) mechanical coupling (phonon tunneling)

Max Ludwig, FM, Phys. Rev. Lett. 111, 073602 (2013)

Optomechanical Arrays

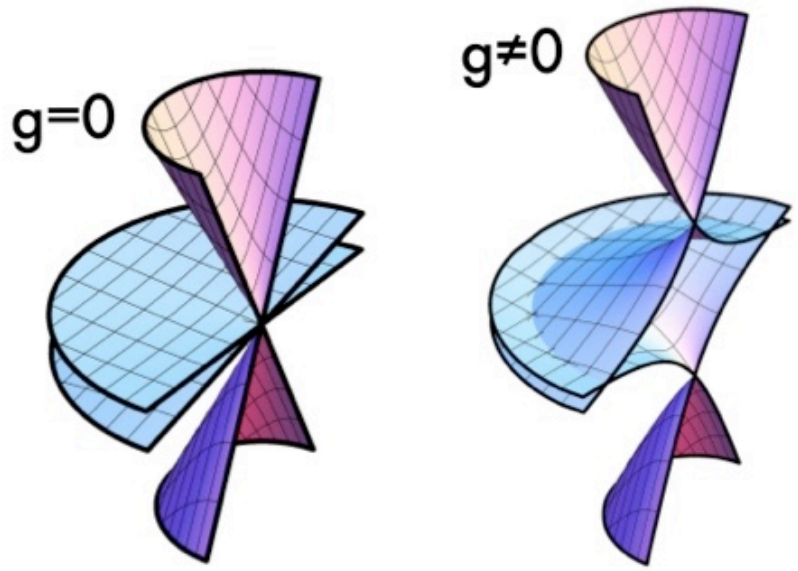
global view:
light-tunable metamaterial for photons & phonons



similar in spirit:
optical lattices
nonlinear optical materials

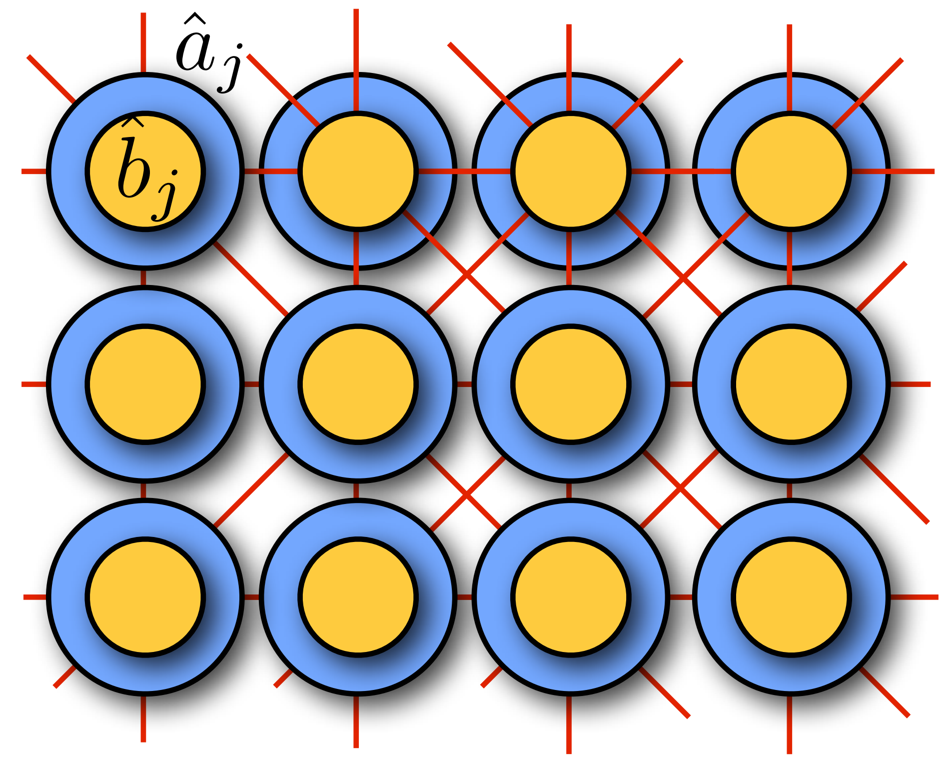
conceptually simple: one material, with holes

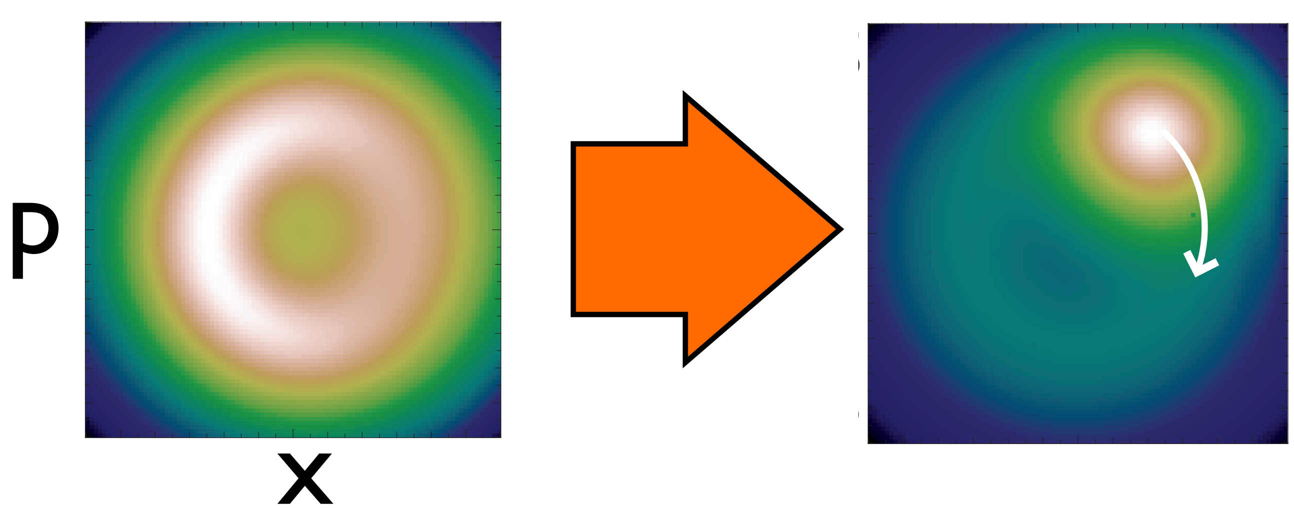
Photons and phonons on a lattice



Tuneable bandstructure for photon-phonon polaritons, Dirac-type dispersion

Schmidt, Peano, FM, New J. Phys. 2015

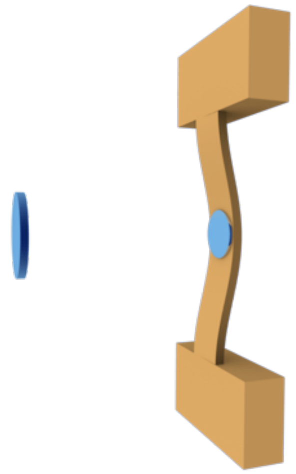




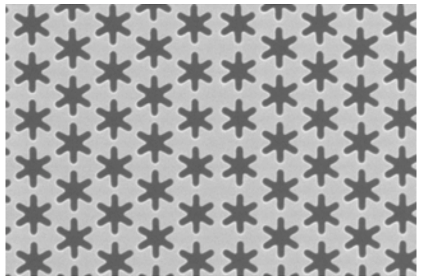
Synchronization, nonequilibrium phase transitions driven by quantum noise

Heinrich et al., Phys. Rev. Lett. 2011

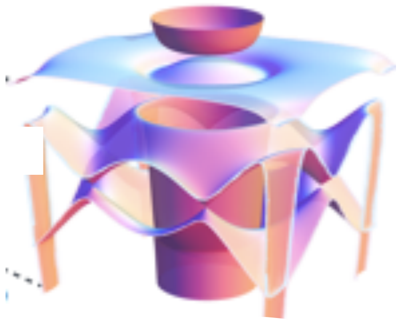
Ludwig, FM,
Phys. Rev. Lett. 111, 073602 (2013)



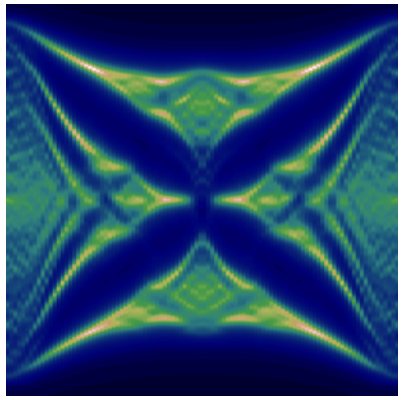
Cavity Optomechanics



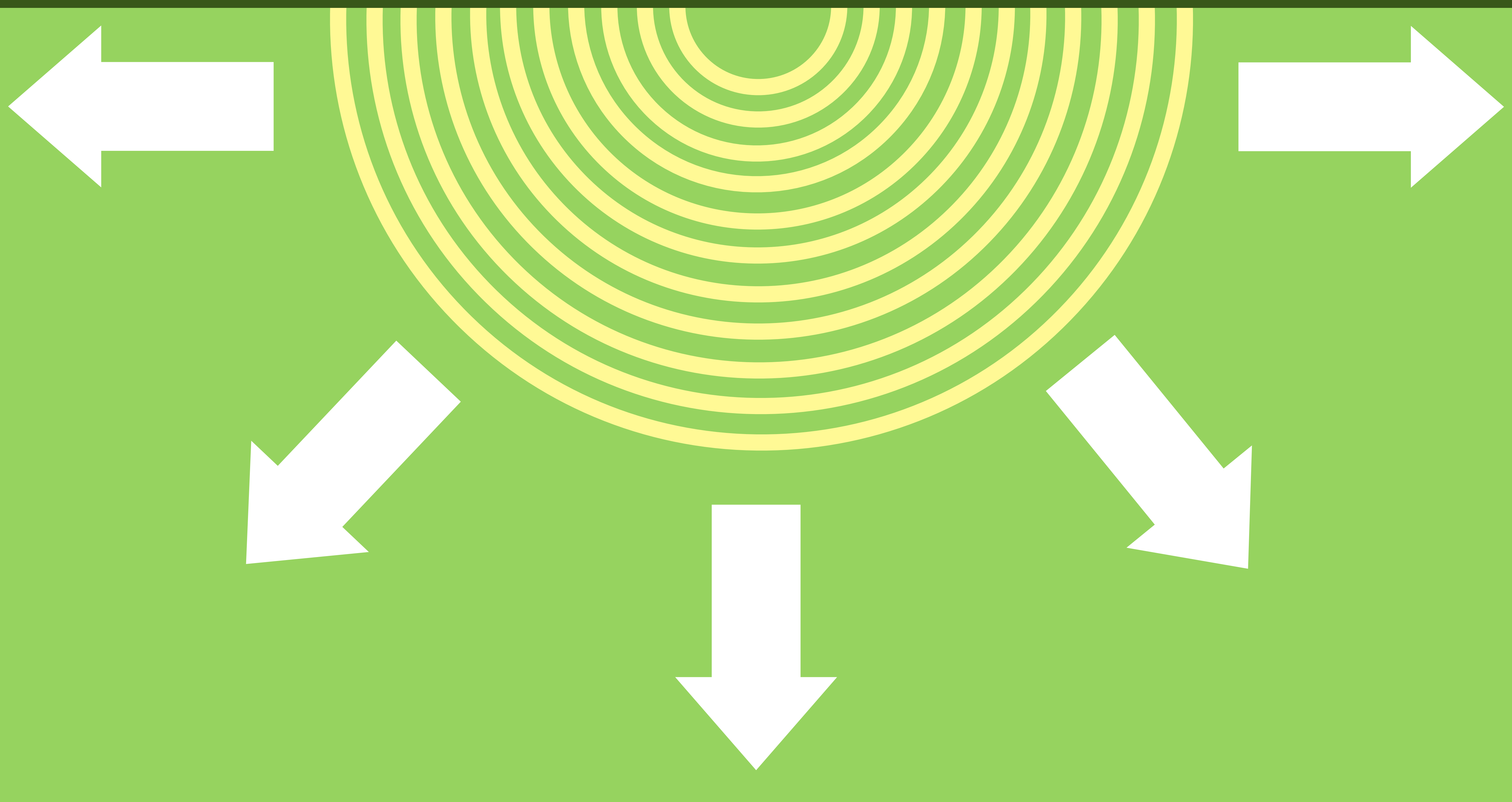
Optomechanical Arrays

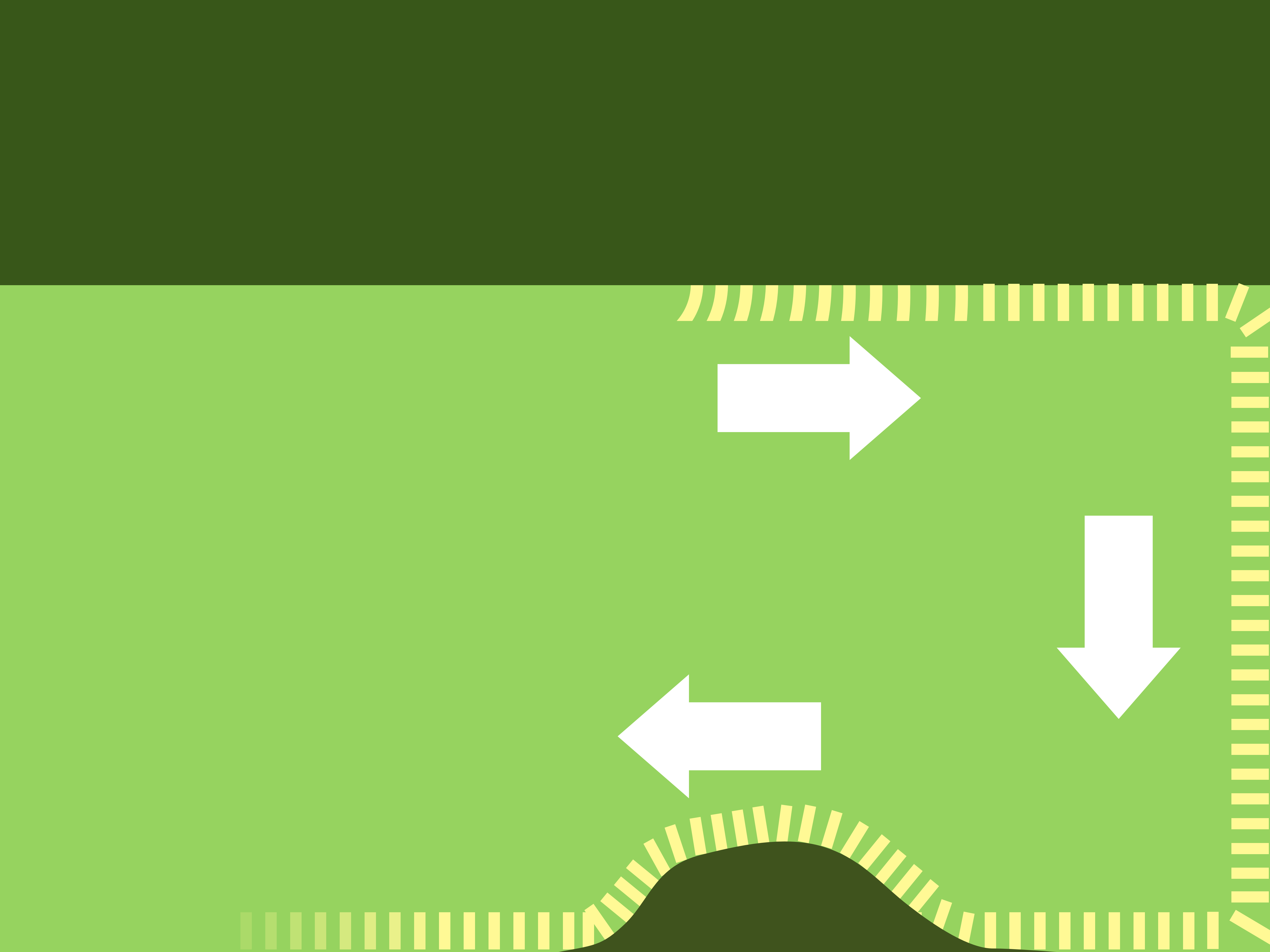


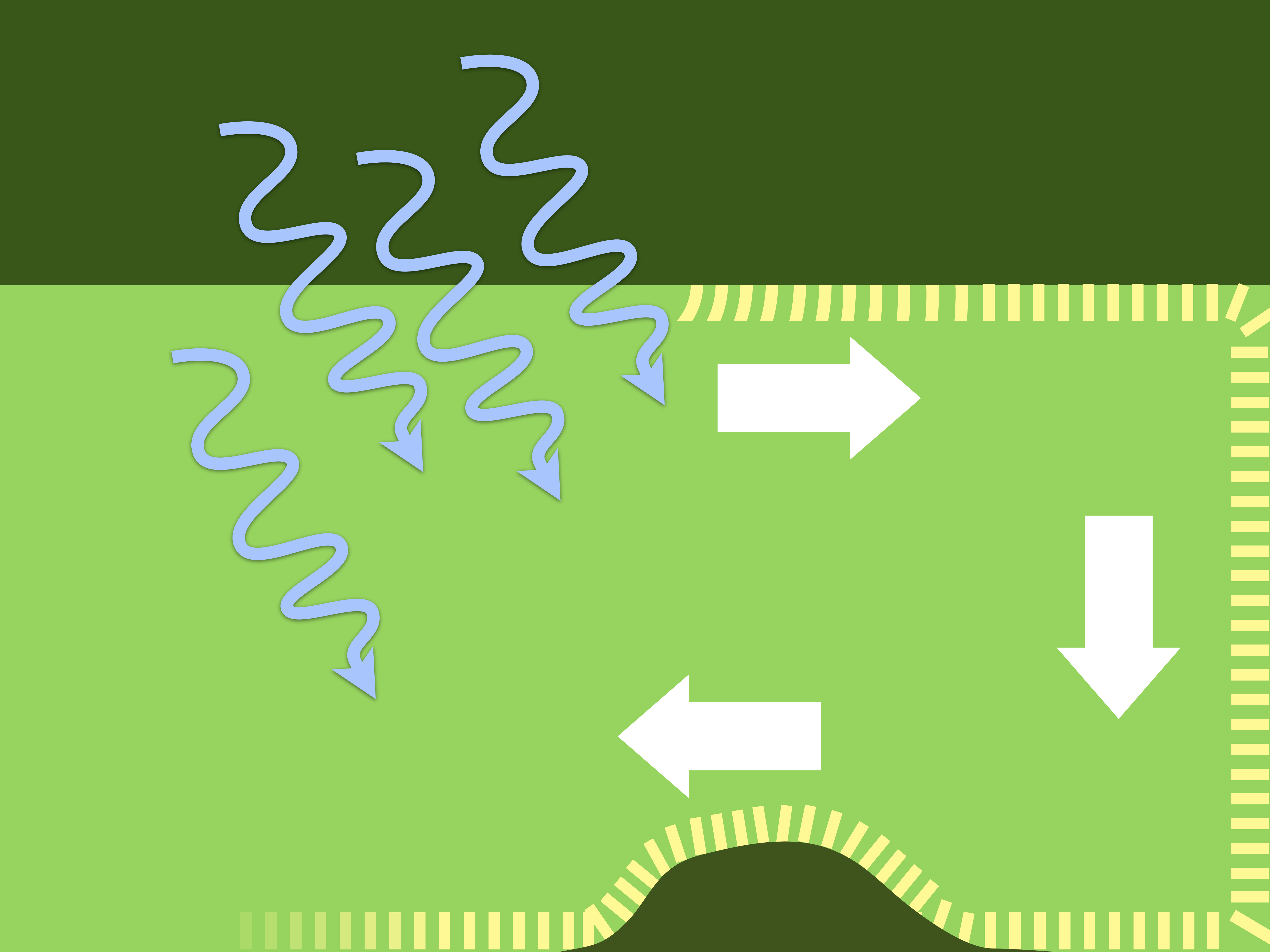
Topological Phases of Sound (and Light)



Artificial magnetic fields for photons



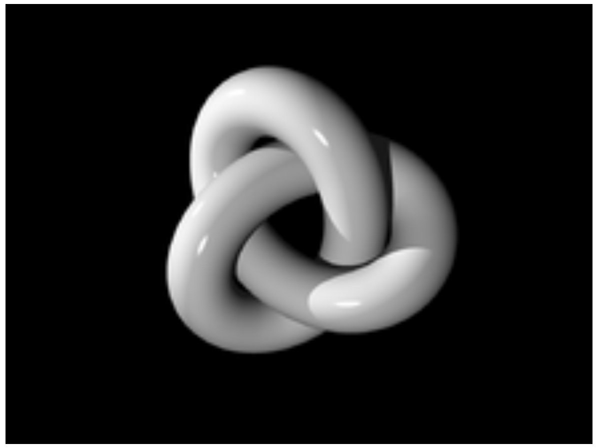




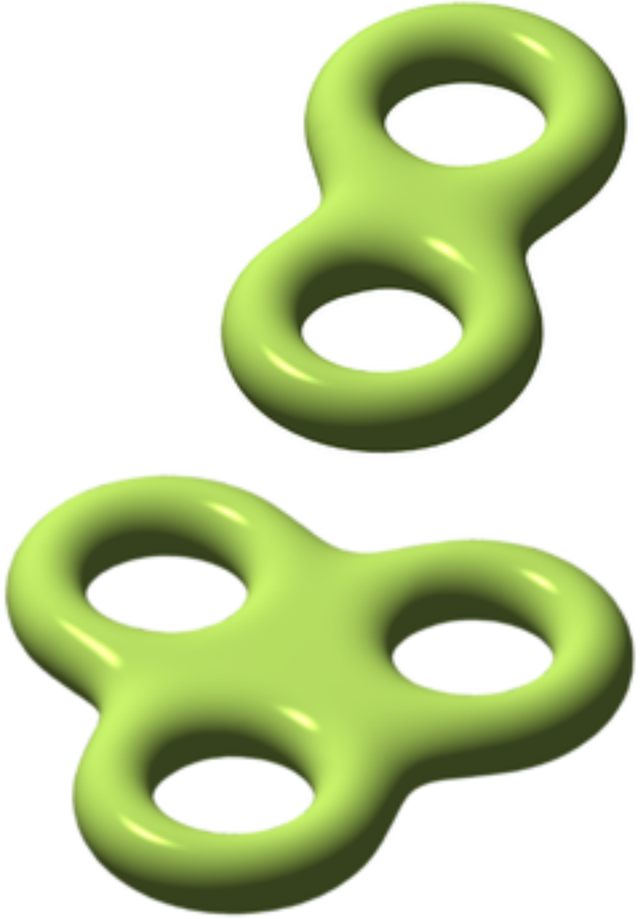
Topological Materials

Topological properties:
robust against smooth changes!

Möbius strip



knots



n-fold torus

superfluid
vortex

Images: Wikipedia

Topological Materials

Waves can show topological robustness!

review: Hasan, Kane RMP 2010

Quantum Hall Effect (Chern number = conductance)

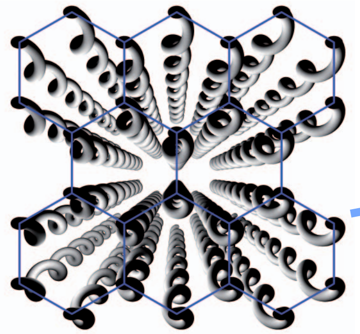
Topological Insulators:

2D topological insulators, e.g. HgTe
3D topological insulators, e.g. BiSe

Other than electronic systems?

Proposals/first experiments for:
atoms, ions, photons, magnons

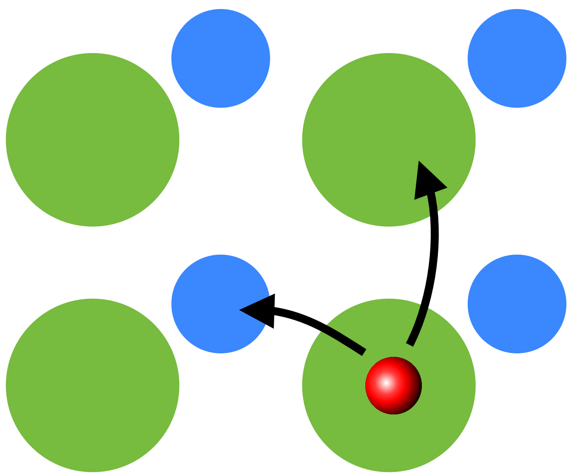
cold atoms experiment: G. Jotzu et al. (Esslinger group), Nature 2014



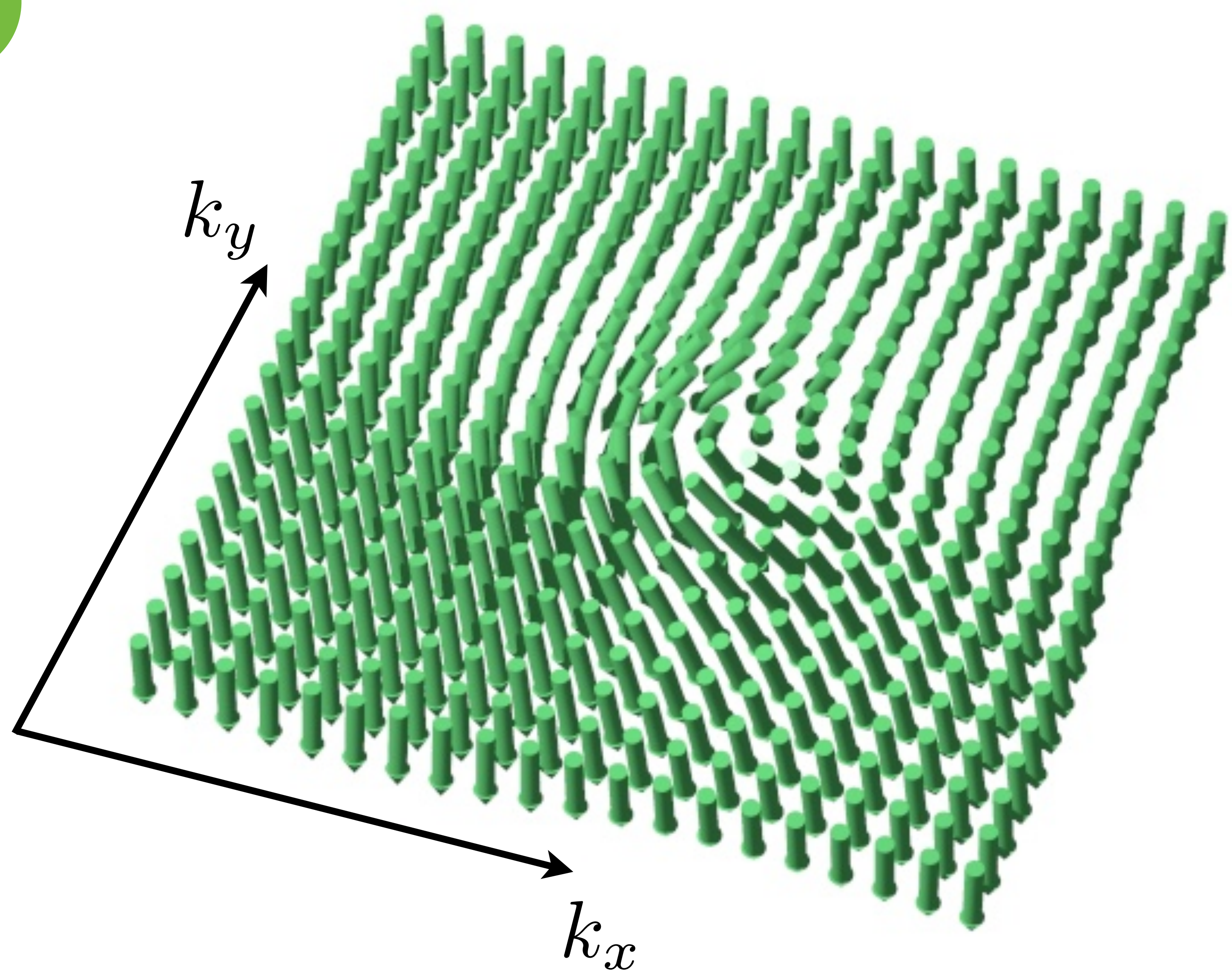
photons:
Khanikaev,...,Shvets, Nature Materials 2012
Rechtsman, ..., Szameit Nature 2013
Mittal, ... , Hafezi PRL 2014
...

magnons: Zhang et al. 2013, Shindou et al 2013, Romhanyi et al 2015, ...

Topological Bandstructures

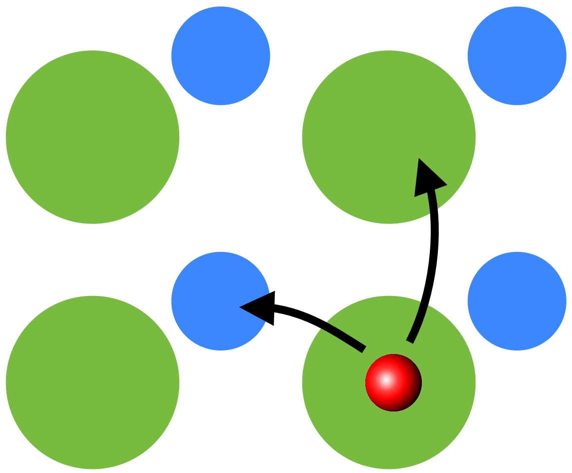


$$\begin{pmatrix} A(\vec{k}) \\ B(\vec{k}) \end{pmatrix} \cdot e^{i\vec{k}\vec{r}}$$

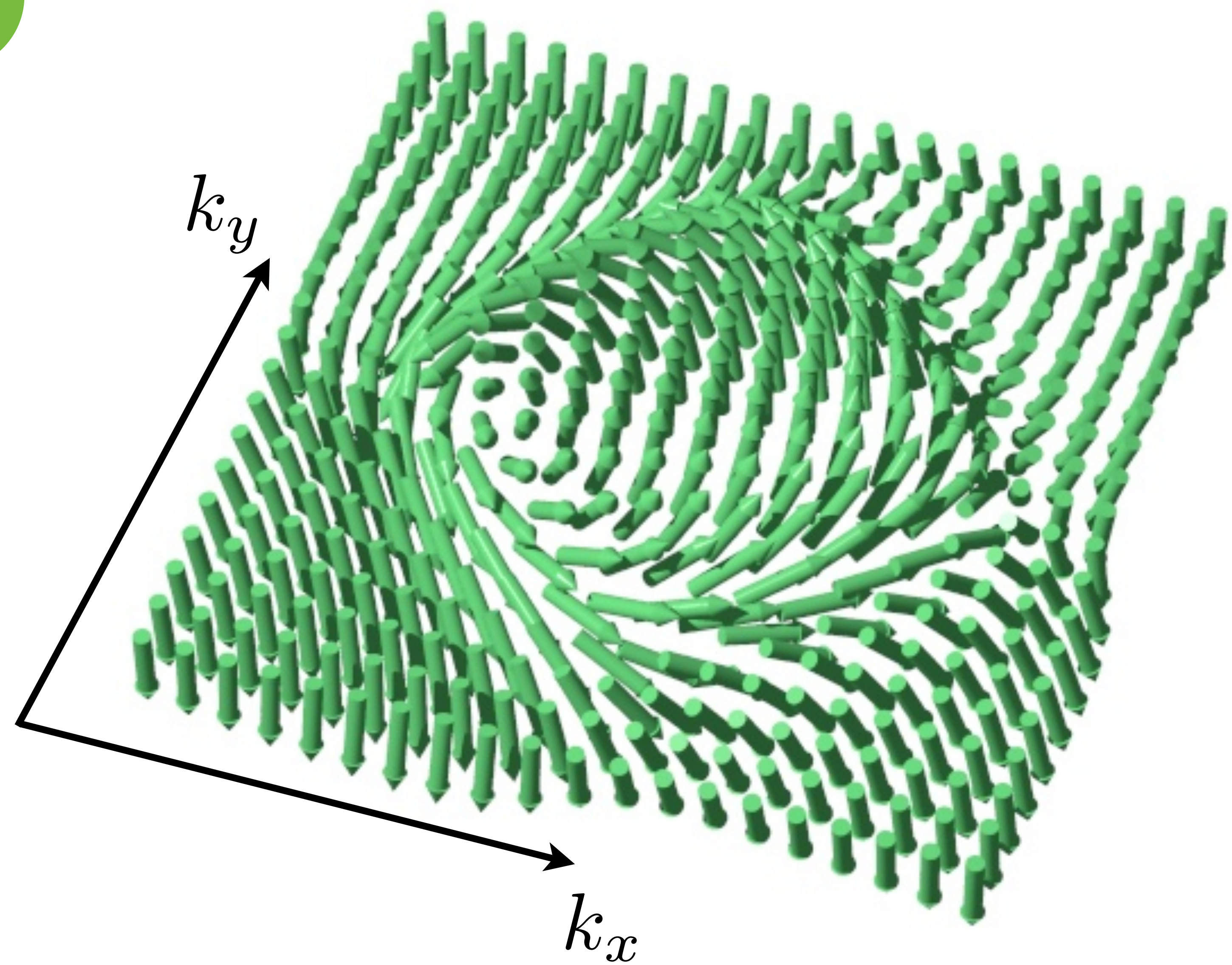


[Bernevig, Hughes, Zhang 2006]

Topological Bandstructures



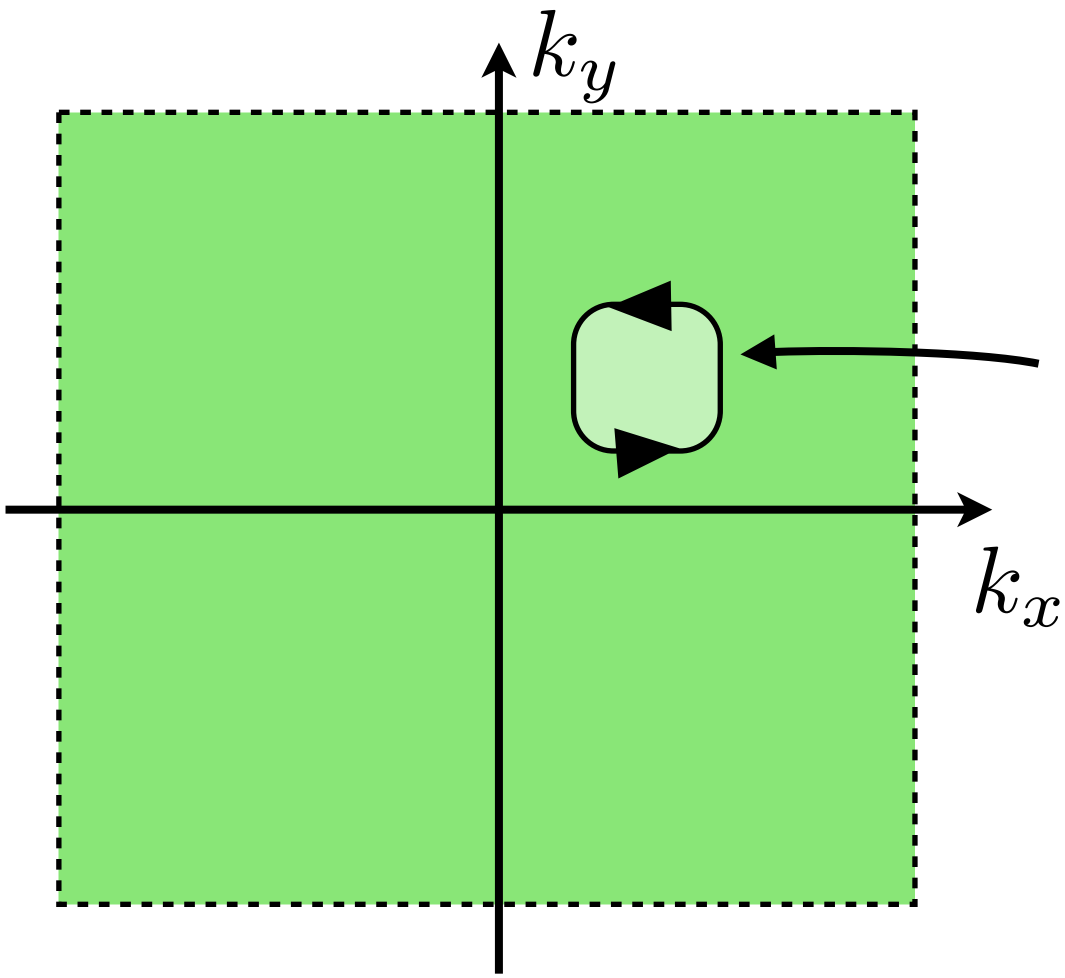
$$\begin{pmatrix} A(\vec{k}) \\ B(\vec{k}) \end{pmatrix} \cdot e^{i\vec{k}\vec{r}}$$



[Bernevig, Hughes, Zhang 2006]

Topological Bandstructures

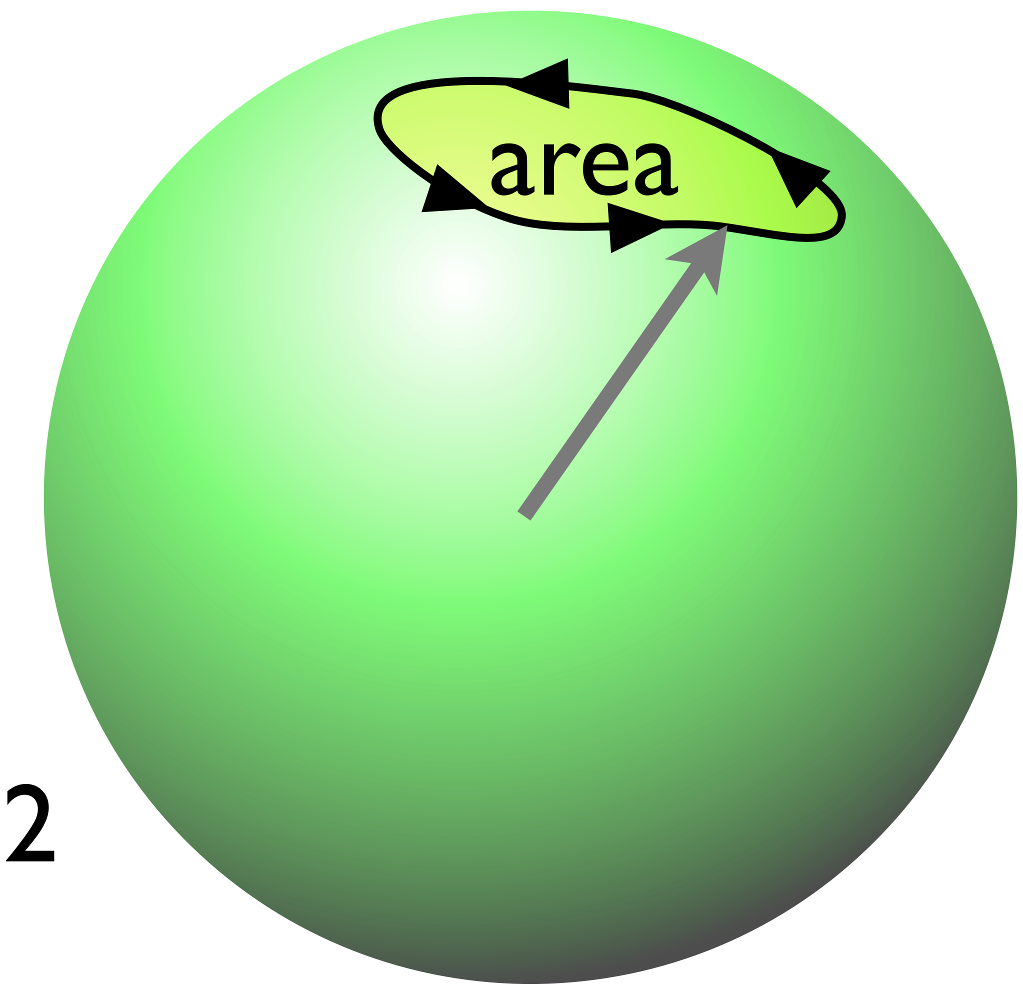
Brillouin zone



$$\begin{pmatrix} A(\vec{k}) \\ B(\vec{k}) \end{pmatrix} \cdot e^{i\vec{k}\vec{r}}$$

path in parameter space

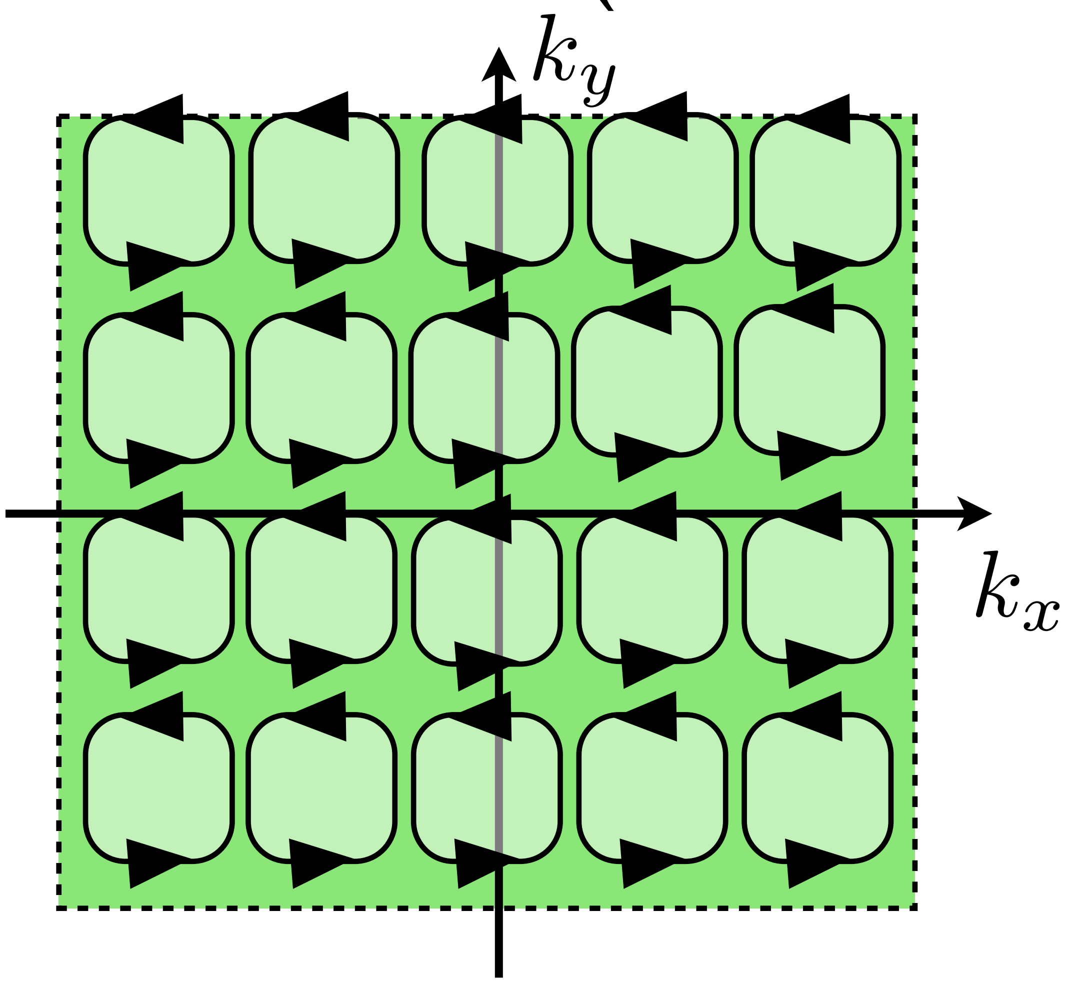
change of wave function



Berry phase = area / 2

Topological Bandstructures

Chern number = (sum of Berry phases across Brillouin zone)/2π

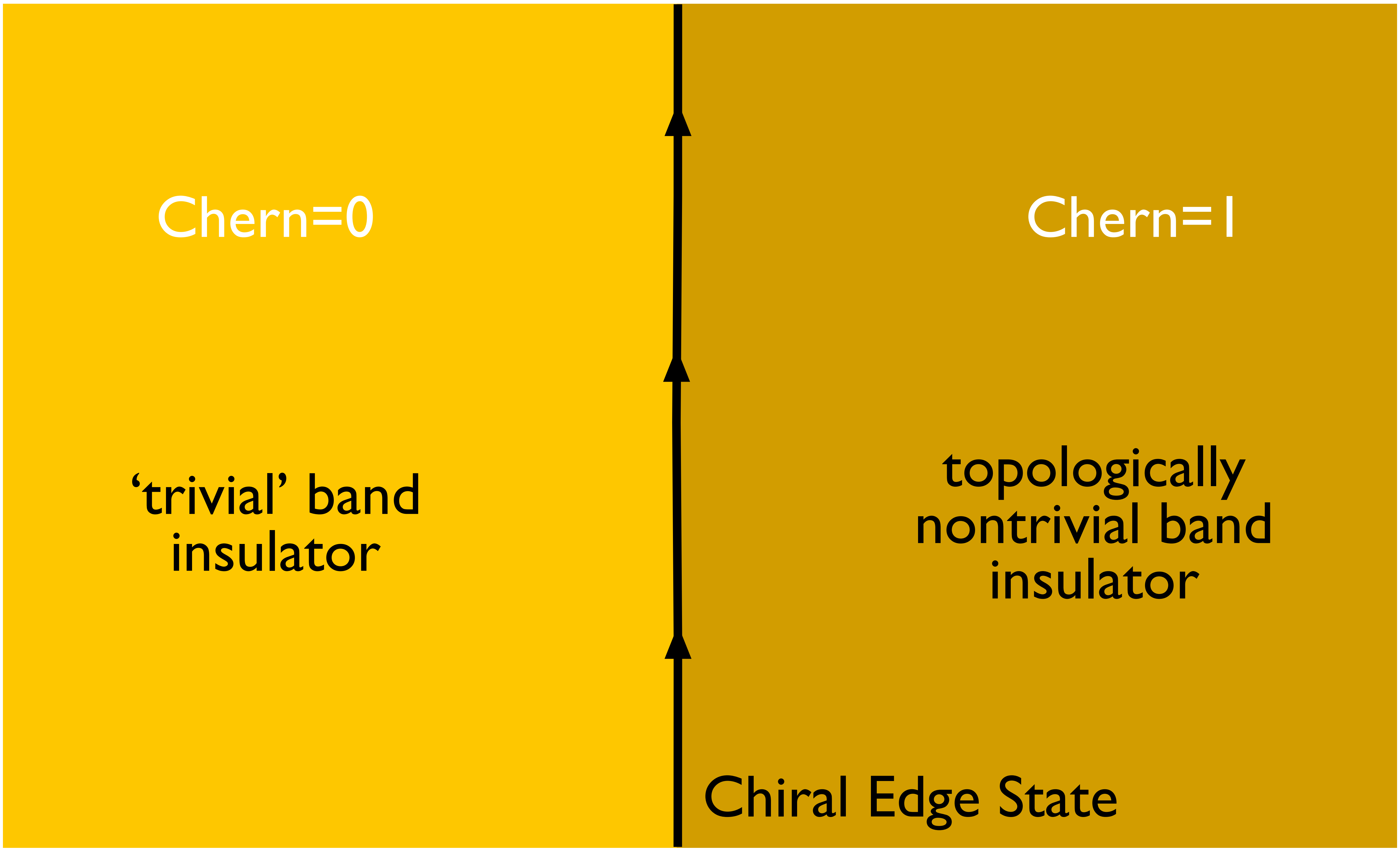


Chern number =

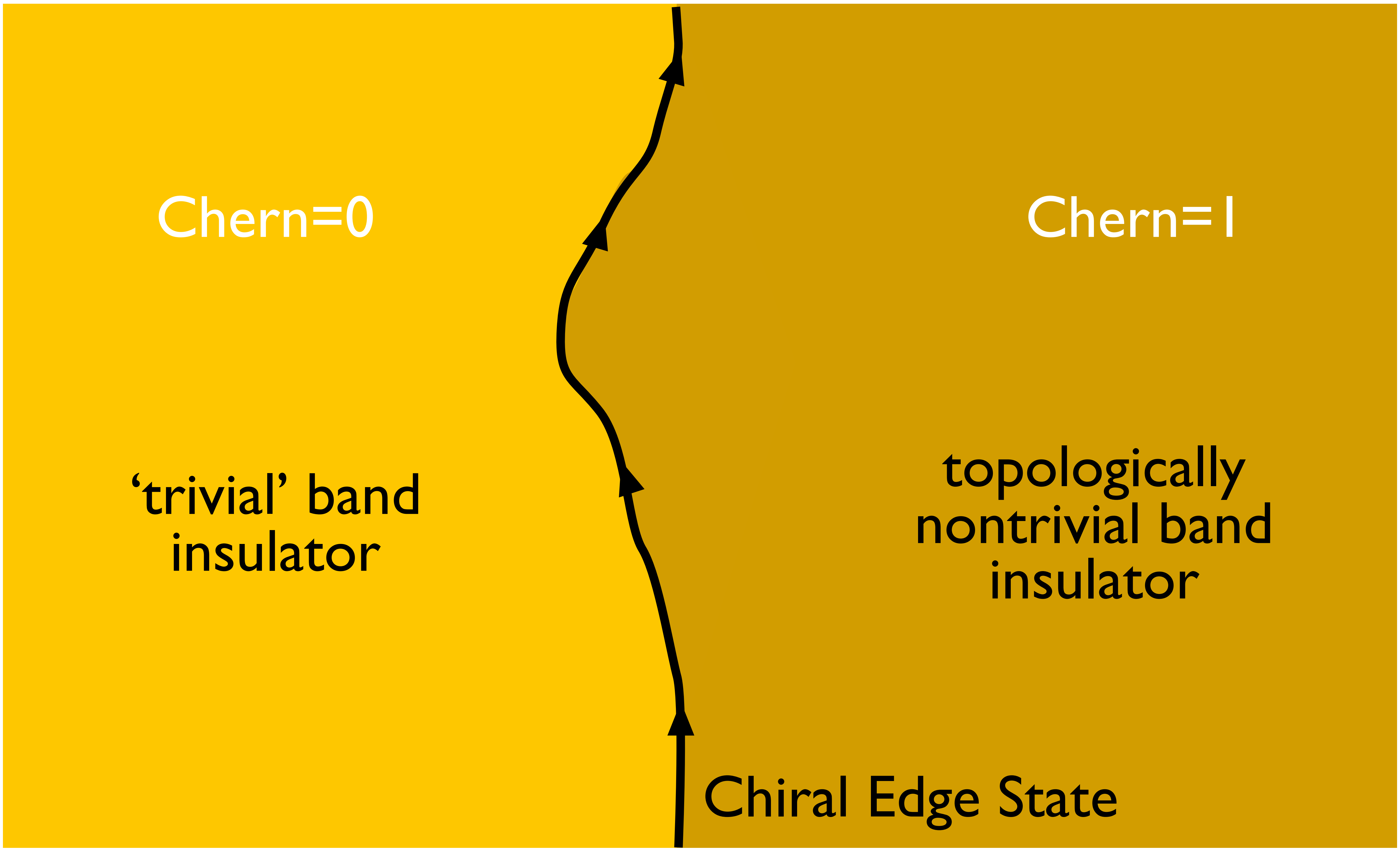
$$\frac{1}{2\pi}\int dk_x dk_y \vec{\nabla} \times \langle \Psi_k | \vec{\nabla} | \Psi_k \rangle$$

Chern number = integer! topologically robust!

Edge States


Chern=0
Chern=1
'trivial' band insulator
topologically nontrivial band insulator
Chiral Edge State

Edge States


Chern=0
Chern=1
'trivial' band insulator
topologically nontrivial band insulator
Chiral Edge State

Phonon Topological Materials

What about topological transport of phonons?

Phonon Topological Materials

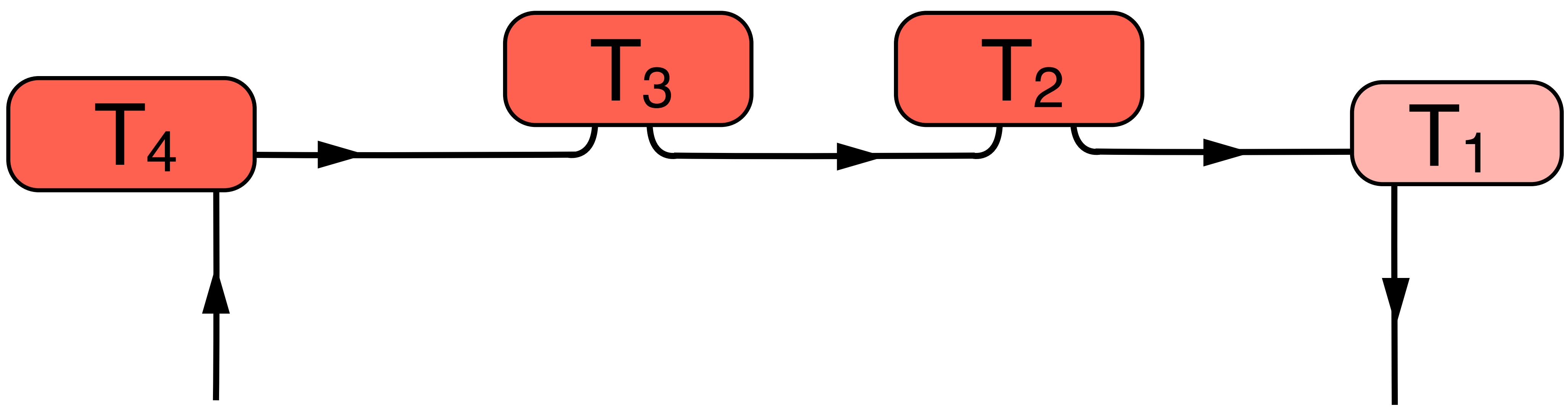
What about topological transport of phonons?

Why?

Transport of sound waves
protected against backscattering

One-way heat transport

Reconfigure channels on-the-fly



Phonon Topological Materials

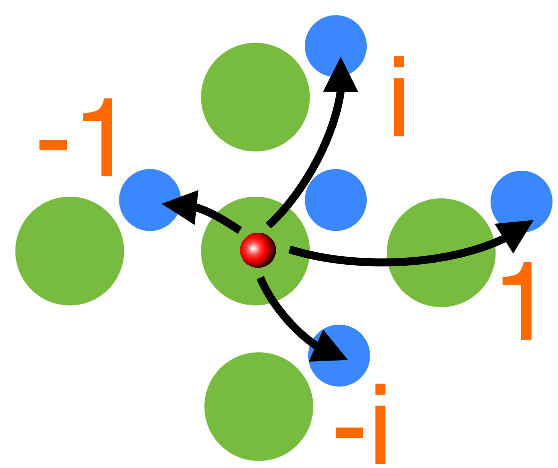
What about topological transport of phonons?

Engineer non-reciprocal phases for phonon transport!

Phonon Topological Materials

What about topological transport of phonons?

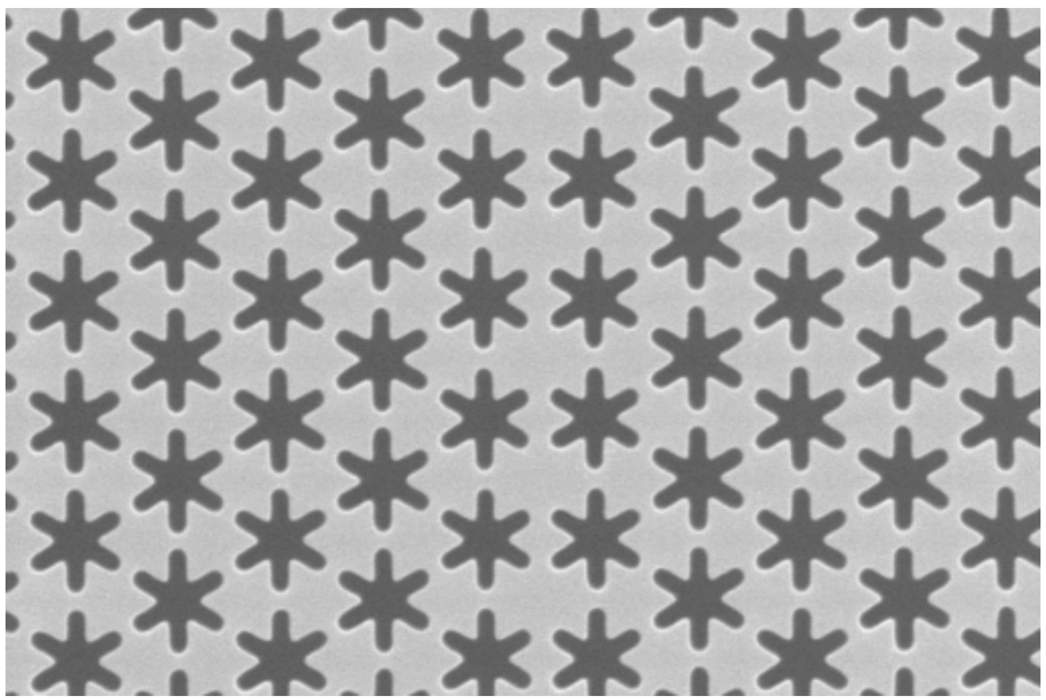
Engineer non-reciprocal phases for phonon transport!



Topological Phases of Sound and Light

What about topological transport of phonons?

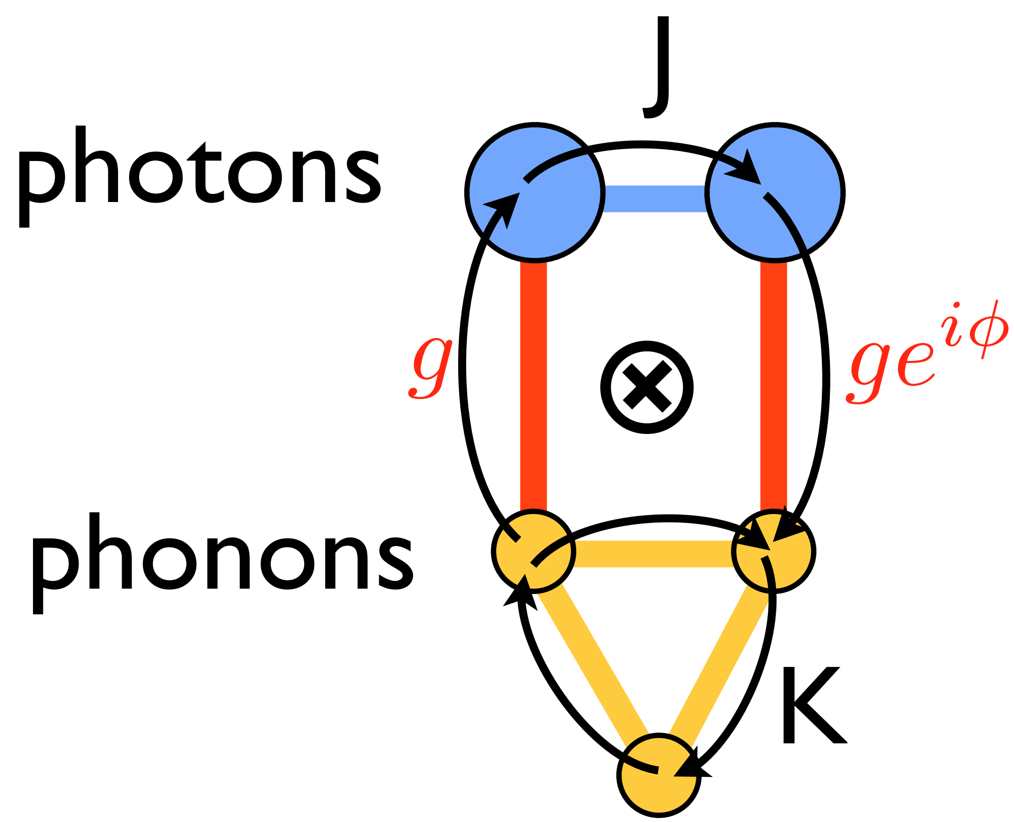
Need:



Dielectric
(with the right
pattern of holes)

One Laser
(with the right
pattern of phases)

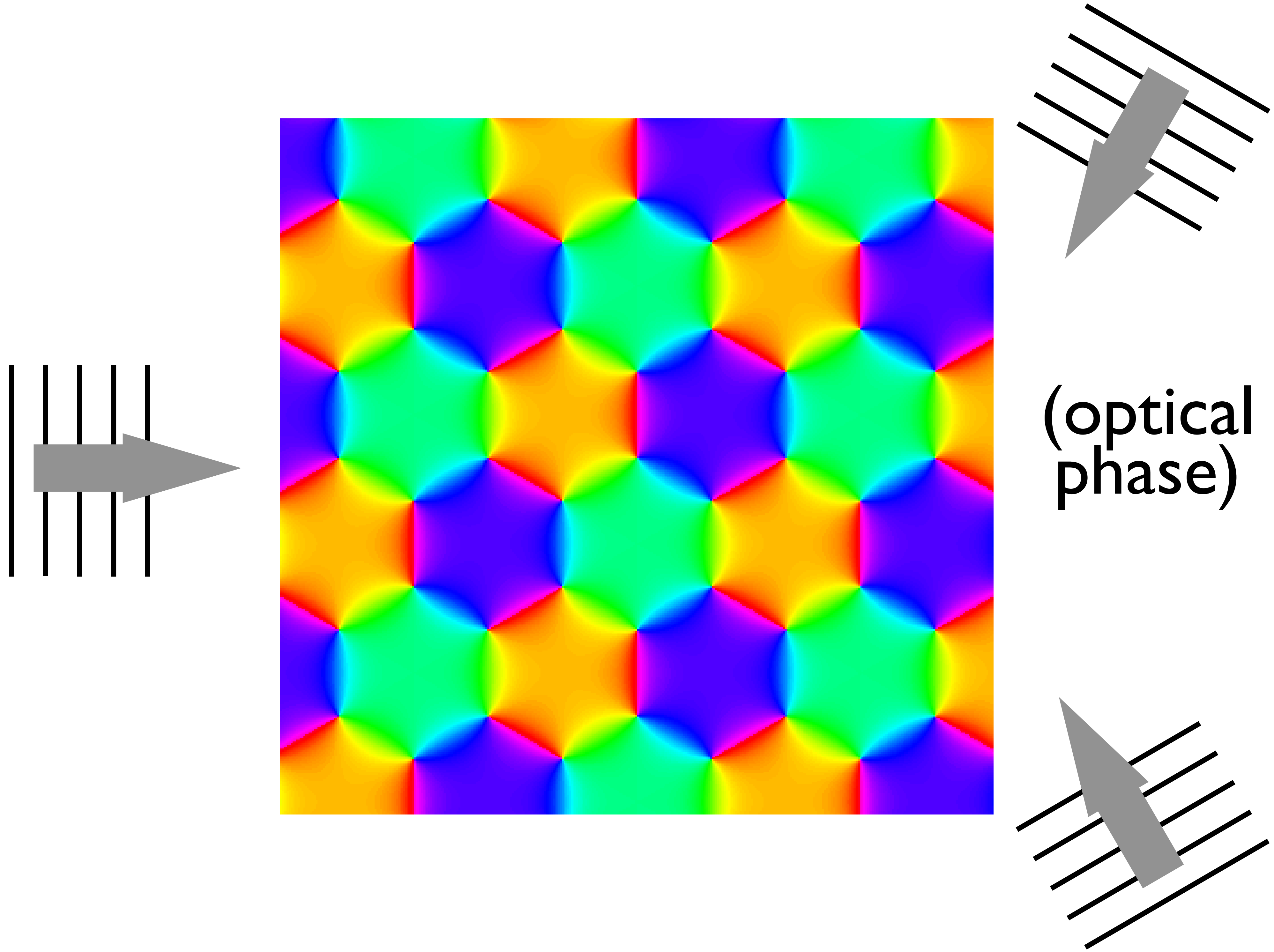
Gauge fields for phonons



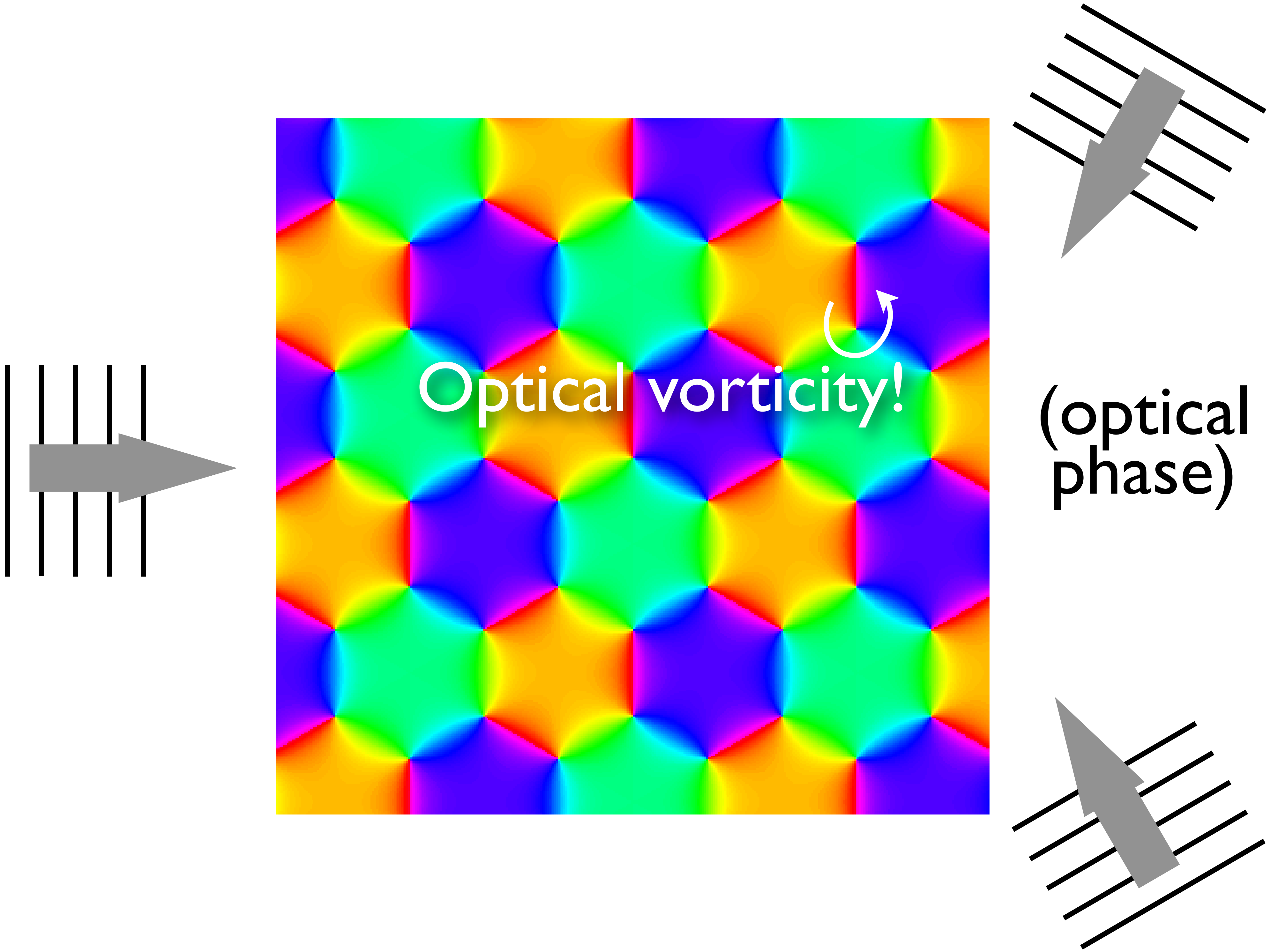
(works best for phonons, due to K<<J)

first such scheme: "phonon circulator",
Habraken, Stannigel, Lukin, Zoller, and Rabl, New Journal of Physics, 14, 115004 (2012)

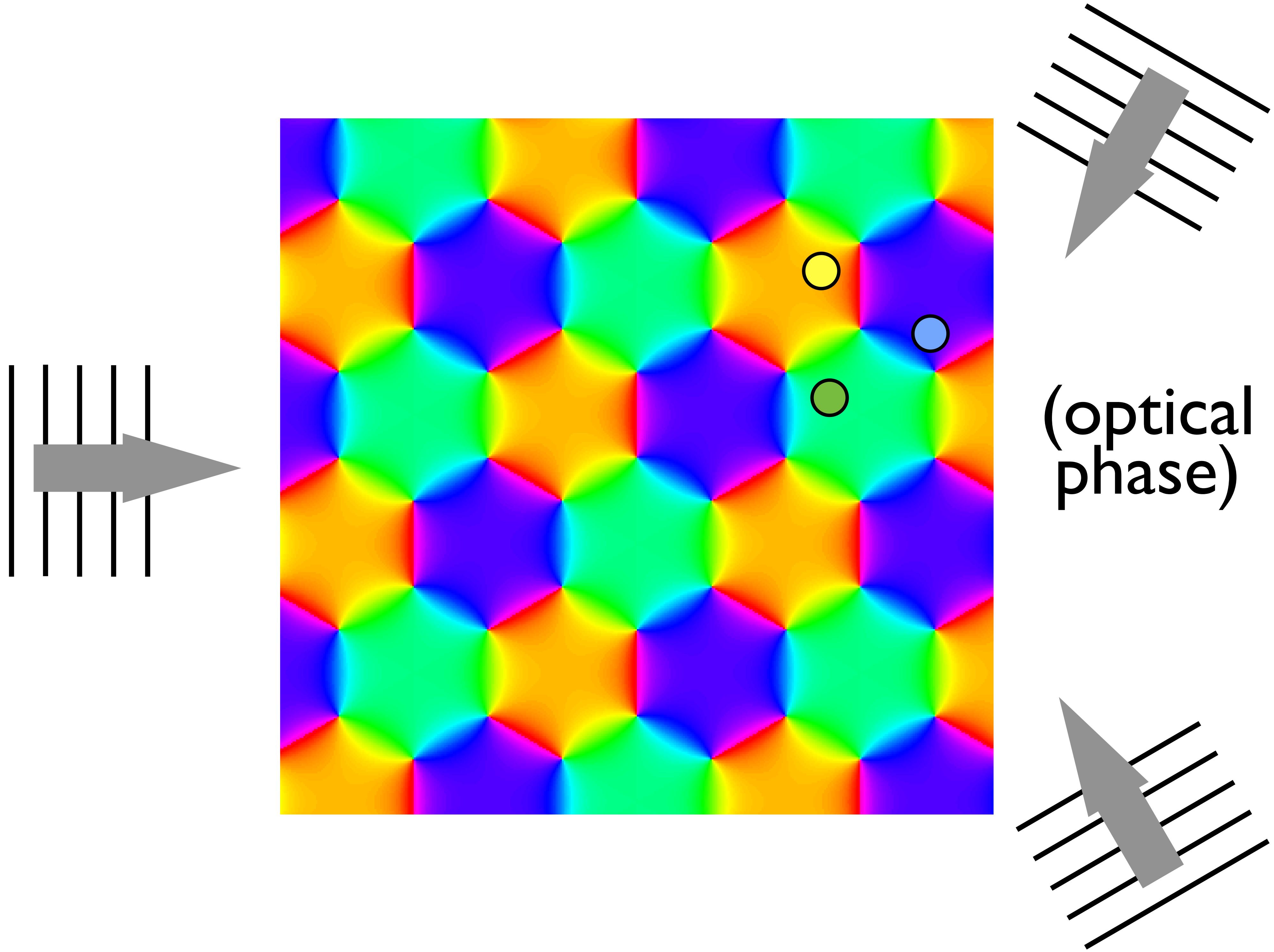
Creating an optical phase pattern



Creating an optical phase pattern

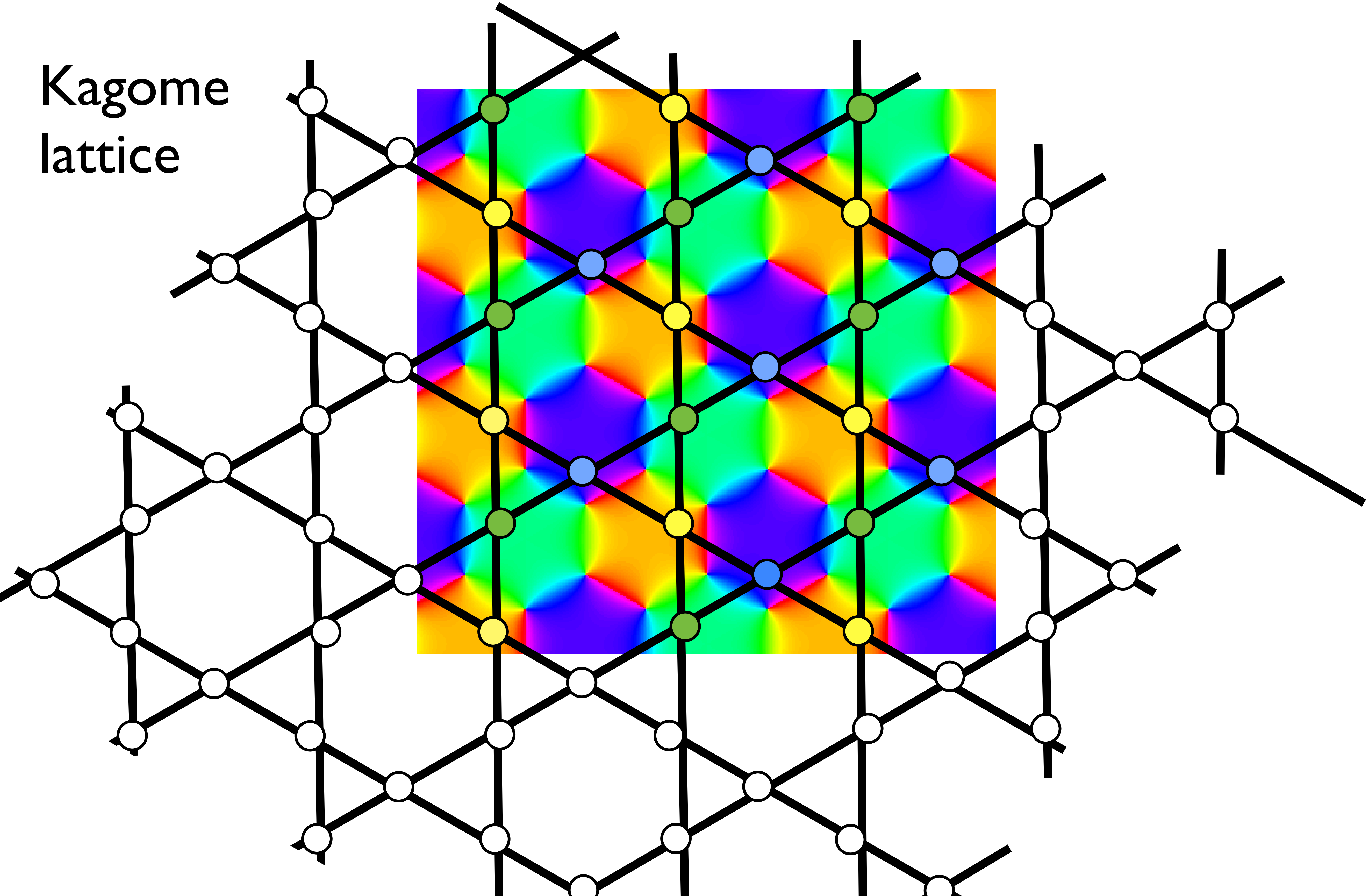


Creating an optical phase pattern

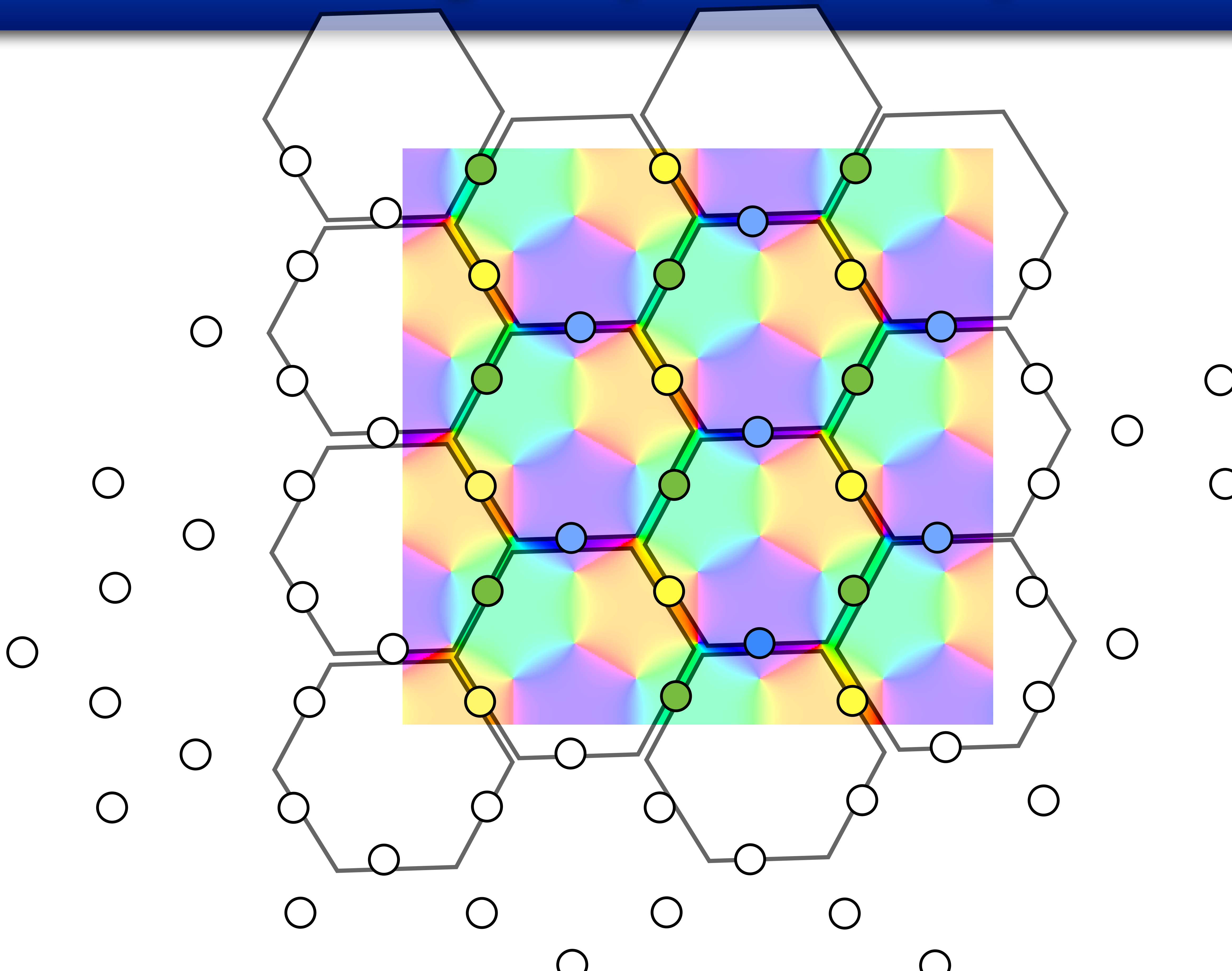


Creating an optical phase pattern

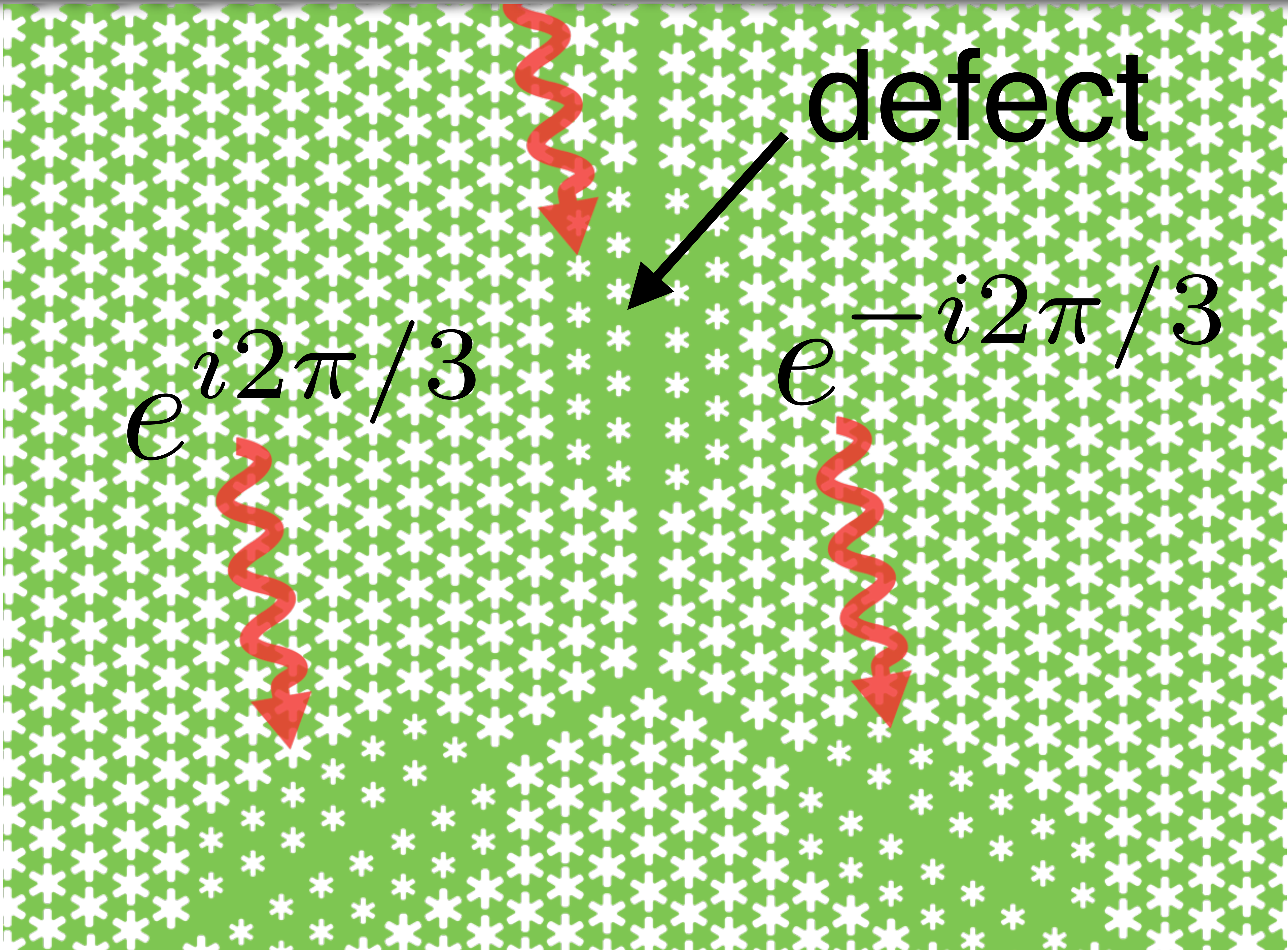
Kagome lattice



Creating an optical phase pattern

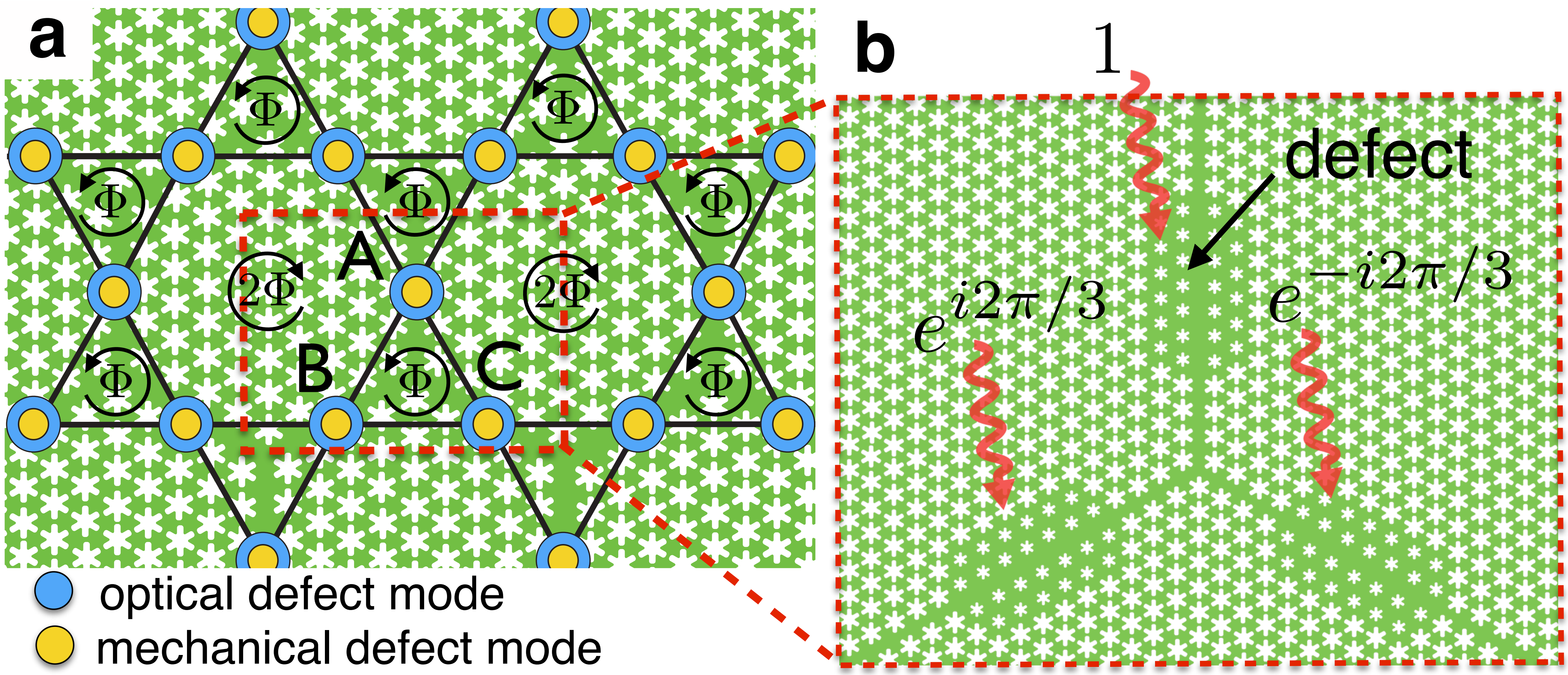


One triangular unit cell



Topological Phases of Sound and Light in an Optomechanical Array

Kagome Optomechanical Array



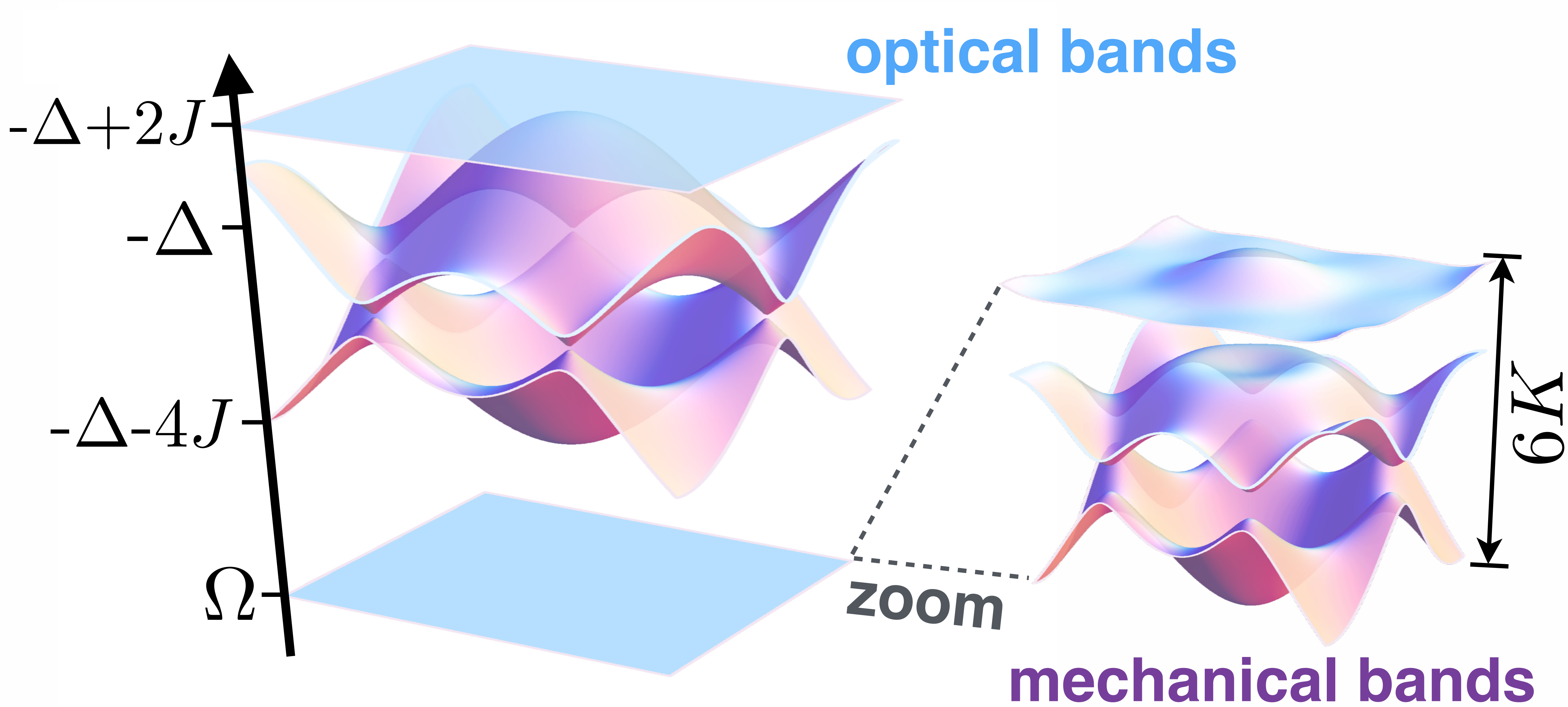
laser-field with different phases on sites A,B,C

see Koch, Houck, LeHur, Girvin PRA 2010 for Kagome lattice in circuit QED

Topological Phases of Sound and Light in an Optomechanical Array

Vittorio Peano, Christian Brendel, Michael Schmidt, and Florian Marquardt,
Phys. Rev. X 2015

Band Structure



"weak coupling": light field modifies phonon hopping

Topological Phases of Sound and Light in an Optomechanical Array

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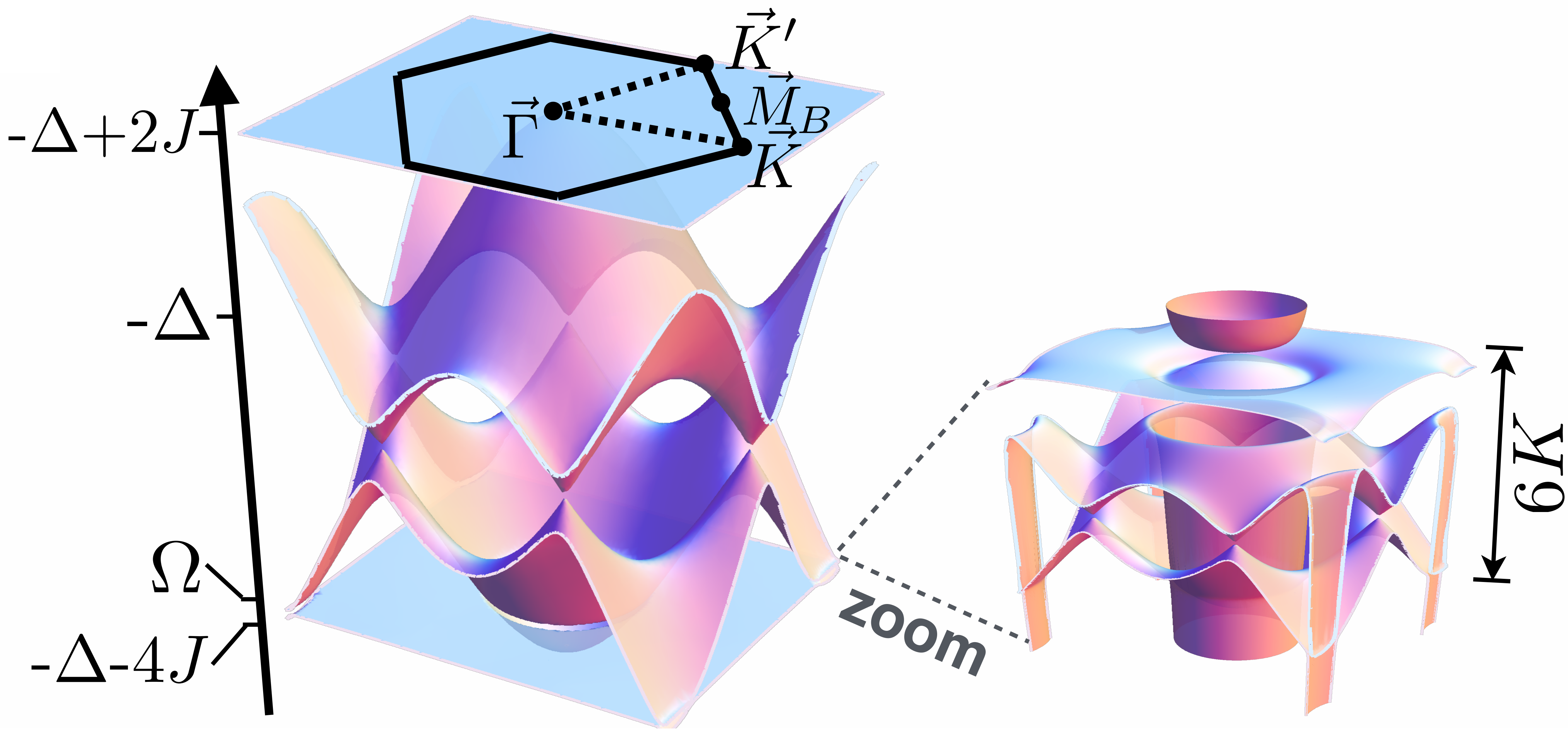
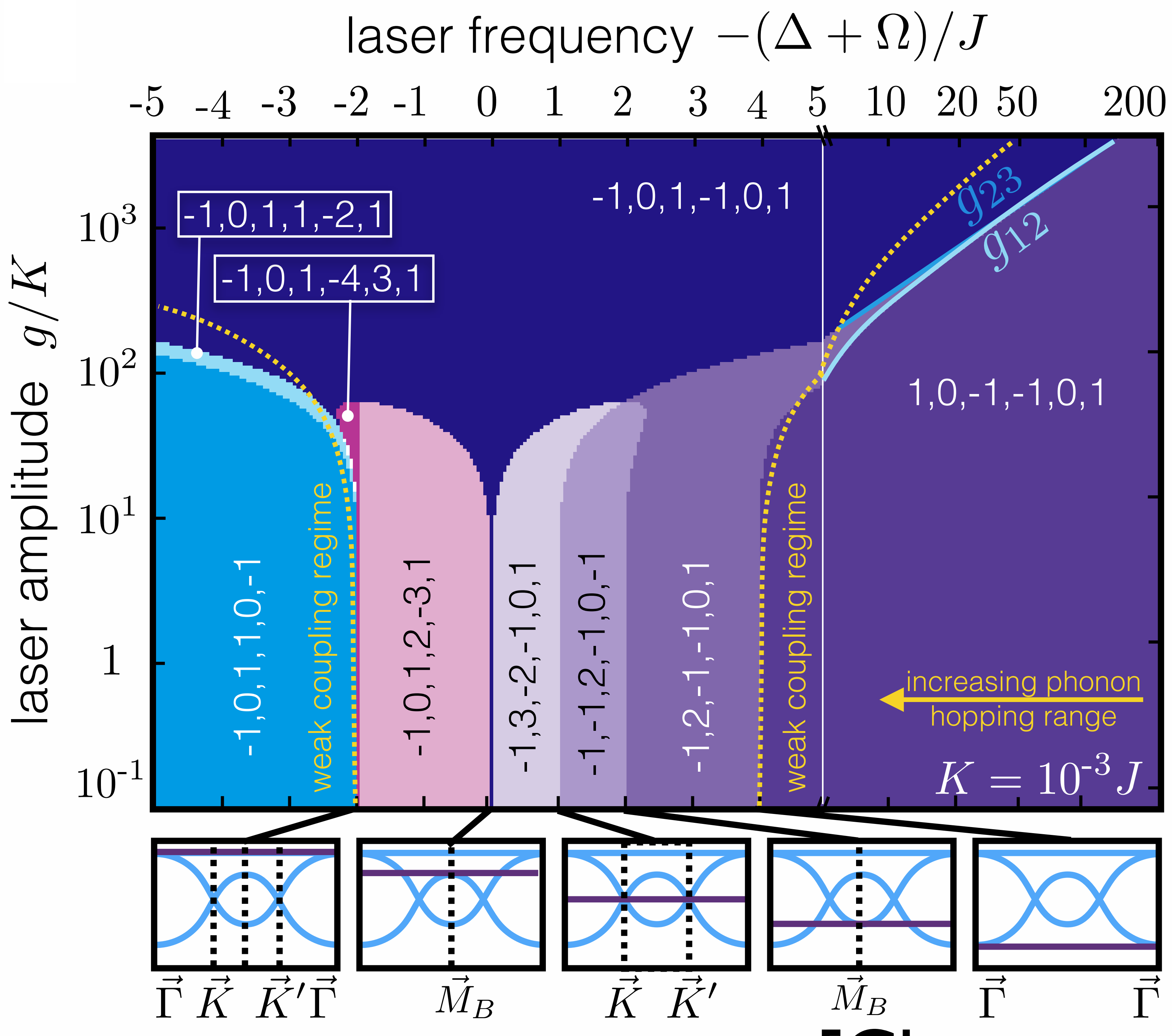
Band Structure



"strong coupling": photon and phonon bands mix
"photon-phonon polaritons"

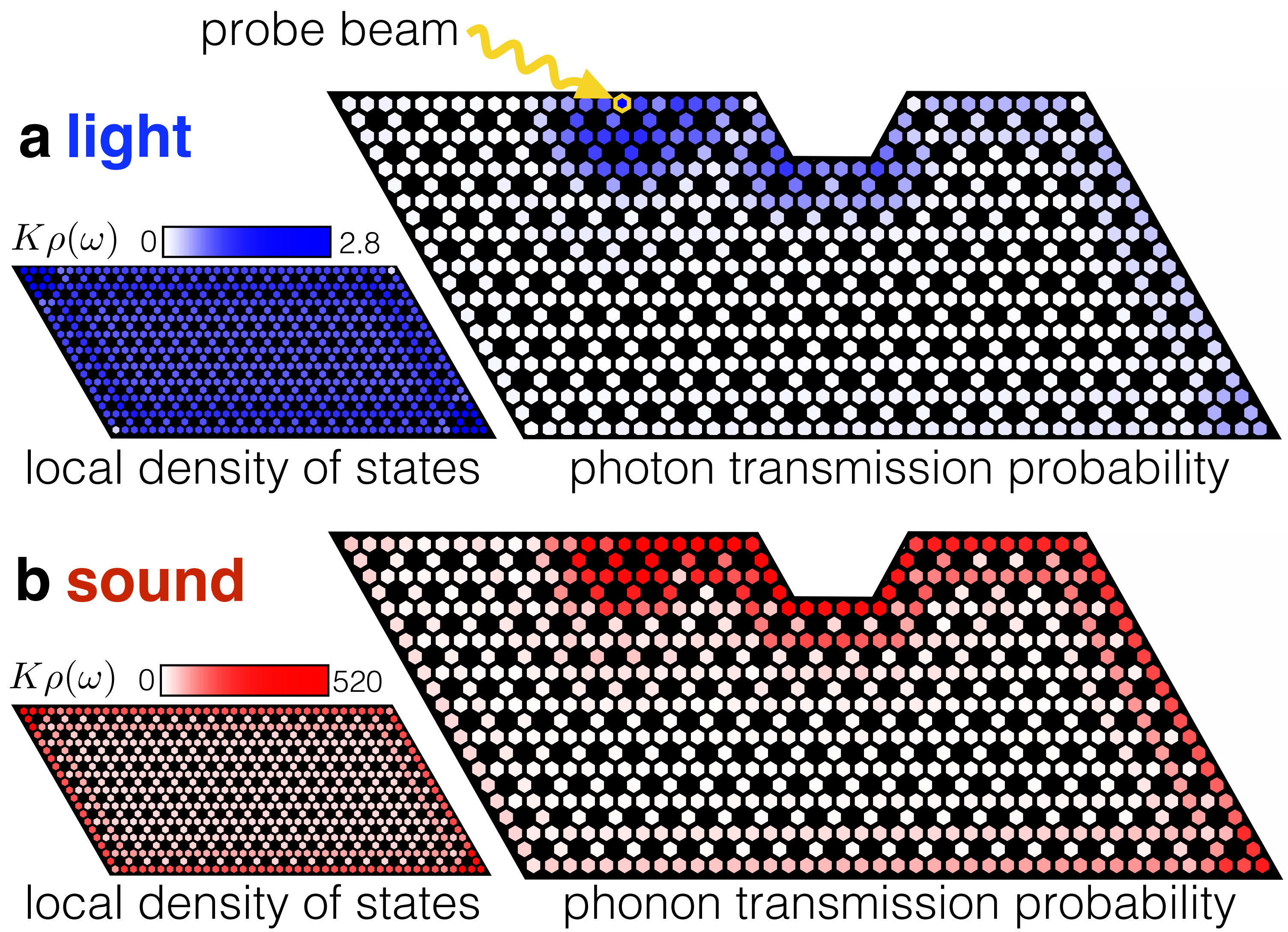
Topological Phases of Sound and Light in an Optomechanical Array

Topological Phase Diagram



[Chern numbers of bands]

Robust chiral transport of phonons



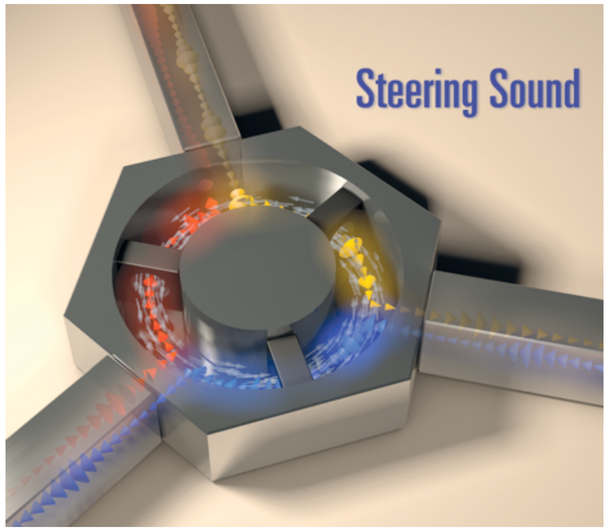
Features

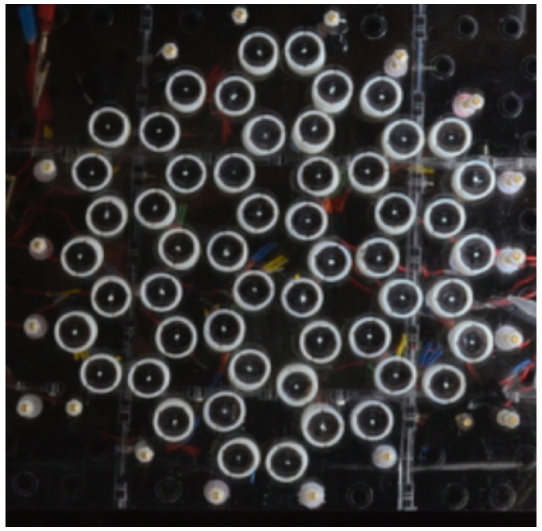
- Topologically protected transport of phonons in the solid state

compare... circulating fluid flow
Alu group 2014/2015 [expt]
Yang,...,Zhang 2015

coupled pendula
Süssstrunk, Huber 2015 [expt]

coupled gyroscopes
Irvine group 2015 [expt]

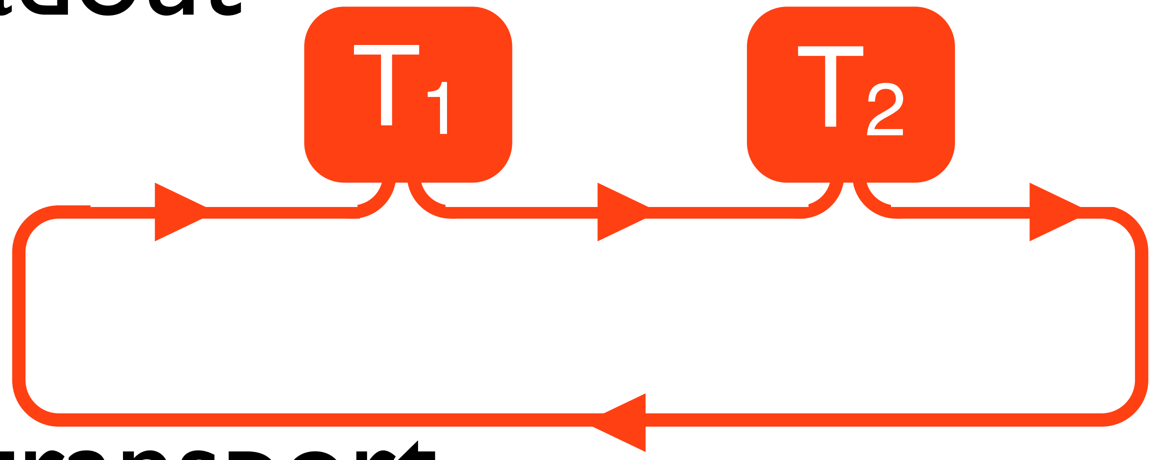




Features

- Topologically protected transport of phonons in the solid state

- Here: nanostructure, tuneable
- Full optical control and readout
- Arbitrary domains
- study one-way phonon transport
- Photon/phonon polariton transport
- Time-dependent control: quenches

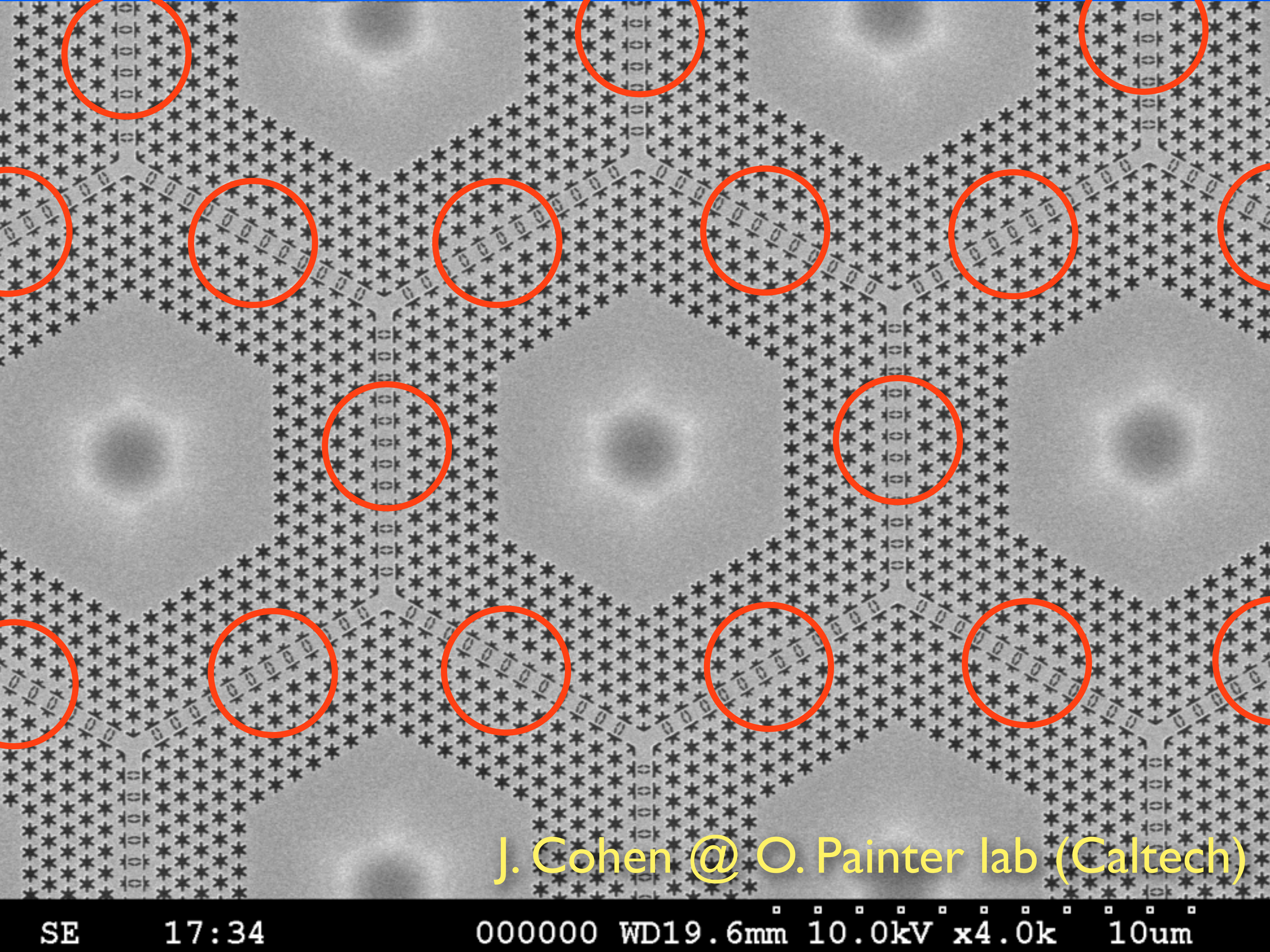


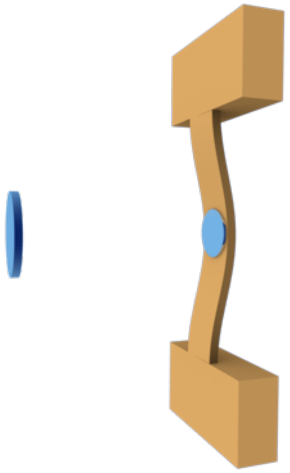
Challenges

Challenges (for optomechanical crystals)

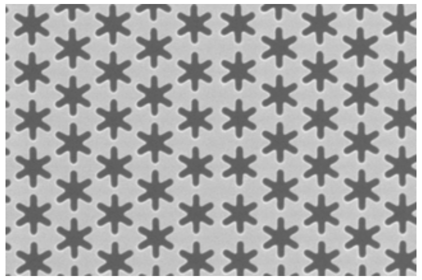
fabrication disorder: current 1%
– need to reduce by factor 100 (postprocessing)

intensity requirement: ca. 10^5-10^6 circulating photons
– OK, but large (optimize, improve coupling g_0)

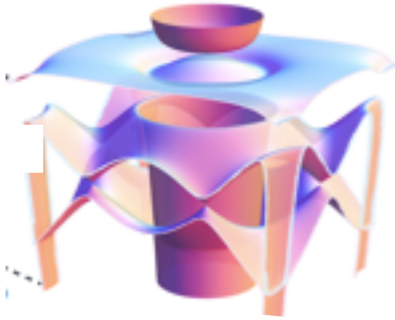

J. Cohen @ O. Painter lab (Caltech)
SE 17:34 000000 WD19.6mm 10.0kV x4.0k 10um



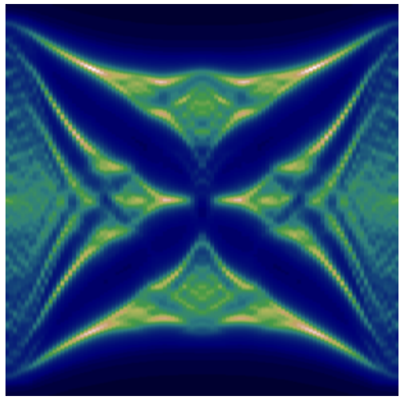
Cavity Optomechanics



Optomechanical Arrays



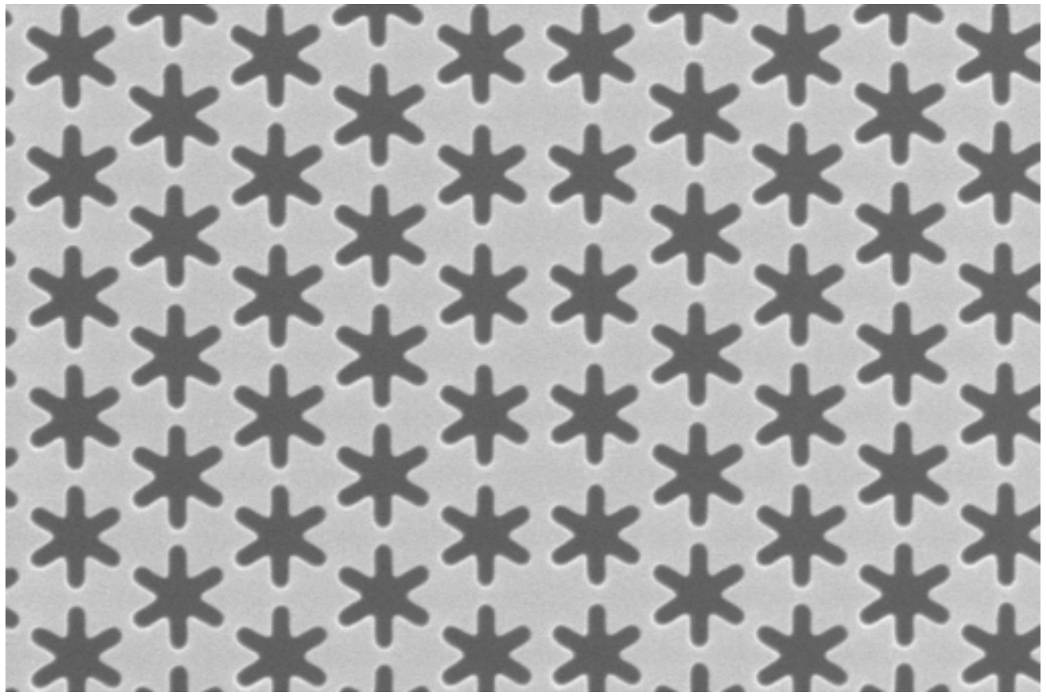
Topological Phases of Sound (and Light)



Artificial magnetic fields for photons

Artificial magnetic fields for photons

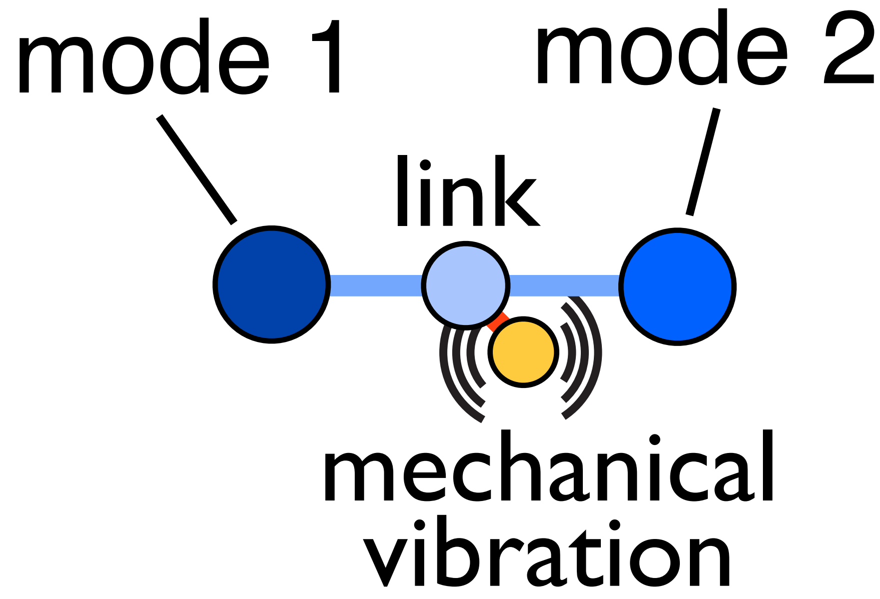
Need:



Dielectric
(with the right
pattern of holes)

Two Lasers
(with the right
pattern of phases)

Phonon-assisted photon tunneling

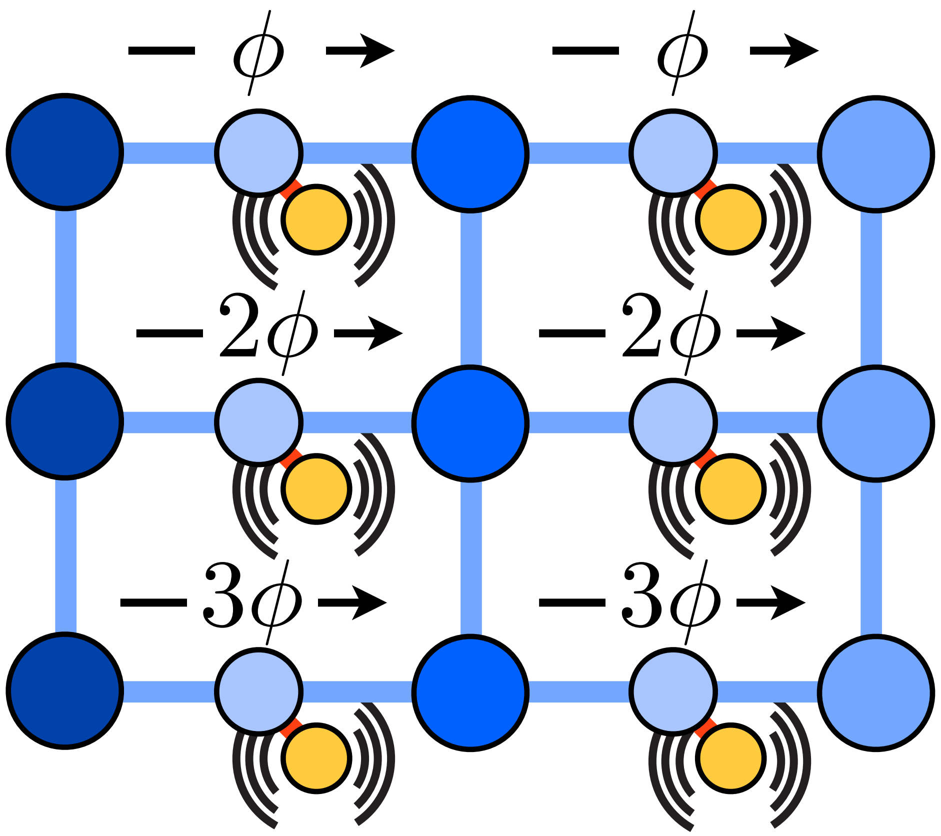


vibration leads to modulation of effective photon tunnel coupling between mode 1 and 2

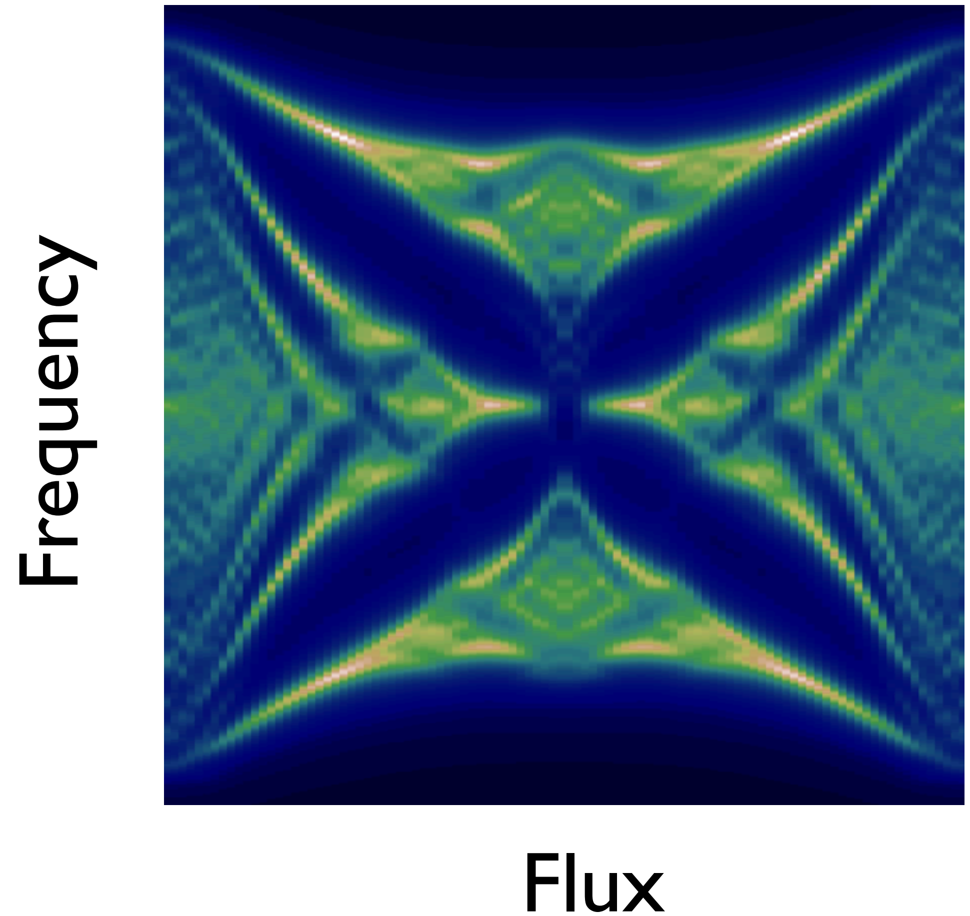
$$2\cos(\omega t+\phi)(\hat{a}_1^\dagger \hat{a}_2+\hat{a}_2^\dagger \hat{a}_1)\approx e^{i(\omega t+\phi)}\hat{a}_1^\dagger \hat{a}_2+e^{-i(\omega t+\phi)}\hat{a}_2^\dagger \hat{a}_1$$

non-reciprocal phase!

Artificial magnetic fields for photons



Hofstadter butterfly spectrum



arbitrary optical re-configuration of magnetic field distribution

M. Schmidt, S. Keßler, V. Peano, O. Painter, F. Marquardt
Optica 2015

“Can these magnetic fields also become time-dependent?”

Yes, of course

“But can they have their own dynamics?”

Let’s see...

Nonlinear Dynamics

blue-detuned laser:
anti-damping!

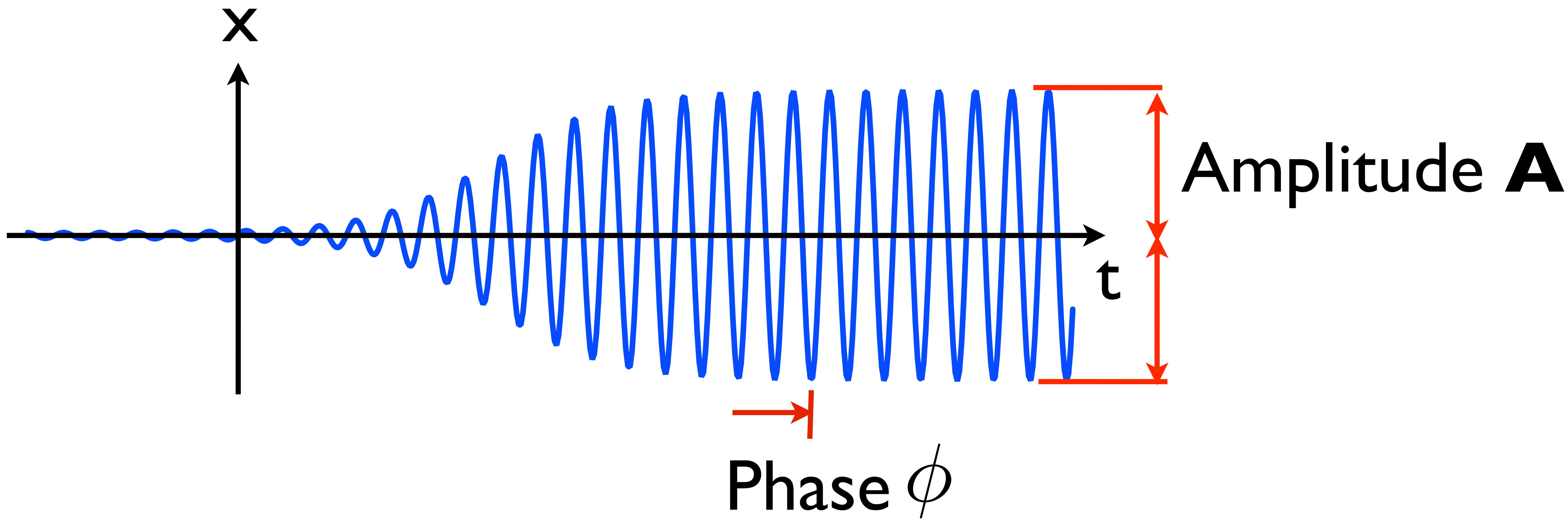
$$\Gamma = \Gamma_M + \underbrace{\Gamma_{\mathrm{opt}}}^{< 0}$$

Nonlinear Dynamics

ϕ

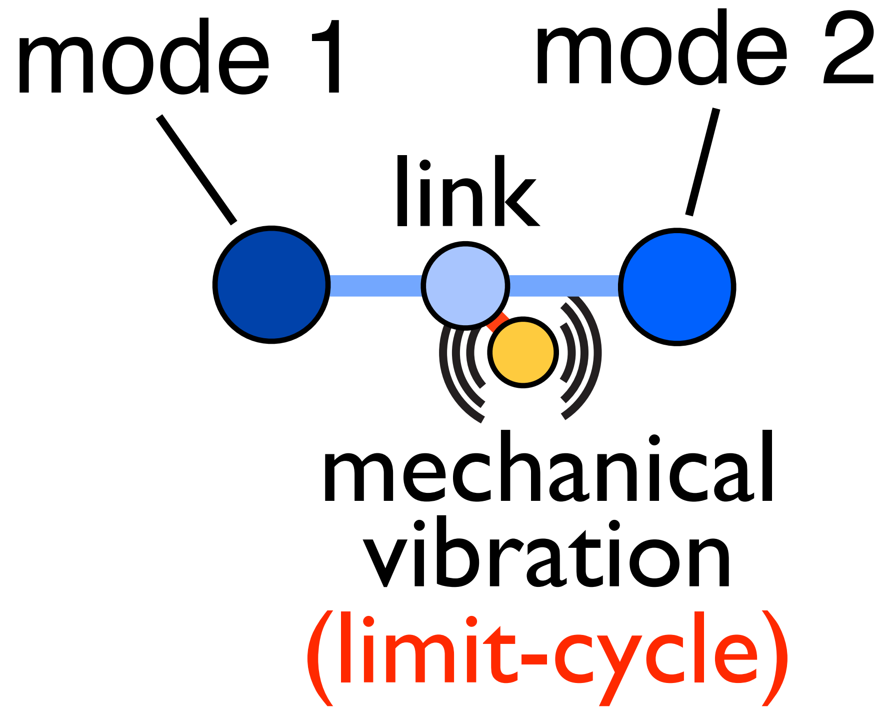
Nonlinear Dynamics

Instability!   (beyond some laser power)



Self-sustained mechanical oscillations!
"Limit cycle"

Phonon-assisted photon tunneling



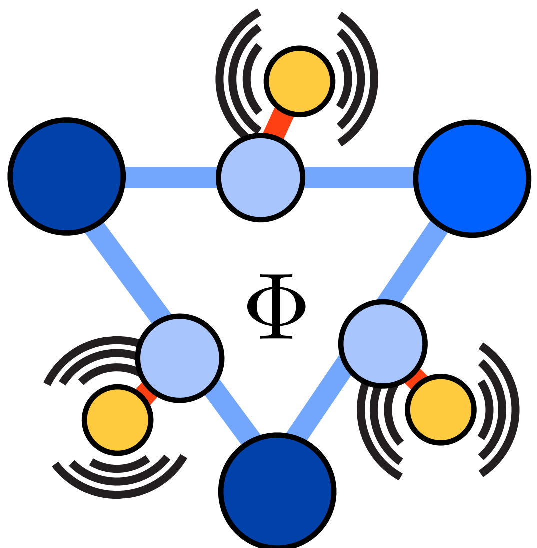
vibration leads to modulation of effective photon tunnel coupling between mode 1 and 2

$$2\cos(\omega t+\phi)(\hat{a}_1^\dagger \hat{a}_2+\hat{a}_2^\dagger \hat{a}_1)\approx e^{i(\omega t+\phi)}\hat{a}_1^\dagger \hat{a}_2+e^{-i(\omega t+\phi)}\hat{a}_2^\dagger \hat{a}_1$$

non-reciprocal phase!

(dynamical, depends on mechanical evolution)

Dynamical Gauge Fields



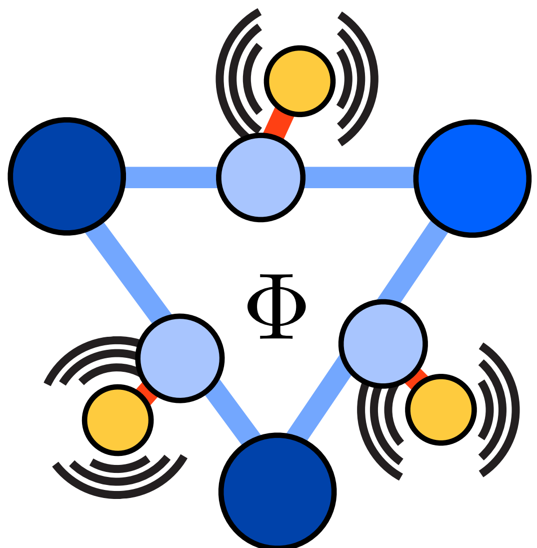
$$\Phi = \int \vec{A} d\vec{s}$$

Mechanical Oscillation Phases= Vector potential for photons

Flux = Sum of oscillation phases

Dynamics?

Dynamical Gauge Fields



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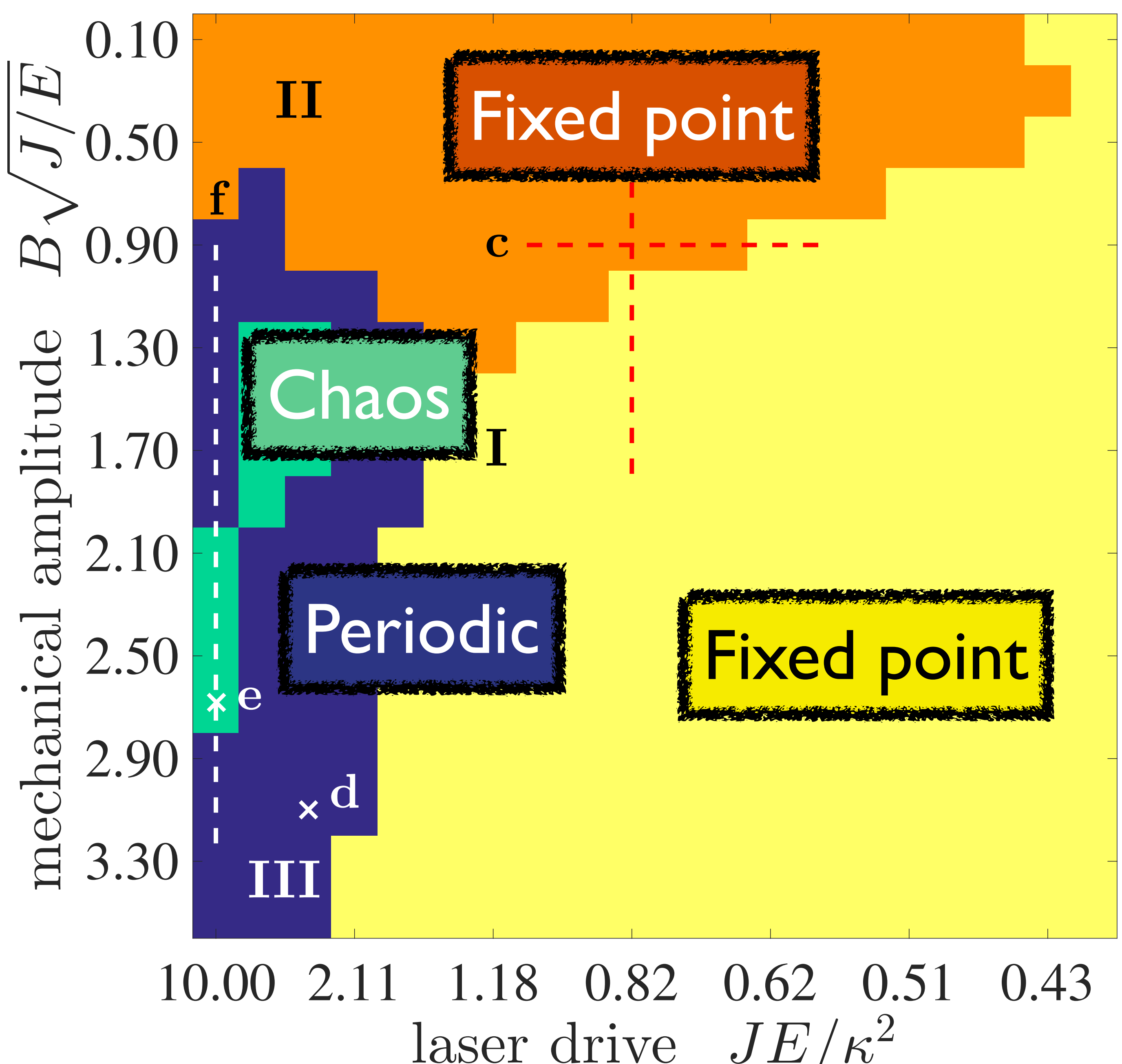


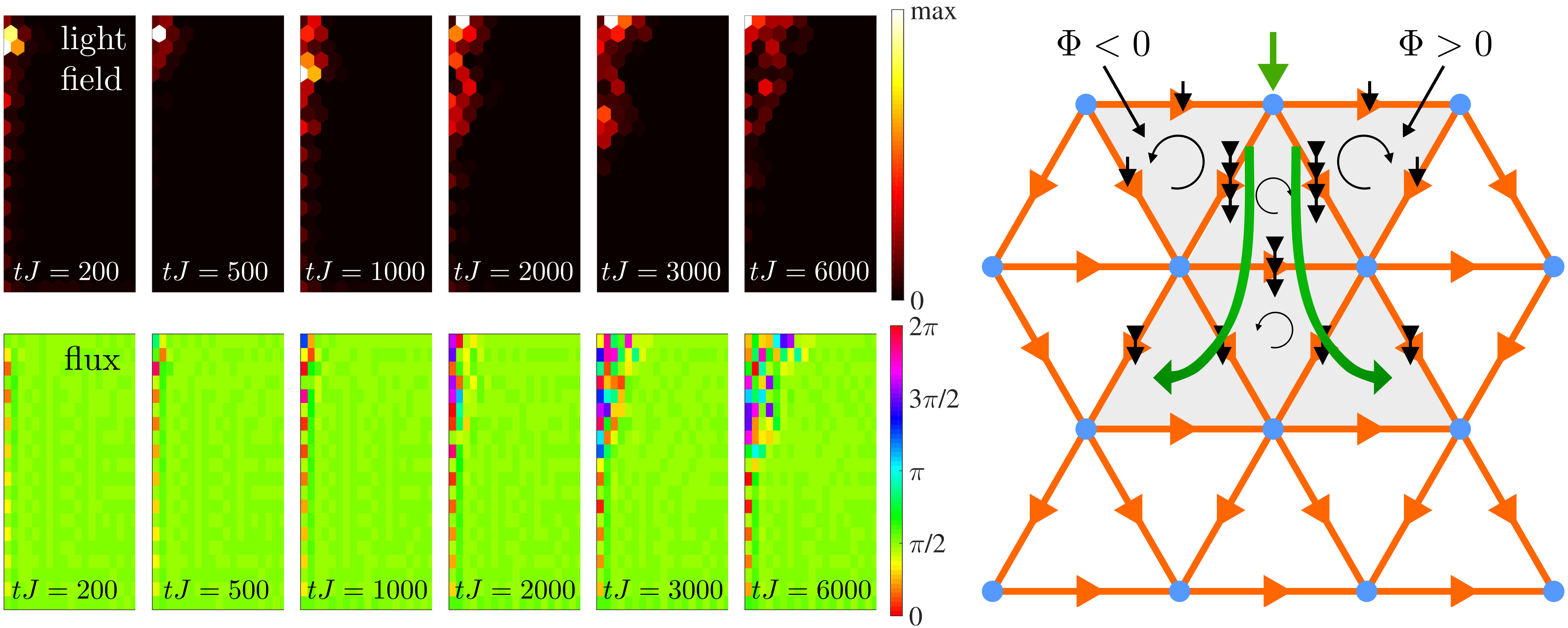
Dynamics of the flux, for a triangle

S. Walter and FM, arXiv:1510.06754

Dynamical Gauge Fields

S. Walter and FM, arXiv:1510.06754

Dynamics on a lattice



Photon flow changes magnetic field
Magnetic field changes photon flow

Optomechanical Arrays: Future possibilities

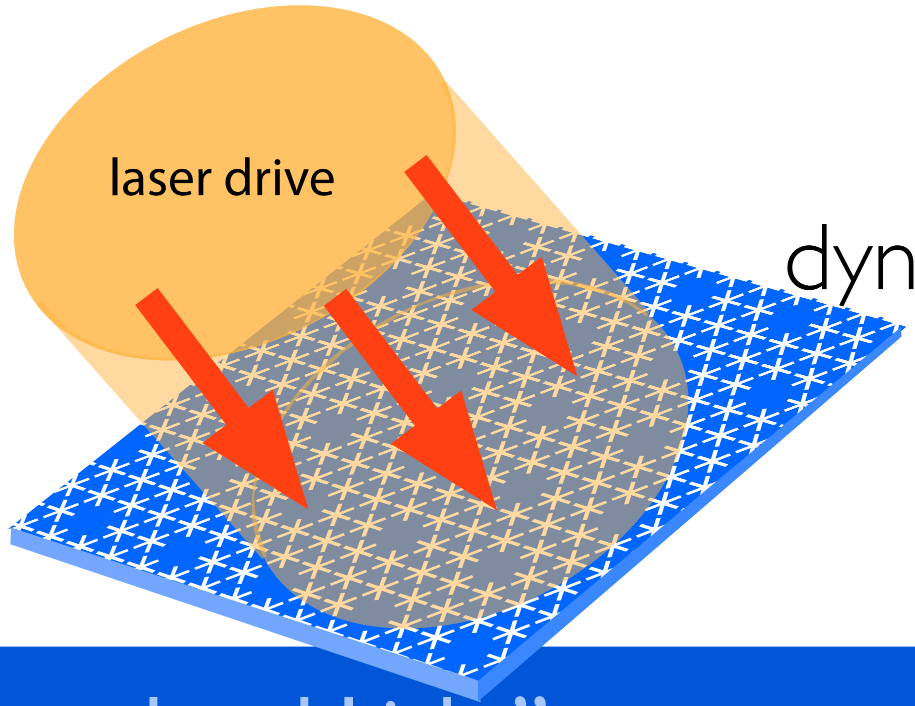
Synthetic magnetic fields for photons/phonons

Dirac Physics and other band structures

Synchronization and Pattern Formation

Quantum Information Processing

All-optical control/readout



Topological Phases

Transport (edge states/wires)

Nonequilibrium dynamics/Quench physics/ Thermalization

Strongly Correlated Quantum Physics?

"Topological Phases of Sound and Light",
Vittorio Peano, Christian Brendel, Michael Schmidt, and FM,
Phys. Rev. X **5**, 031011 (2015)

"Optomechanical creation of magnetic fields for photons on a lattice",
M. Schmidt, S. Keßler, V. Peano, O. Painter, FM
Optica **2**, 635 (2015)

"Dynamical Gauge Fields in Optomechanics",
S. Walter and FM, arXiv:1510.06754

Max Planck Institute for the Science of Light

Erlangen, Germany

since 2008
now 4 divisions
new building Oct 2016

MAX-PLANCK-GESELLSCHAFT