Topological Phases of Sound and Light

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Former: Andreas Kronwald, Michael Schmidt, Georg Heinrich, Max Ludwig, Jiang Qian, Huai-Zhi Wu, Deng Zhijiao, Björn Kubala, Stefan Keßler, Steve Habraken

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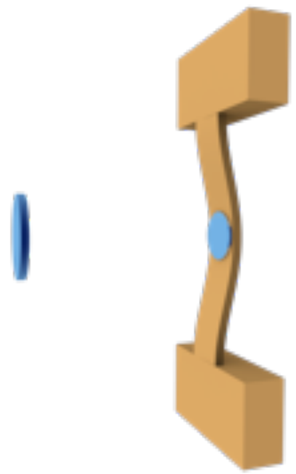
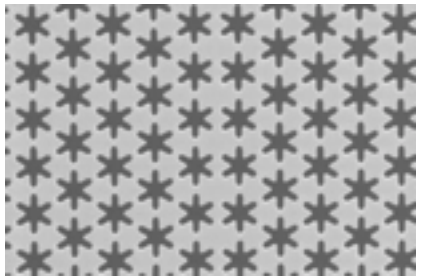
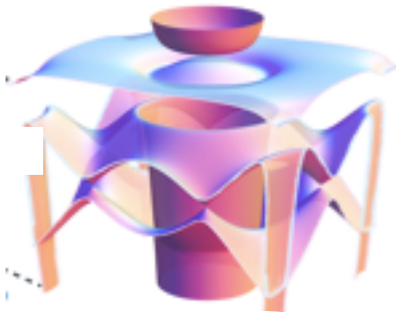
DARPA ORCHID
cQOM



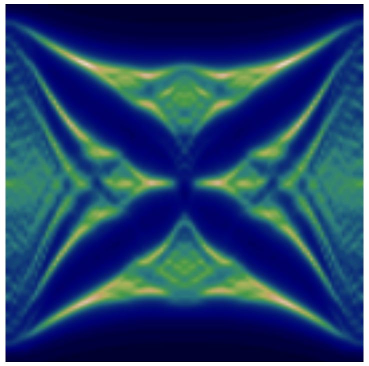
Cavity Optomechanics



Optomechanical Arrays

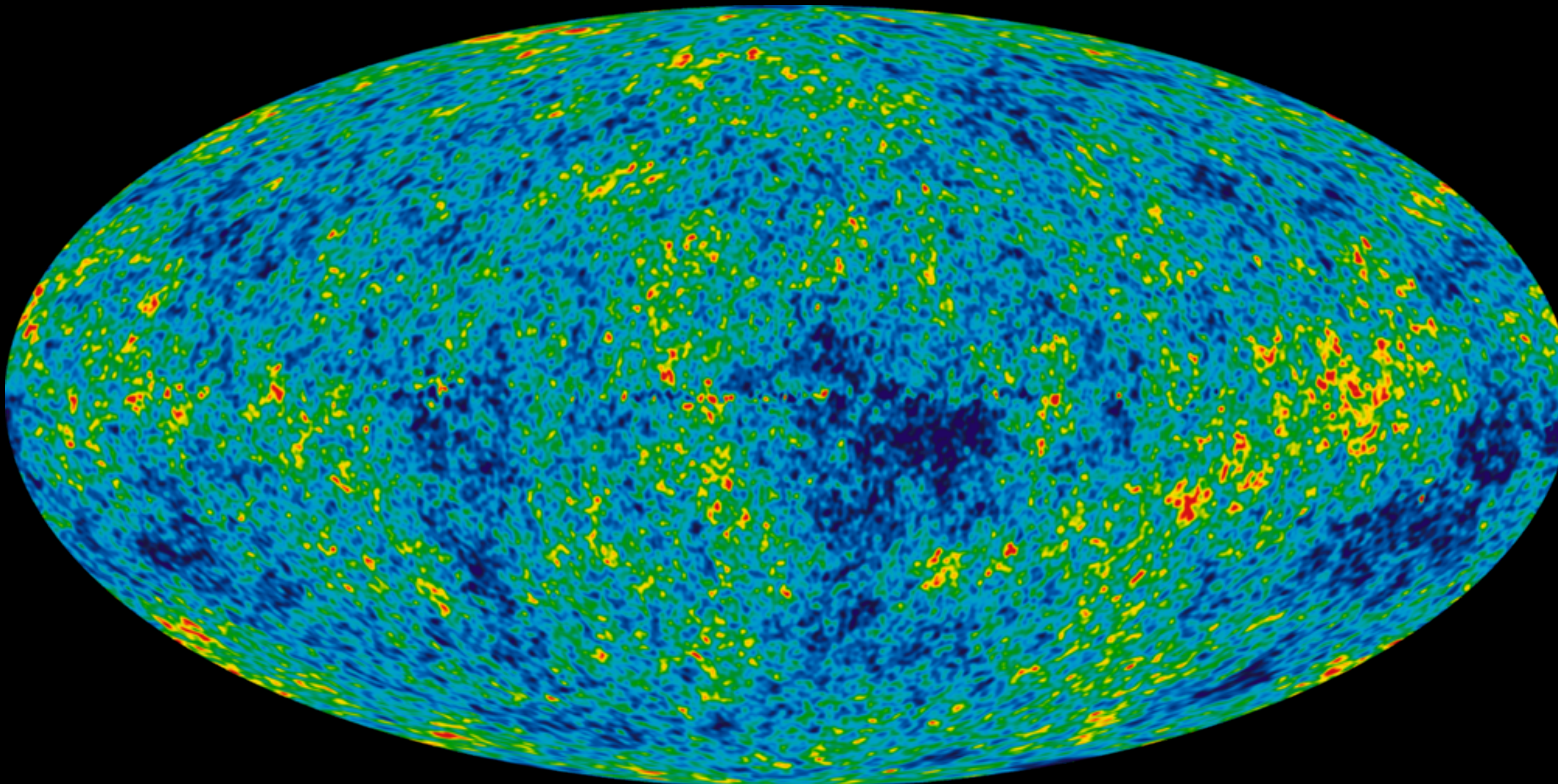


Topological Phases of Sound (and Light)

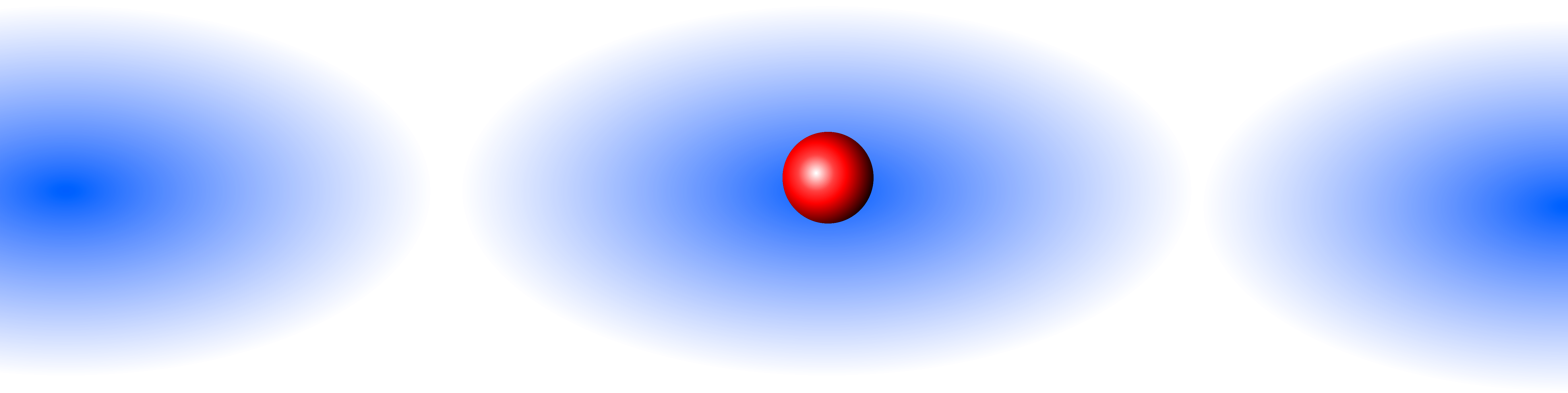


Dynamical Gauge Fields for the photons

baryon-photon fluid: sound speed $c/\sqrt{3}$



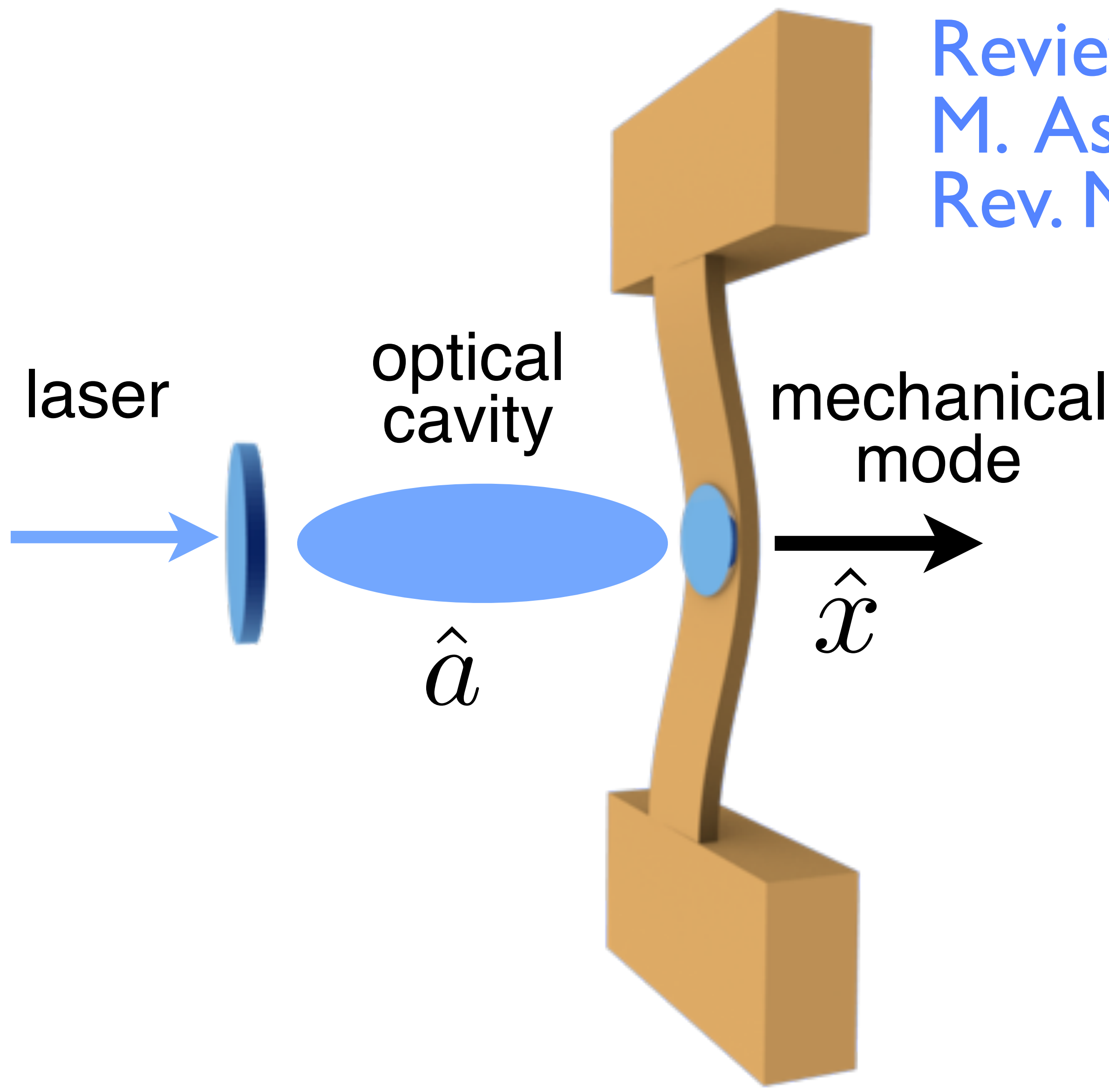
Radiation forces



Trapping and cooling

- Optical tweezers
- Optical lattices

Optomechanical Hamiltonian



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

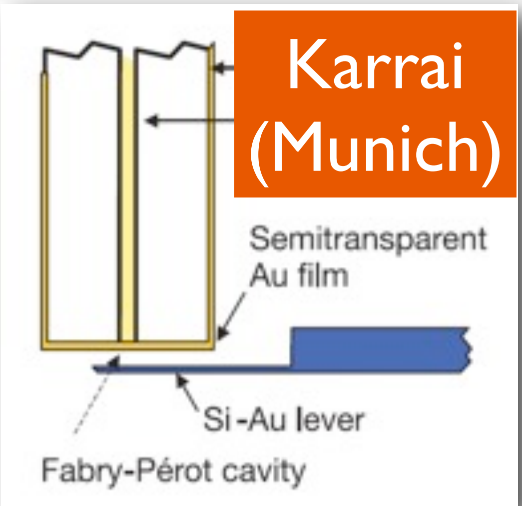
$$\hat{H} = \hbar\omega_{\mathrm{cav}} \cdot (1 - \hat{x}/L)\hat{a}^\dagger\hat{a} + \hbar\Omega\hat{b}^\dagger\hat{b} + \ldots$$

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

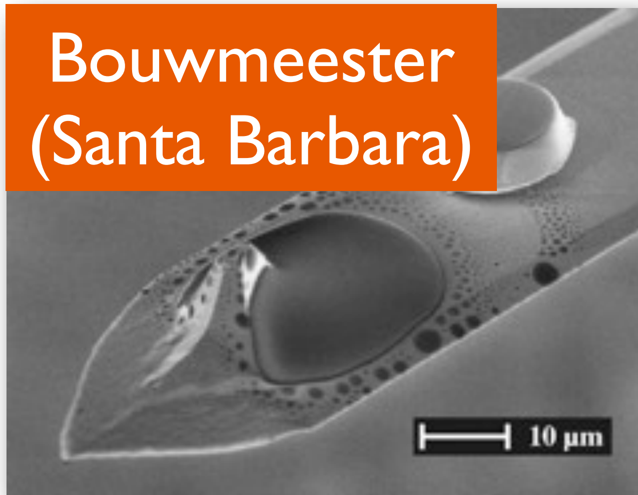
$$x_{\mathrm{ZPF}} = \sqrt{\hbar/2m\Omega}$$

The zoo of experimental setups in cavity optomechanics, 2005-now

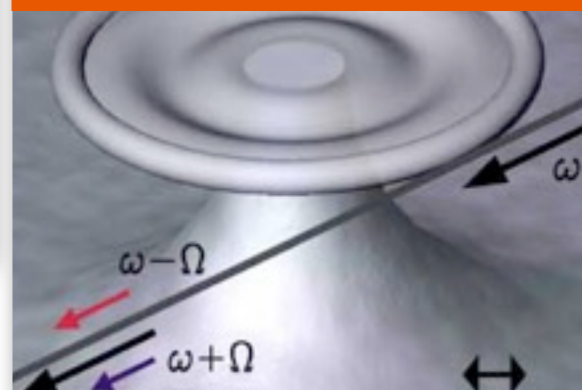
Karrai (Munich)



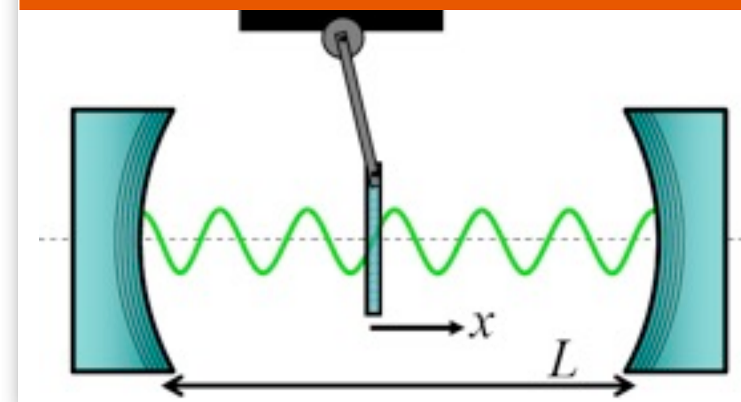
Bouwmeester (Santa Barbara)



Vahala (Caltech) Kippenberg (EPFL), Carmon, ...

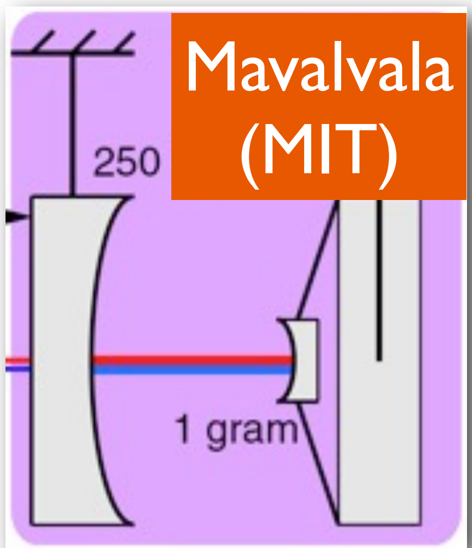


Harris (Yale)

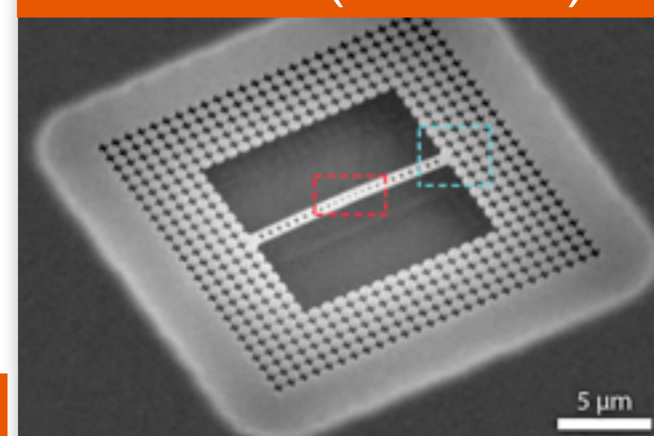


LKB group (Paris)

Mavalvala (MIT)



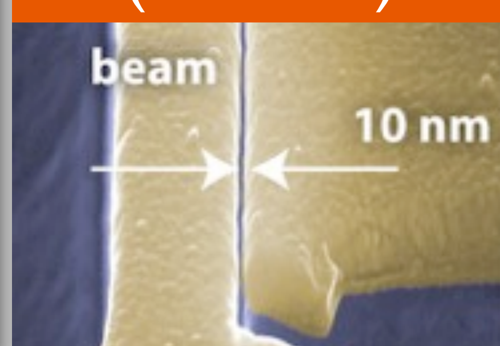
Painter (Caltech)



Teufel, Lehnert (Boulder)

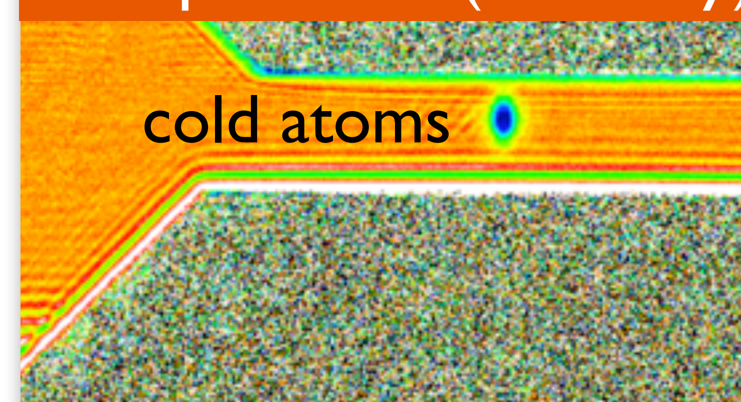
Aspelmeyer (Vienna)

Sillanpää (Aalto U)

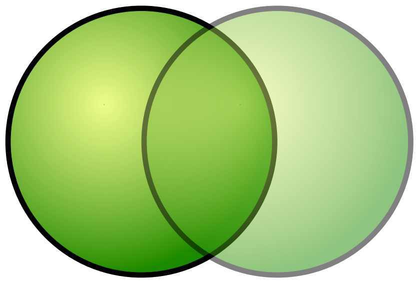


Lipson (Cornell)

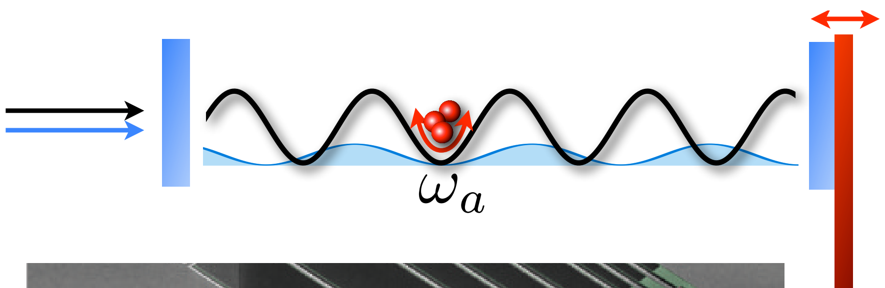
Stamper-Kurn (Berkeley)



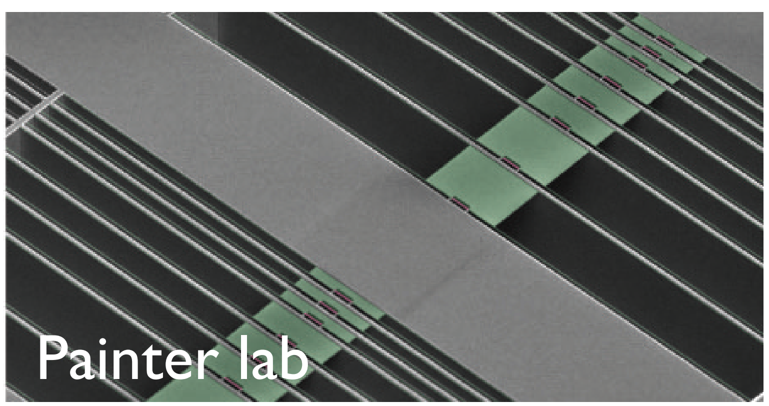
Optomechanics: general outlook



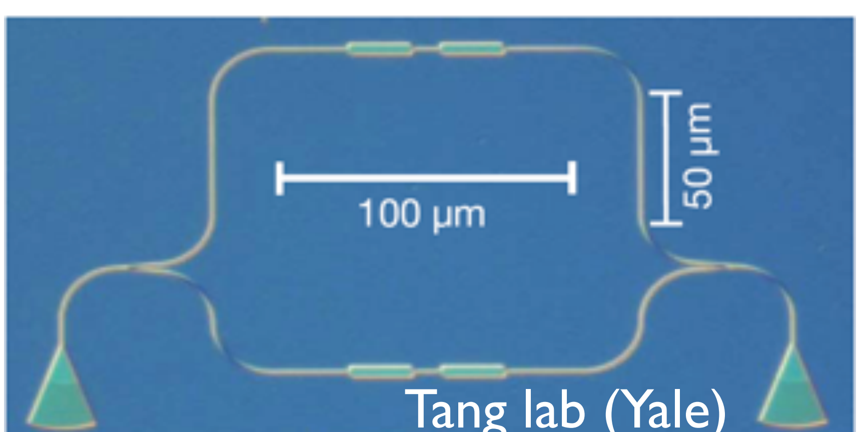
Fundamental tests of quantum mechanics in a new regime:
entanglement with 'macroscopic' objects, unconventional decoherence? [e.g.: gravitationally induced?]



Mechanics as a 'bus' for connecting hybrid components: superconducting qubits, spins, photons, cold atoms, ...

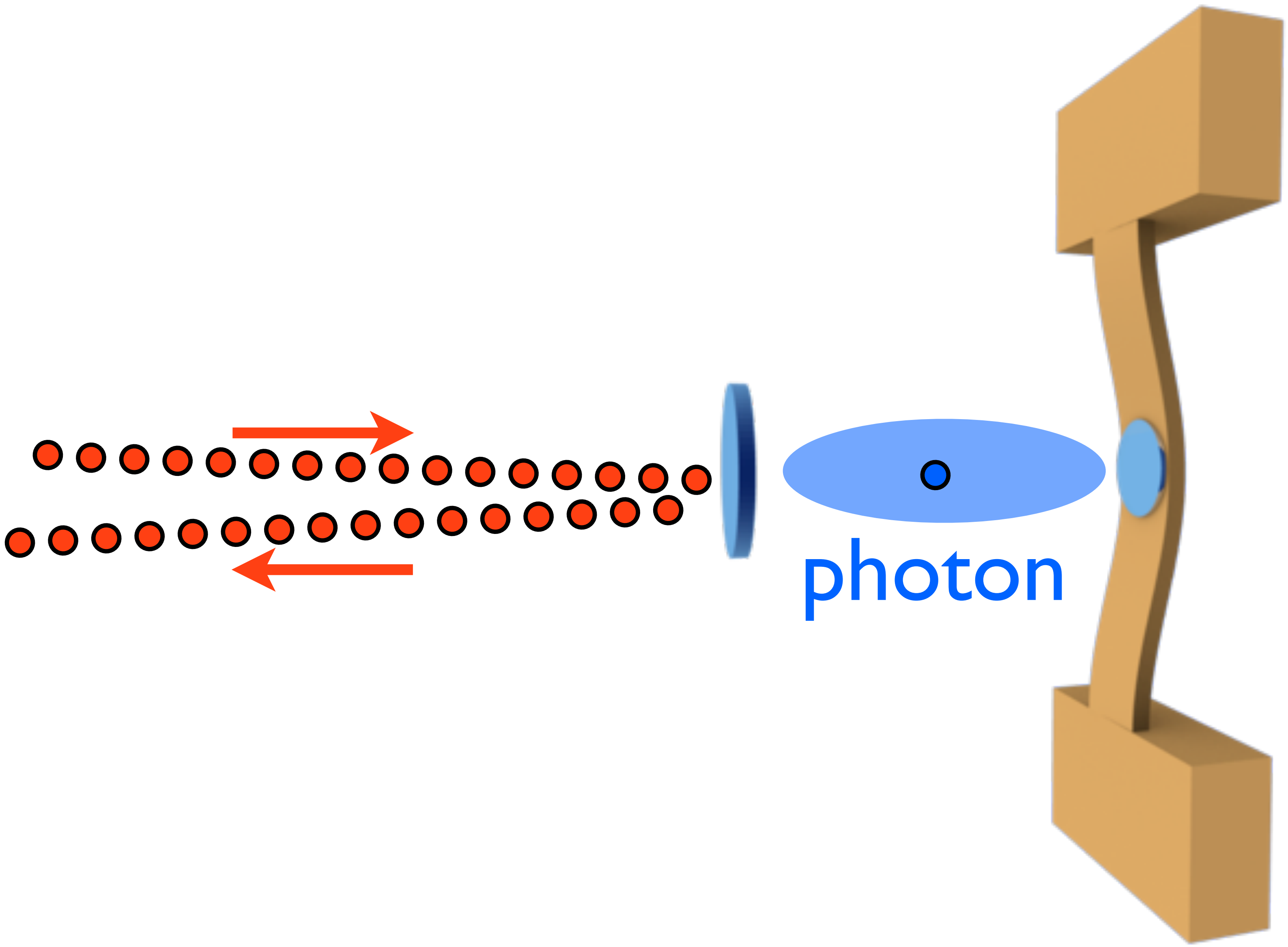


Precision measurements
small displacements, masses, forces, and accelerations

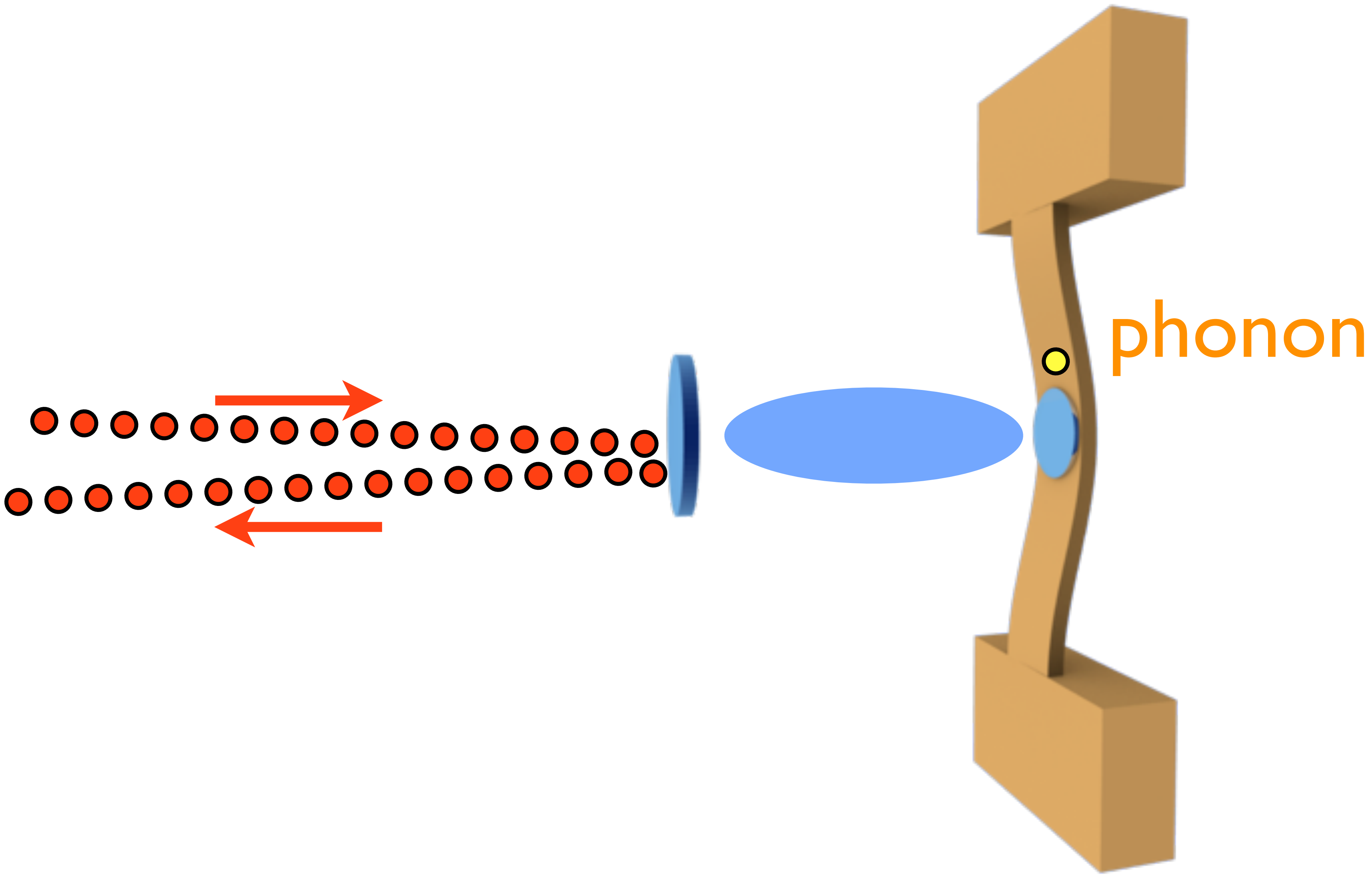


Optomechanical circuits & arrays
Exploit nonlinearities for classical and quantum information processing, storage, and amplification; study collective dynamics in arrays

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": $g = g_0 \alpha$

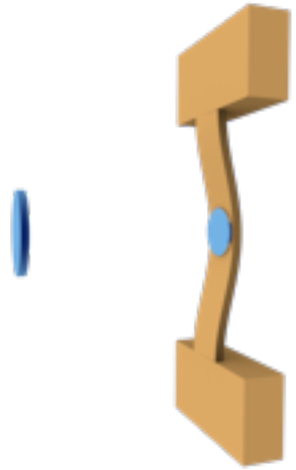
$$g_0 \sim \mathrm{Hz} - \mathrm{MHz}$$

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

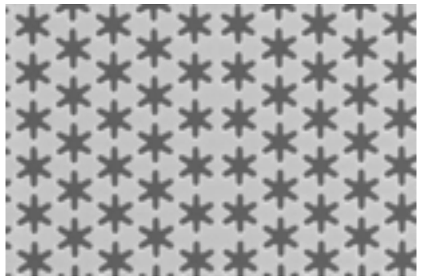
$$\alpha$$

laser-driven
cavity amplitude

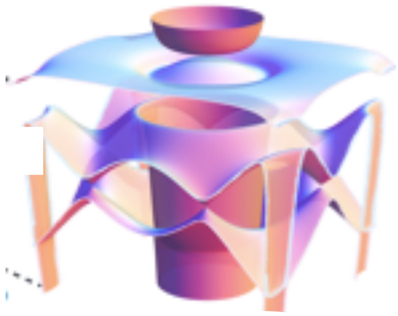
tuneable! **phase**!



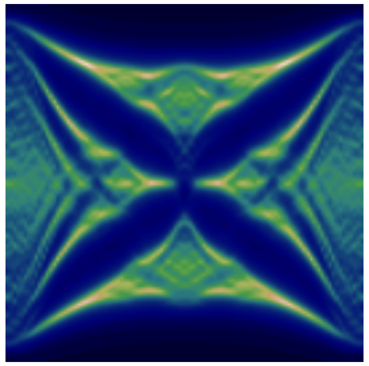
Cavity Optomechanics



Optomechanical Arrays

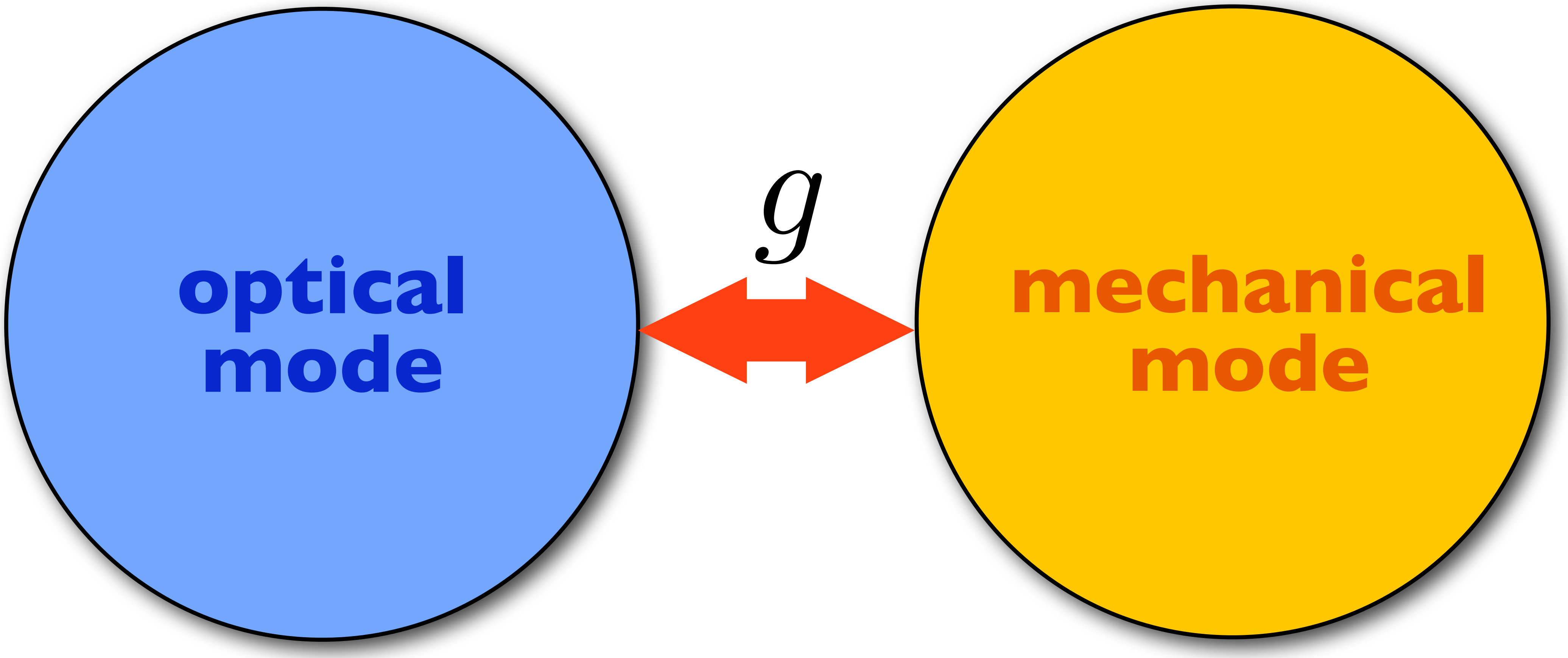


Topological Phases of Sound (and Light)



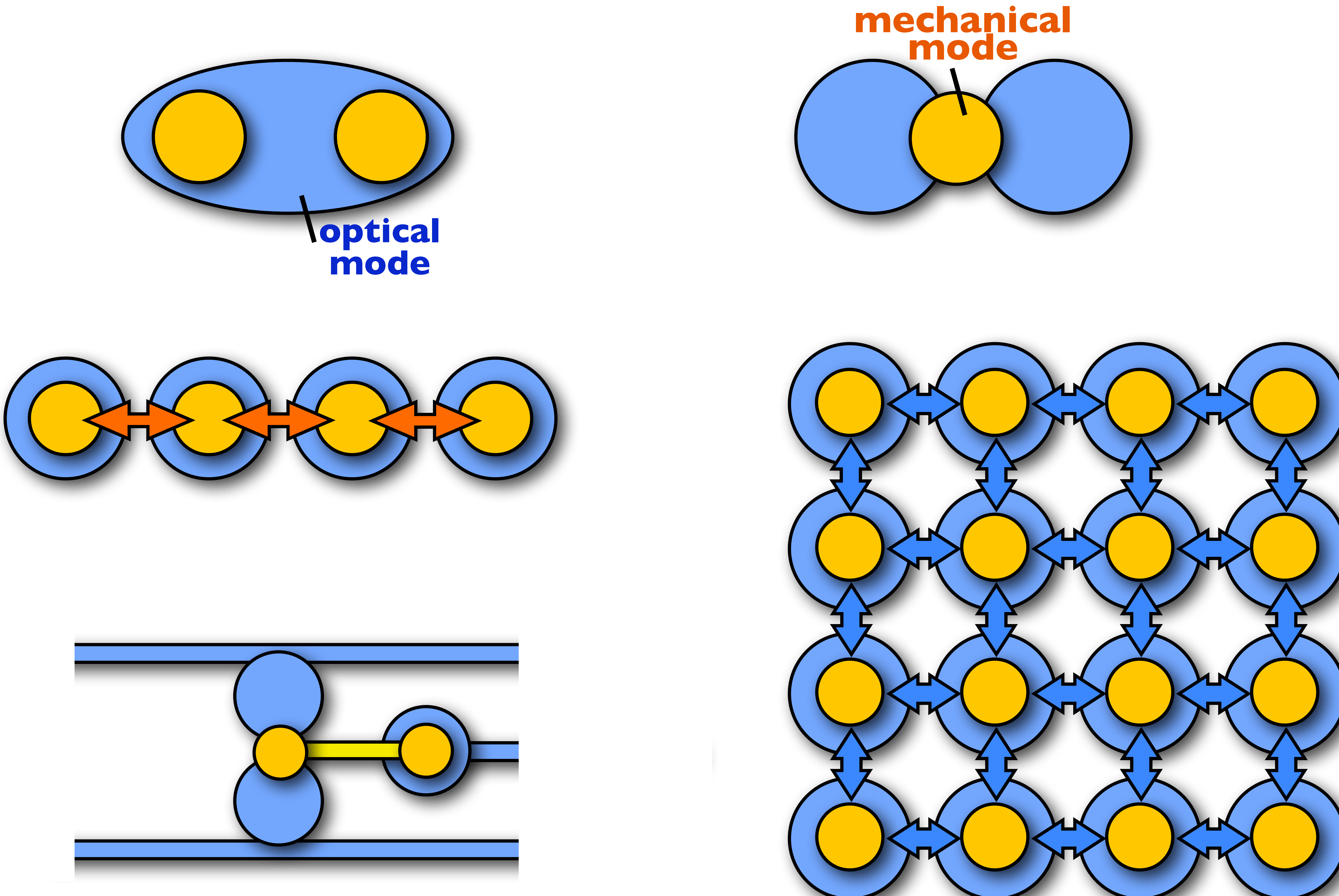
Dynamical Gauge Fields for the photons

Single-mode optomechanics

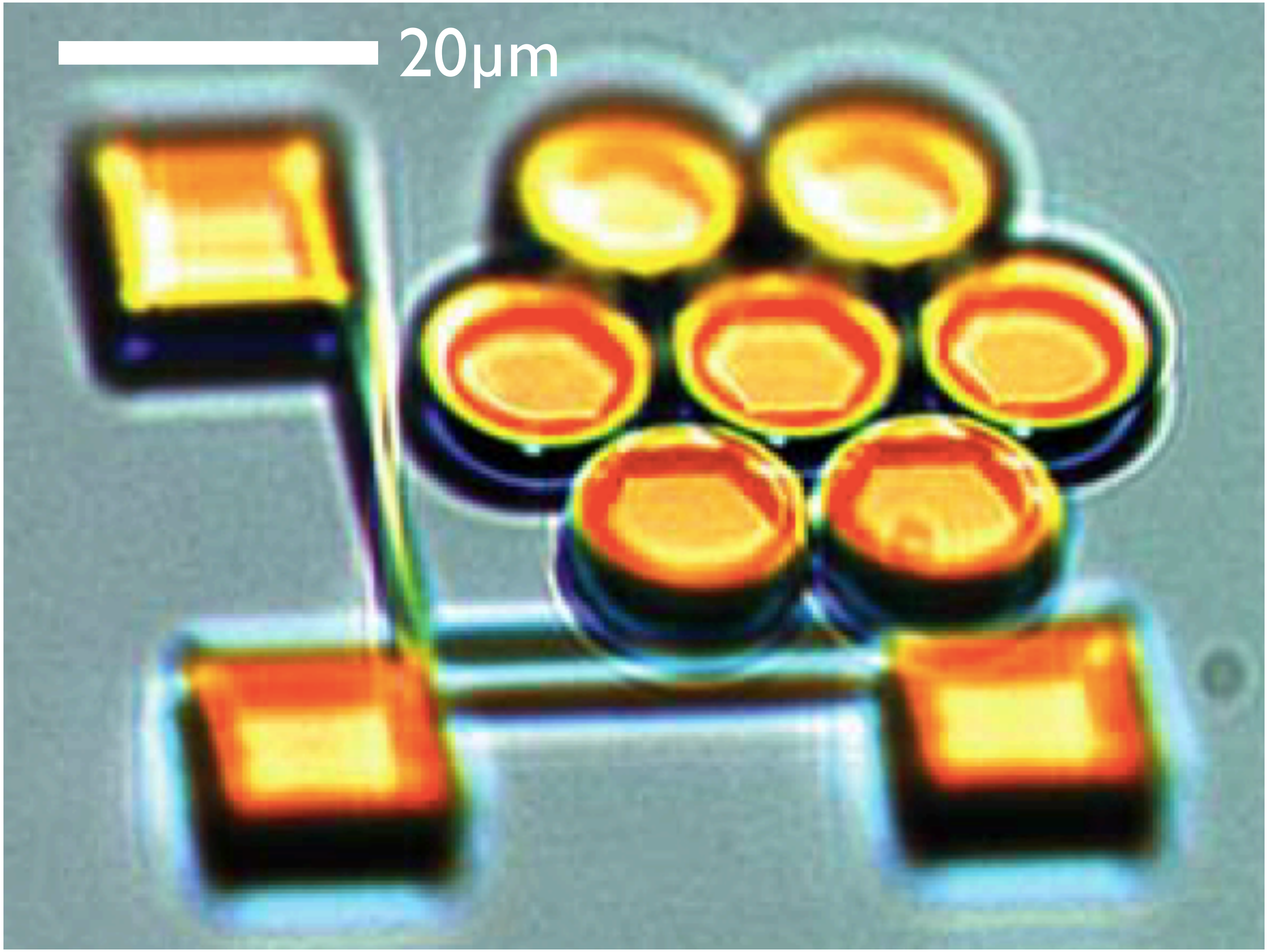


✓displacement sensing
✓cooling
✓strong coupling
✓self-oscillations (limit cycles)

Many modes



First realizations

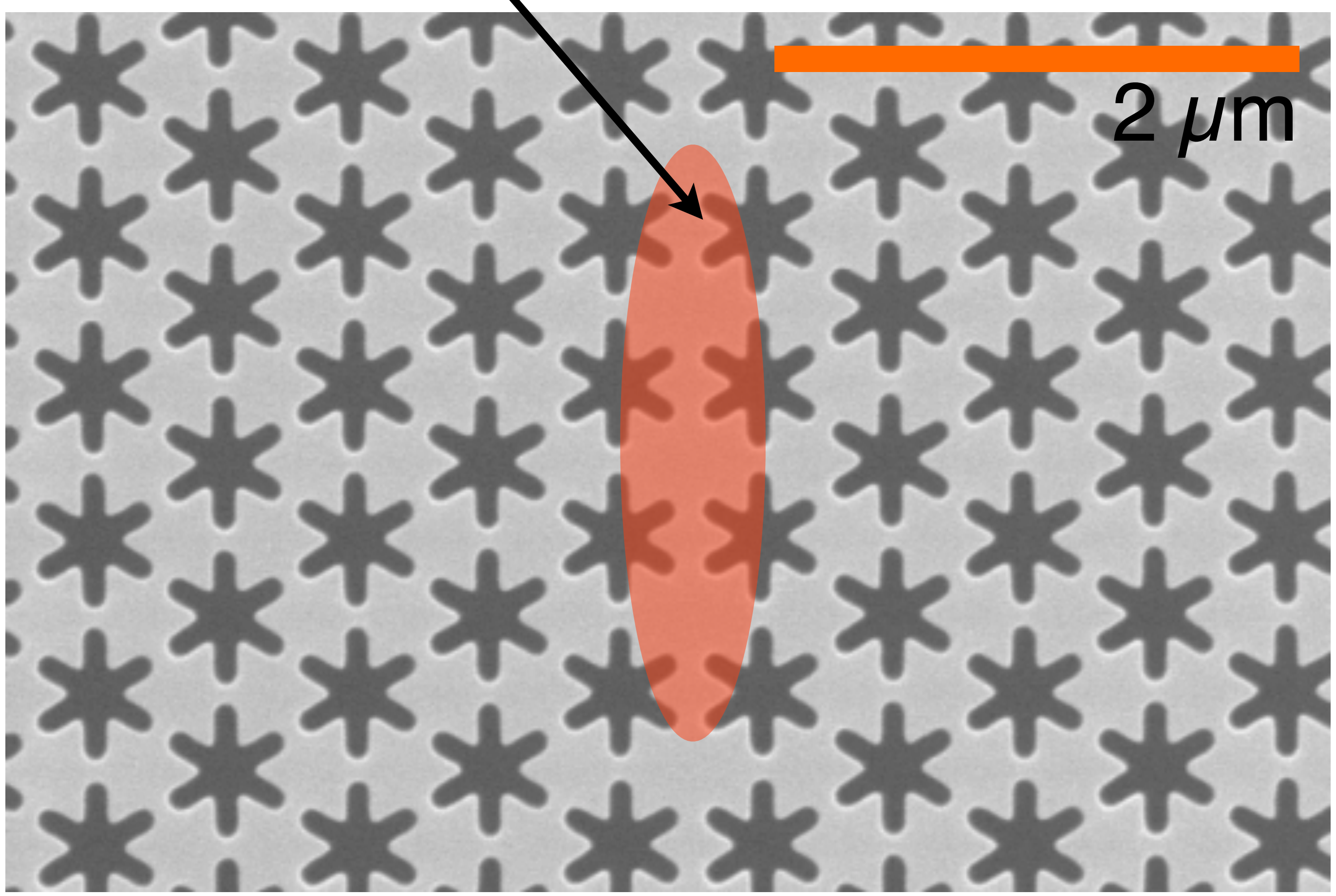


Lipson group, Cornell arXiv:1505.02009 (synchronization)

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)

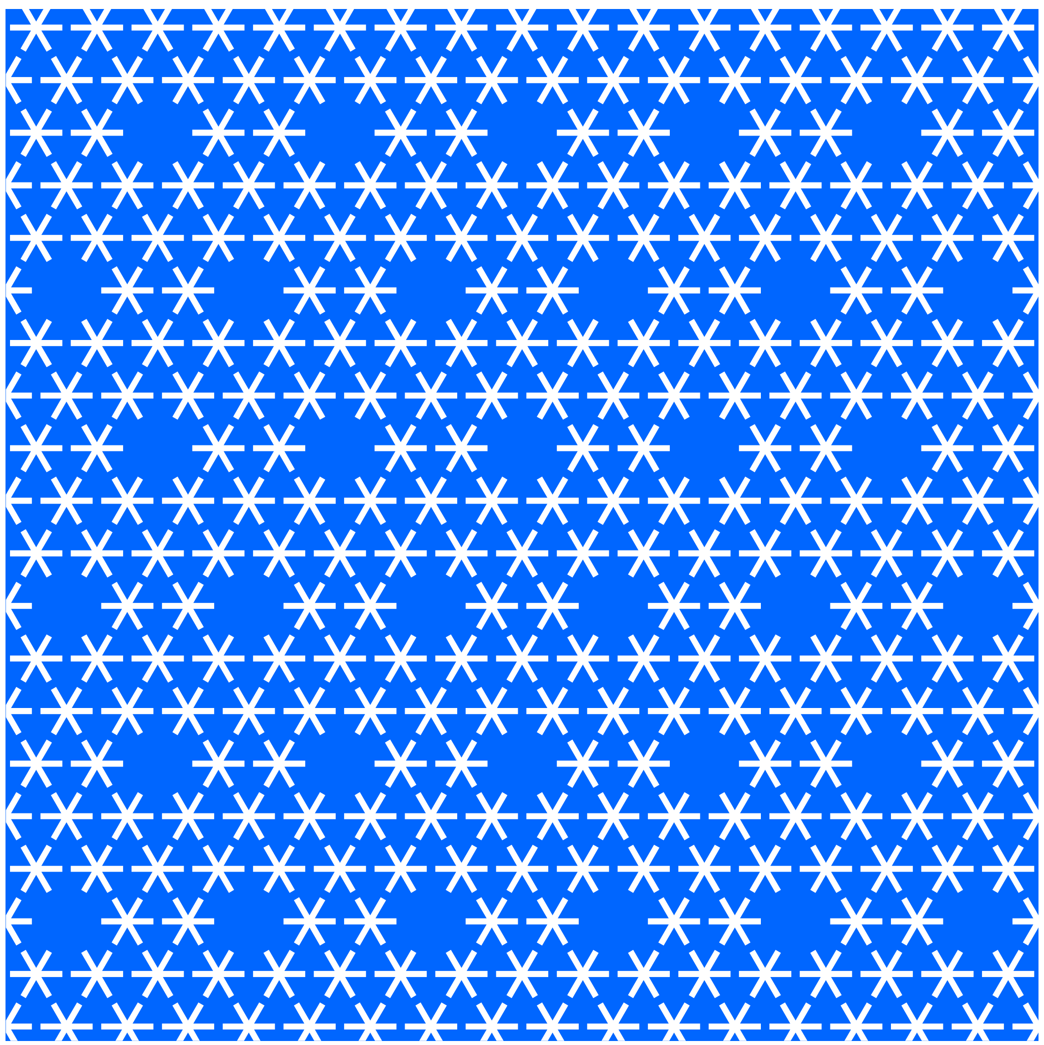
tight optical confinement:
large optomechanical coupling
(100 GHz/nm)

integrated on a chip

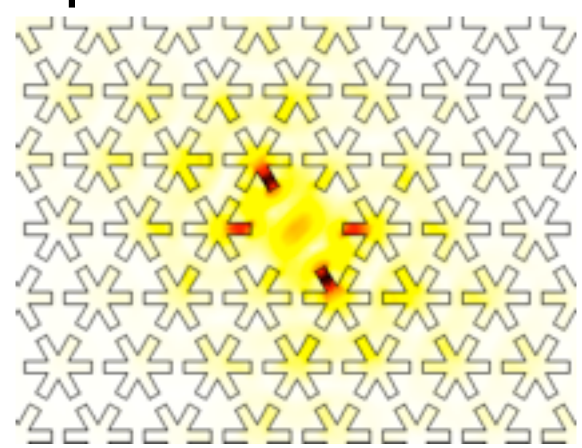
Safavi-Naeini et al PRL 2014
Eichenfield et al Nature 2009

Optomechanical arrays

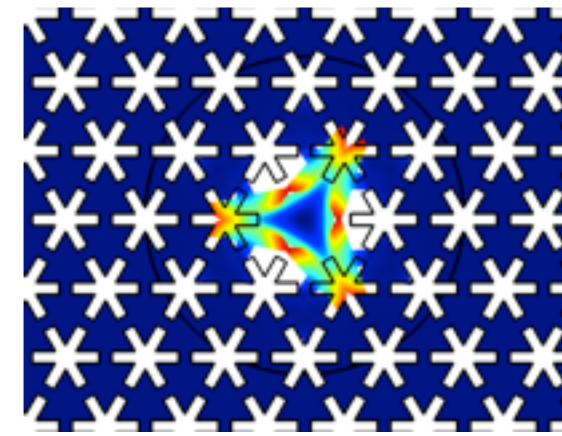
Optomechanical array: Many coupled optomechanical cells

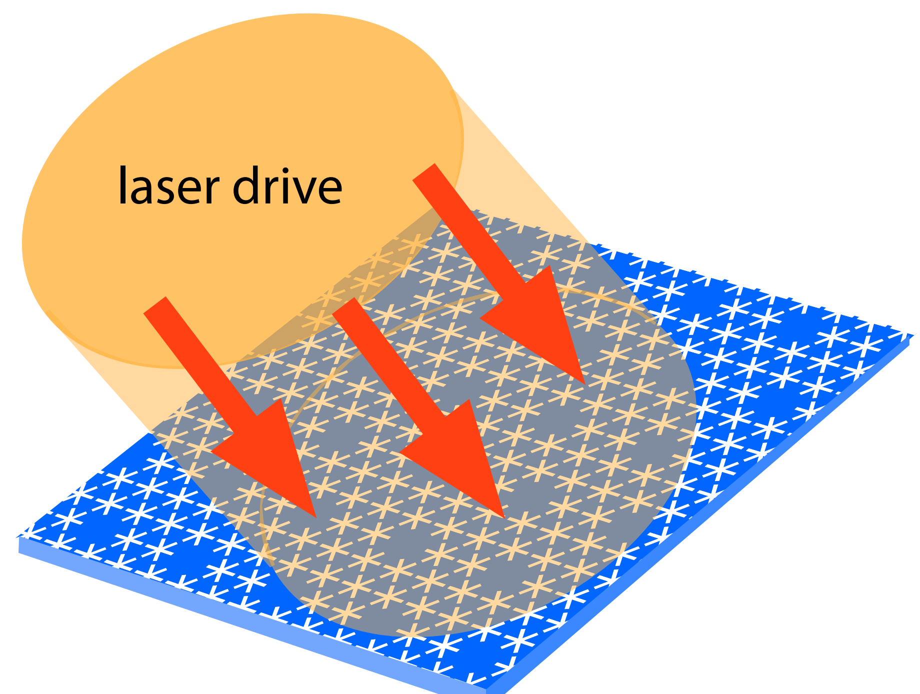


optical mode



mechanical mode

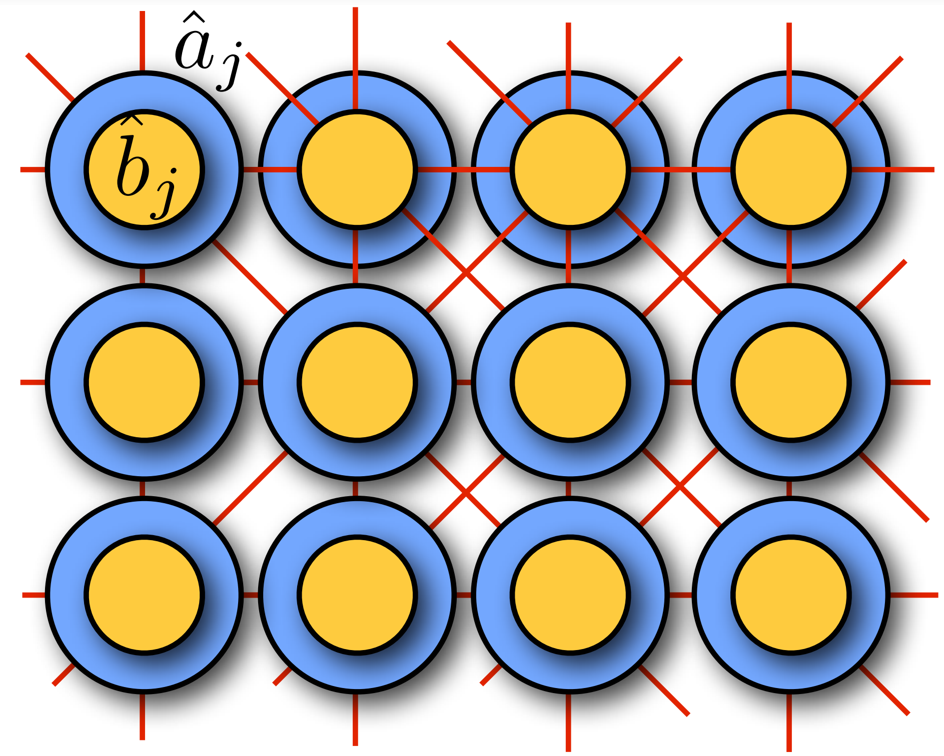




Possible design based on "snowflake" 2D optomechanical crystal (Painter group), here: with suitable defects forming a superlattice (array of cells)

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)

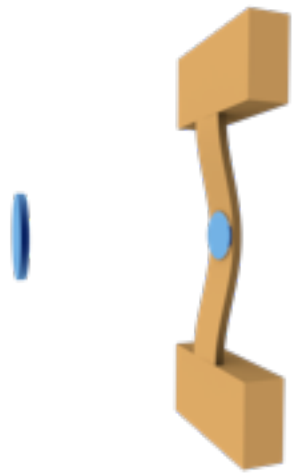
Optomechanical Arrays

global view:

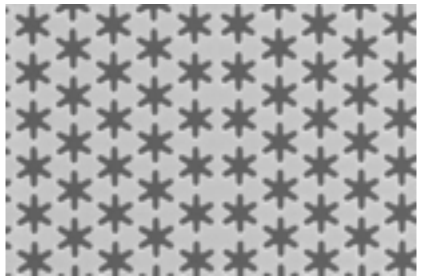
light-tunable metamaterial for photons & phonons

similar in spirit:
optical lattices
nonlinear optical materials

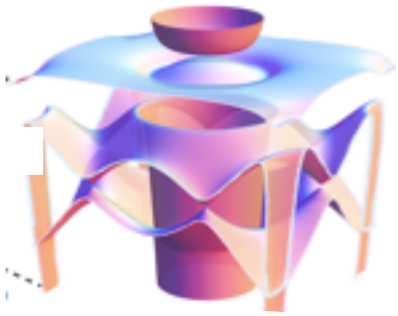
conceptually simple: one material, with holes



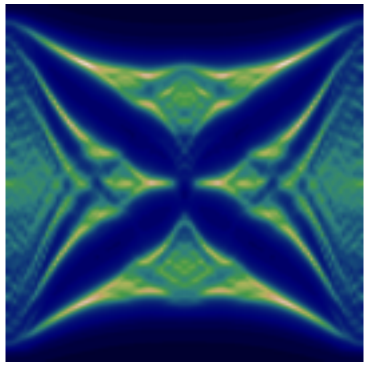
Cavity Optomechanics



Optomechanical Arrays



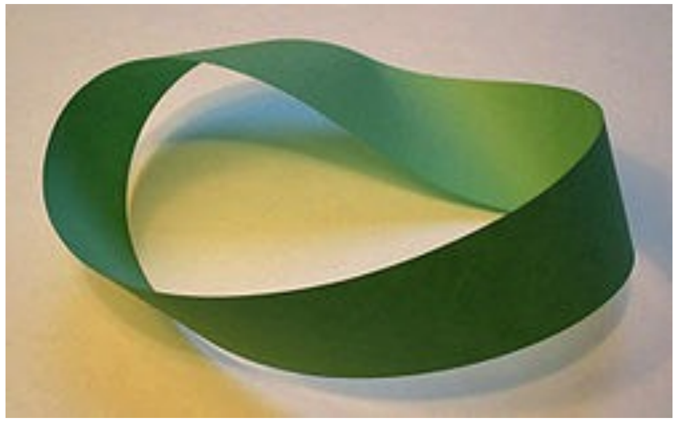
Topological Phases of Sound (and Light)



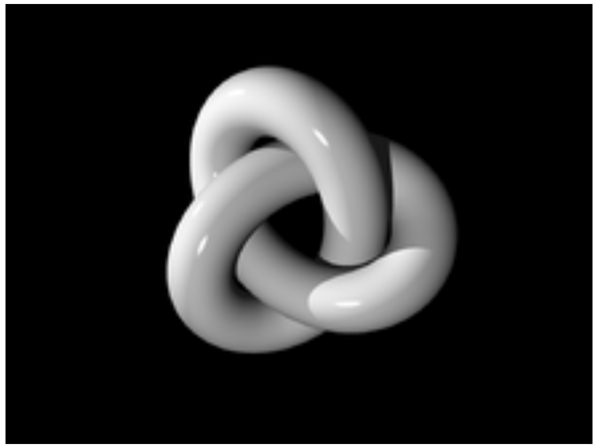
Dynamical Gauge Fields for the photons

Topological Materials

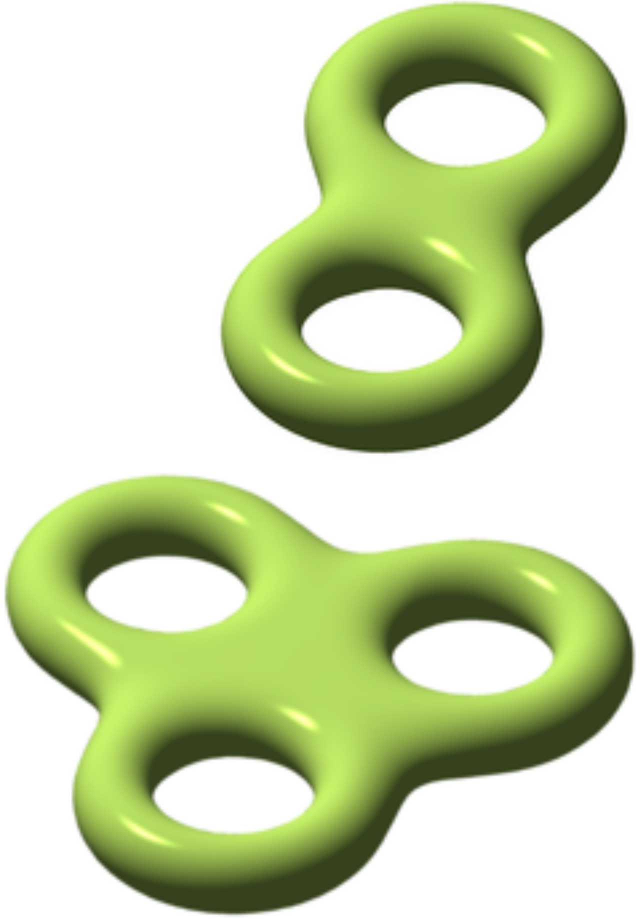
Topological properties:
robust against smooth changes!



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)

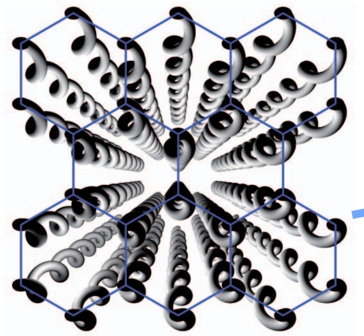
Topological Insulators:

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

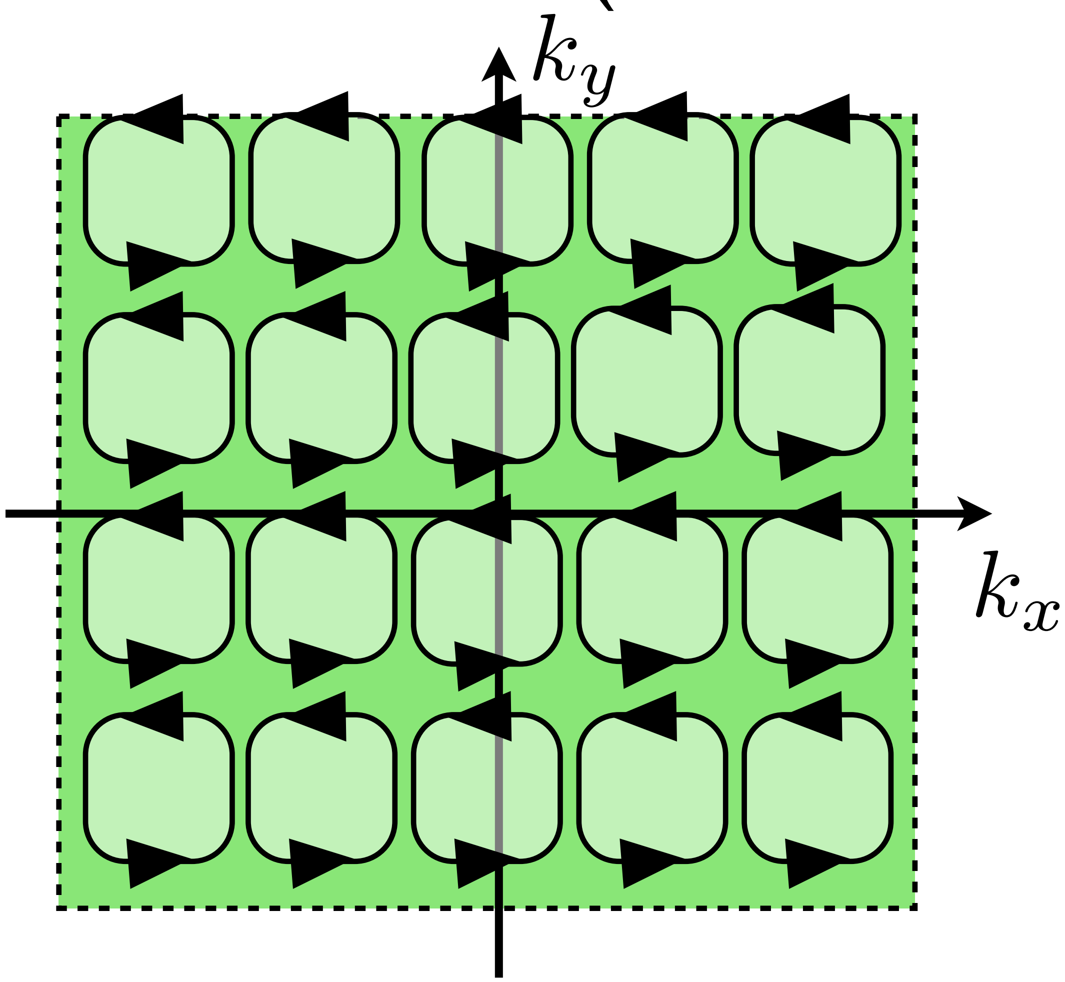


photons:
Khanikaev,...,Shvets, Nature Materials 2012
Rechtsman, ..., Szameit Nature 2013
Mittal, ... , Hafezi PRL 2014
...

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

Topological Bandstructures

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

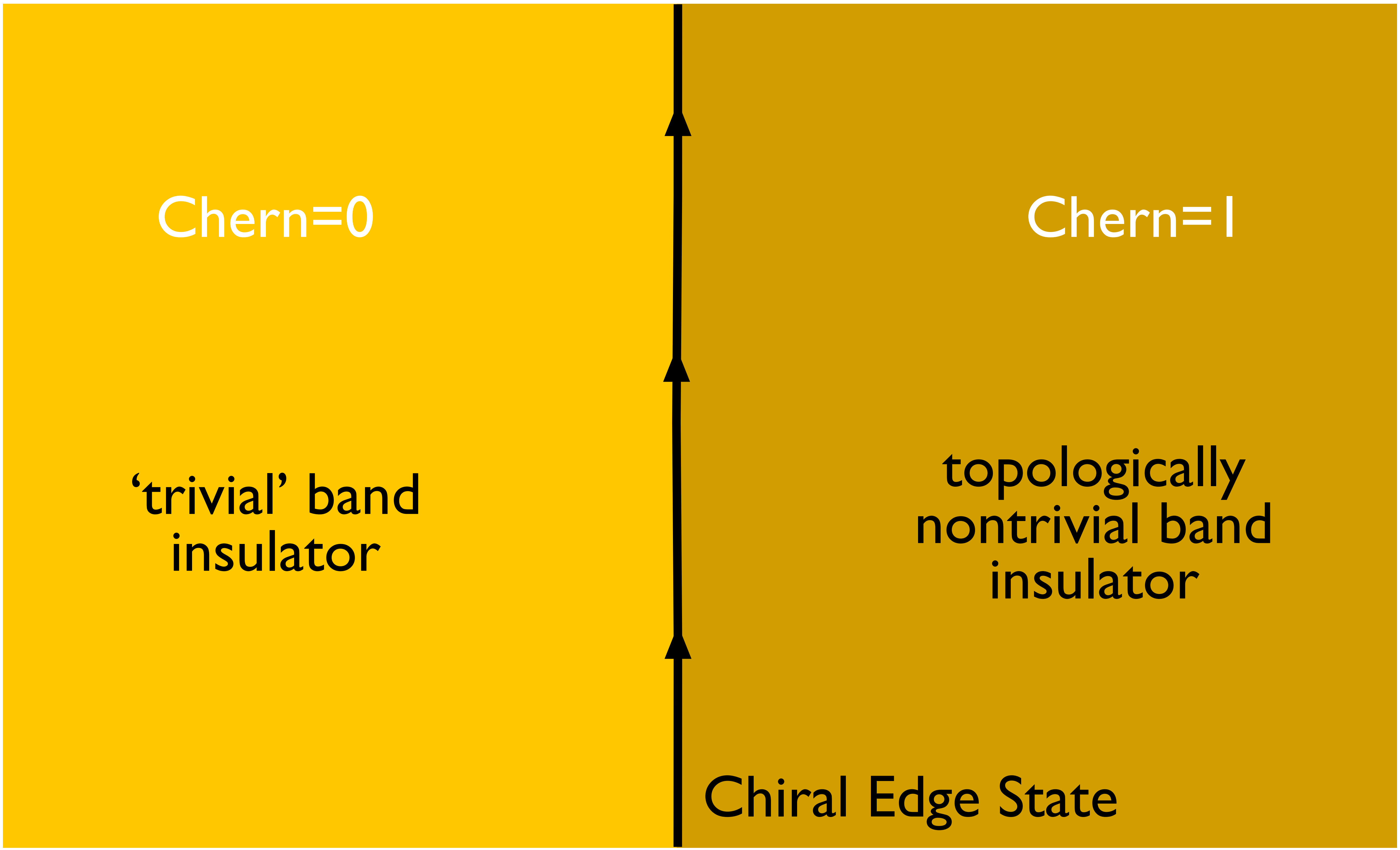


Chern number =

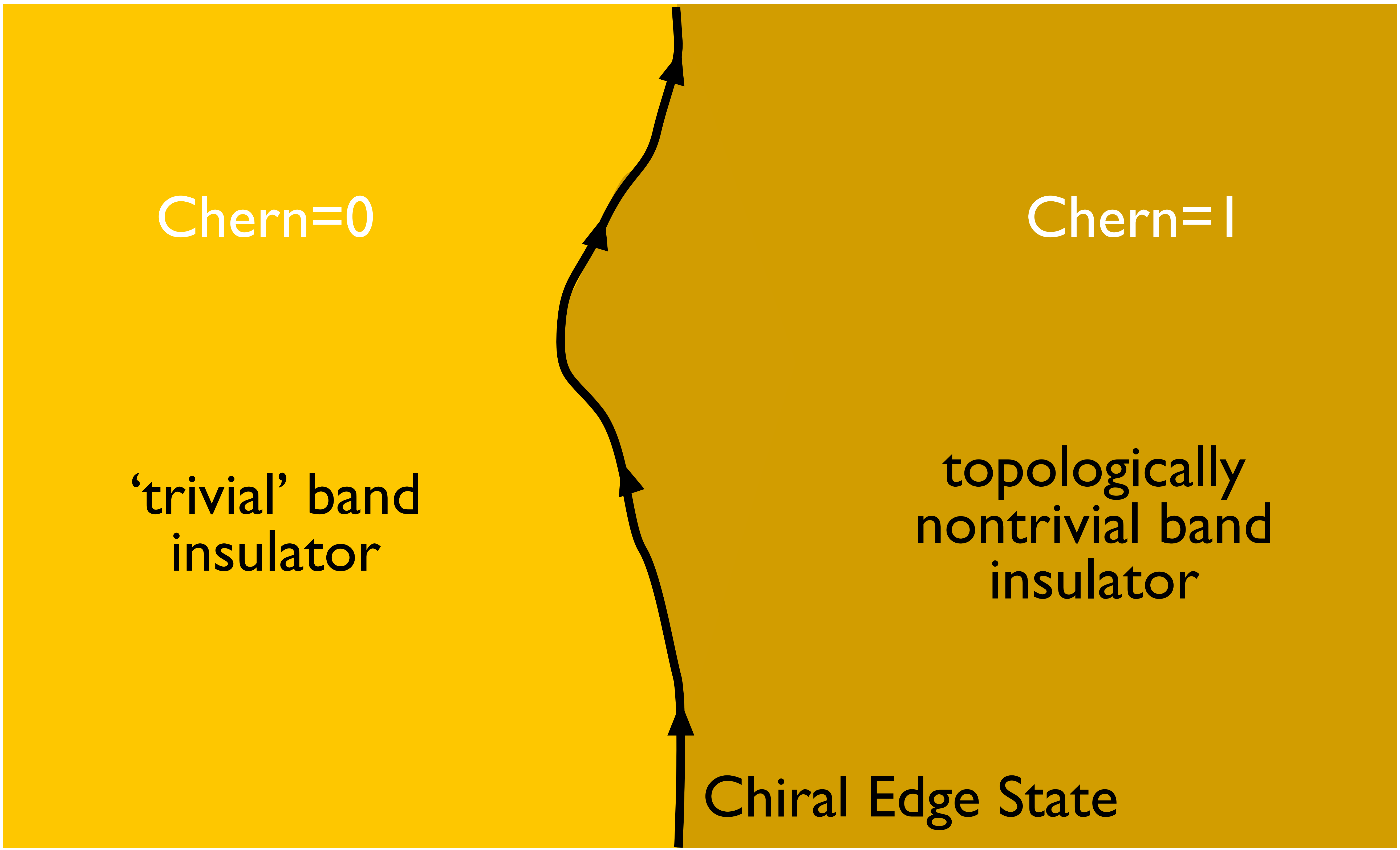
$$\frac{1}{2\pi}\int dk_x dk_y \vec{\nabla} \times \langle \Psi_k | \vec{\nabla} | \Psi_k \rangle$$

Chern number = integer! topologically robust!

Edge States


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

Edge States

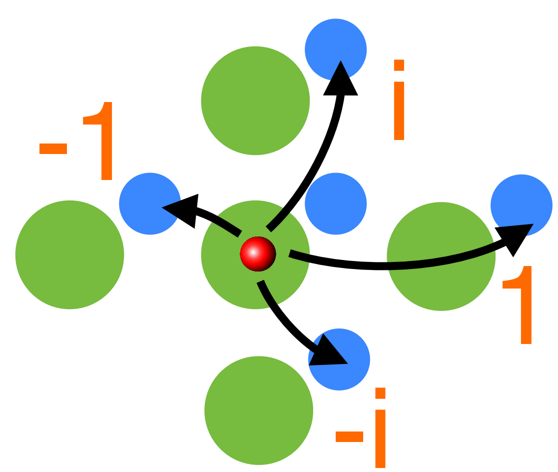


Chern=0
Chern=1
'trivial' band insulator
topologically nontrivial band insulator
Chiral Edge State

Phonon Topological Materials

What about topological transport of phonons?

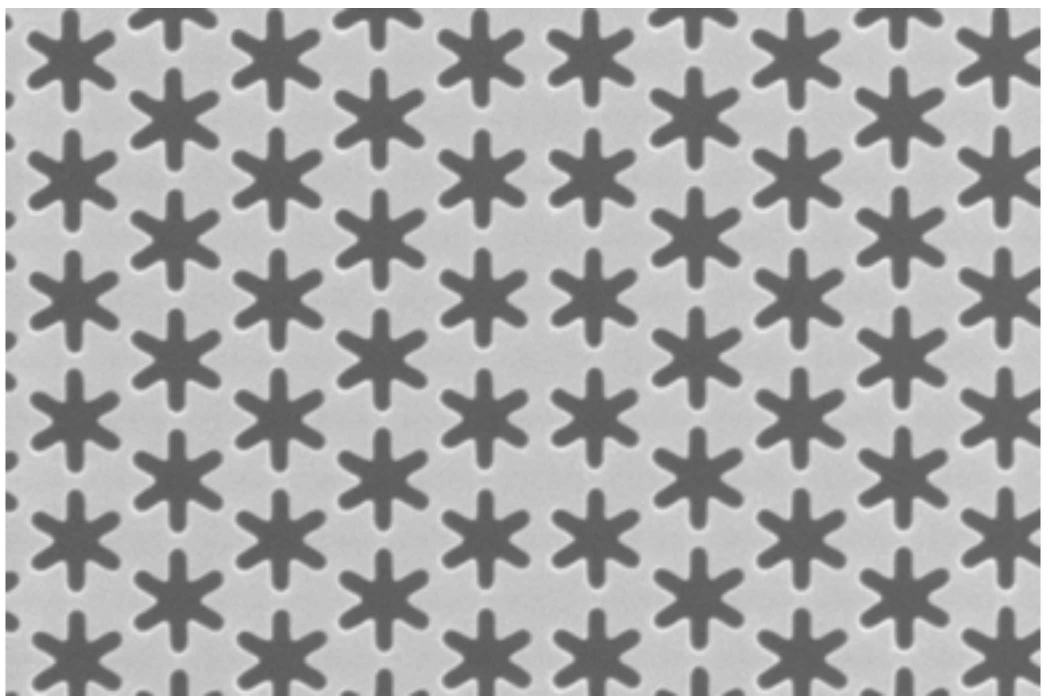
Engineer non-reciprocal phases for phonon transport!



Topological Phases of Sound and Light

What about topological transport of phonons?

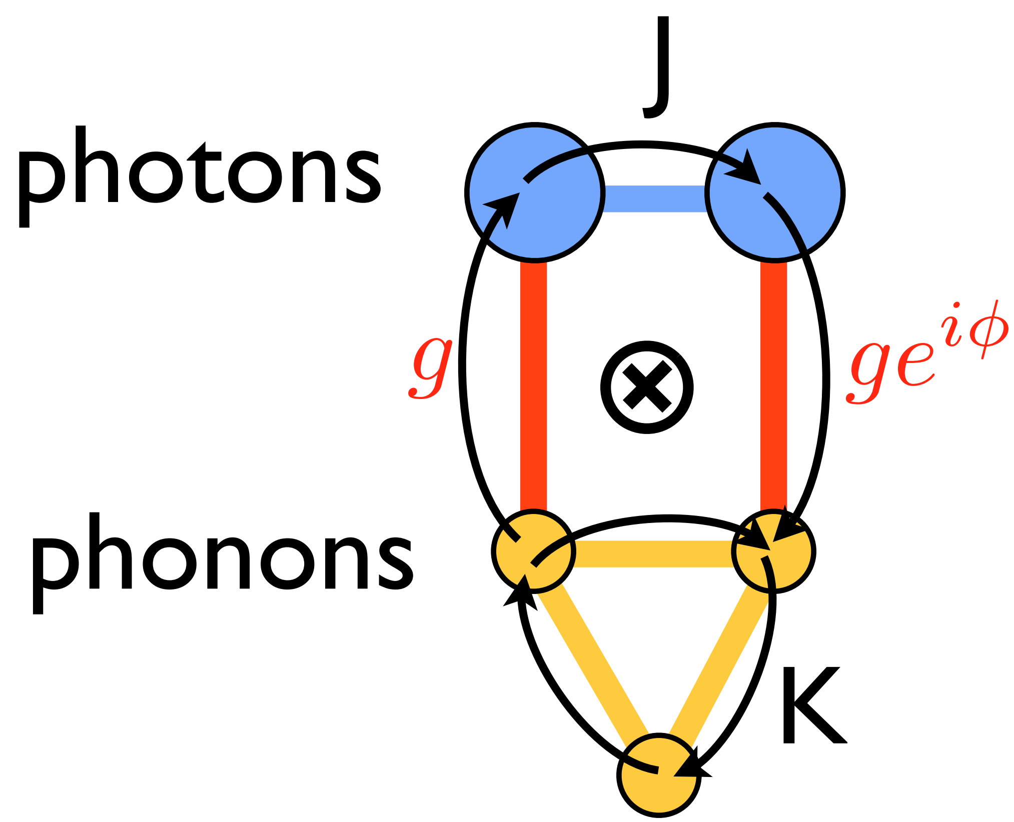
Need:



Dielectric
(with the right
pattern of holes)

One Laser
(with the right
pattern of phases)

Gauge fields for phonons

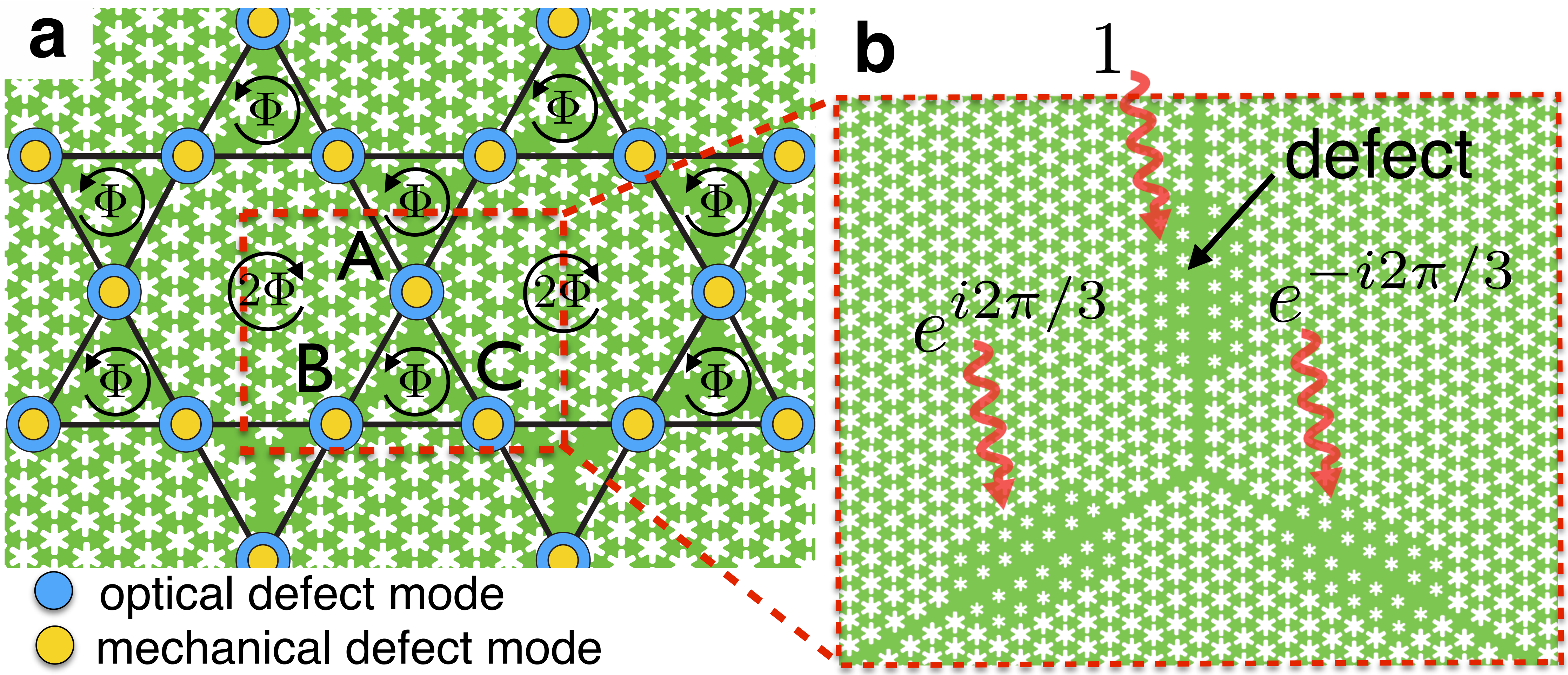


(works best for phonons, due to K<<J)

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

Topological Phases of Sound and Light in an Optomechanical Array

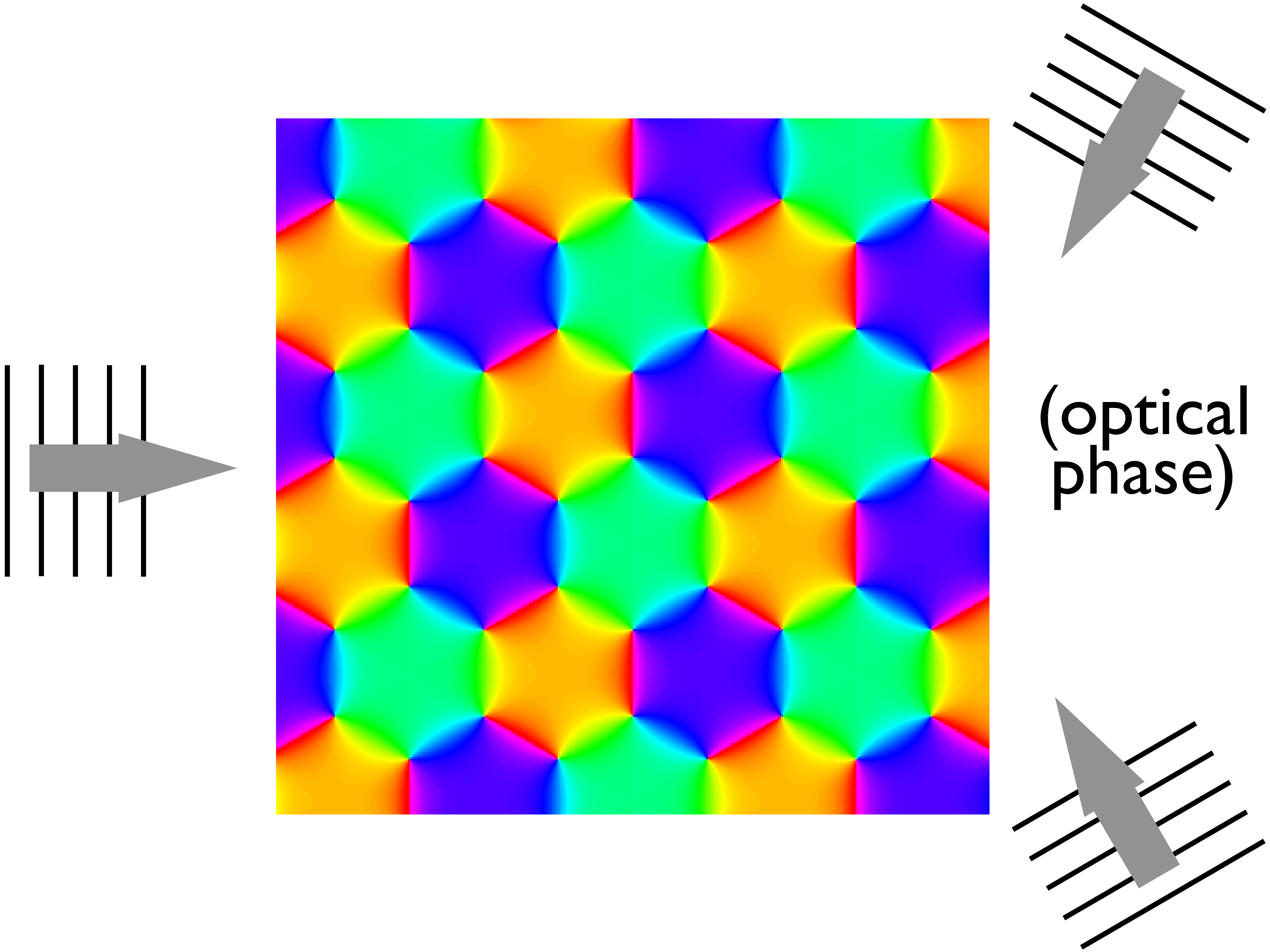
Kagome Optomechanical Array



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

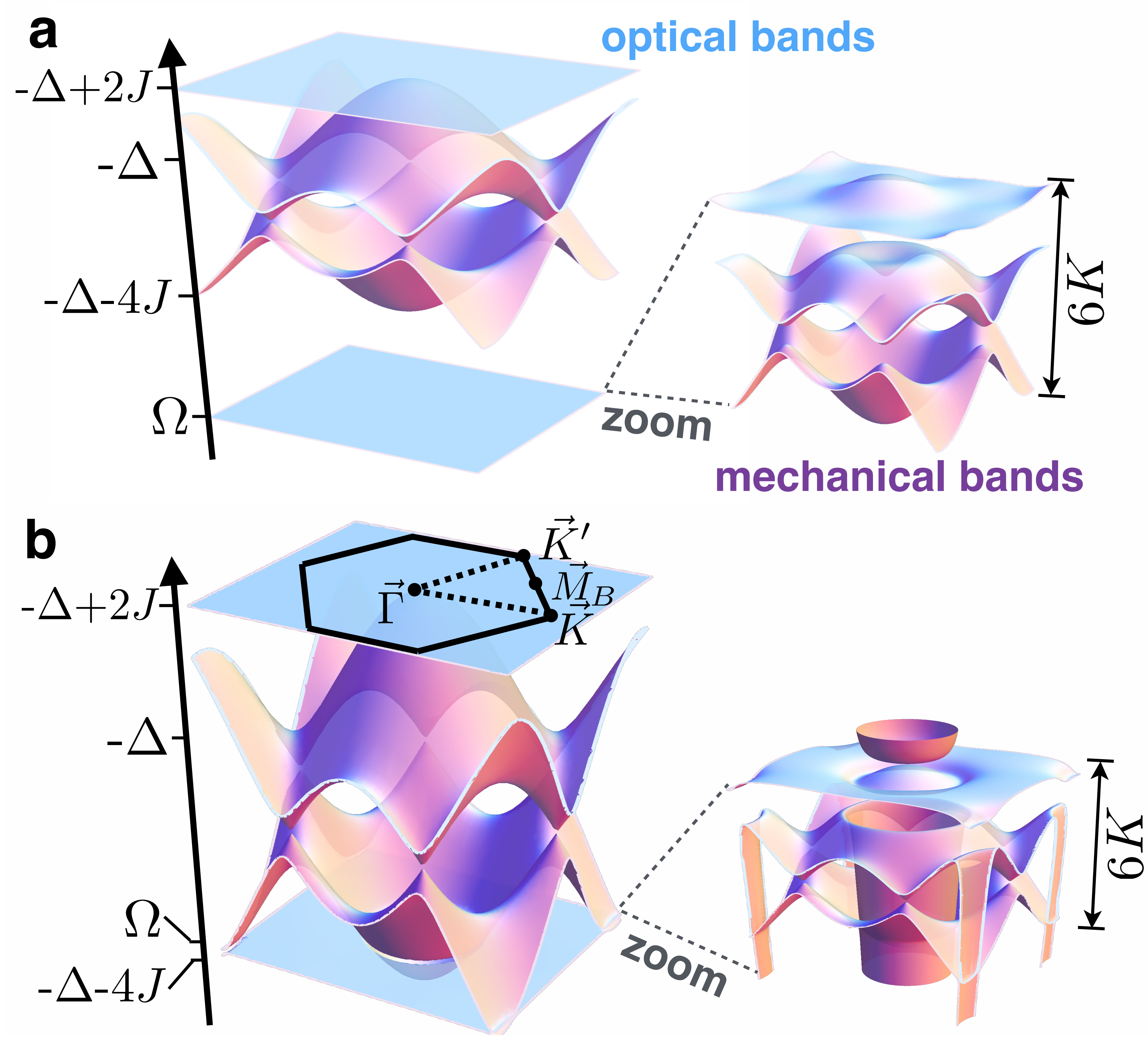
see Koch, Houck, LeHur, Girvin PRA 2010 for Kagome lattice in circuit QED

Creating an optical phase pattern



Topological Phases of Sound and Light in an Optomechanical Array

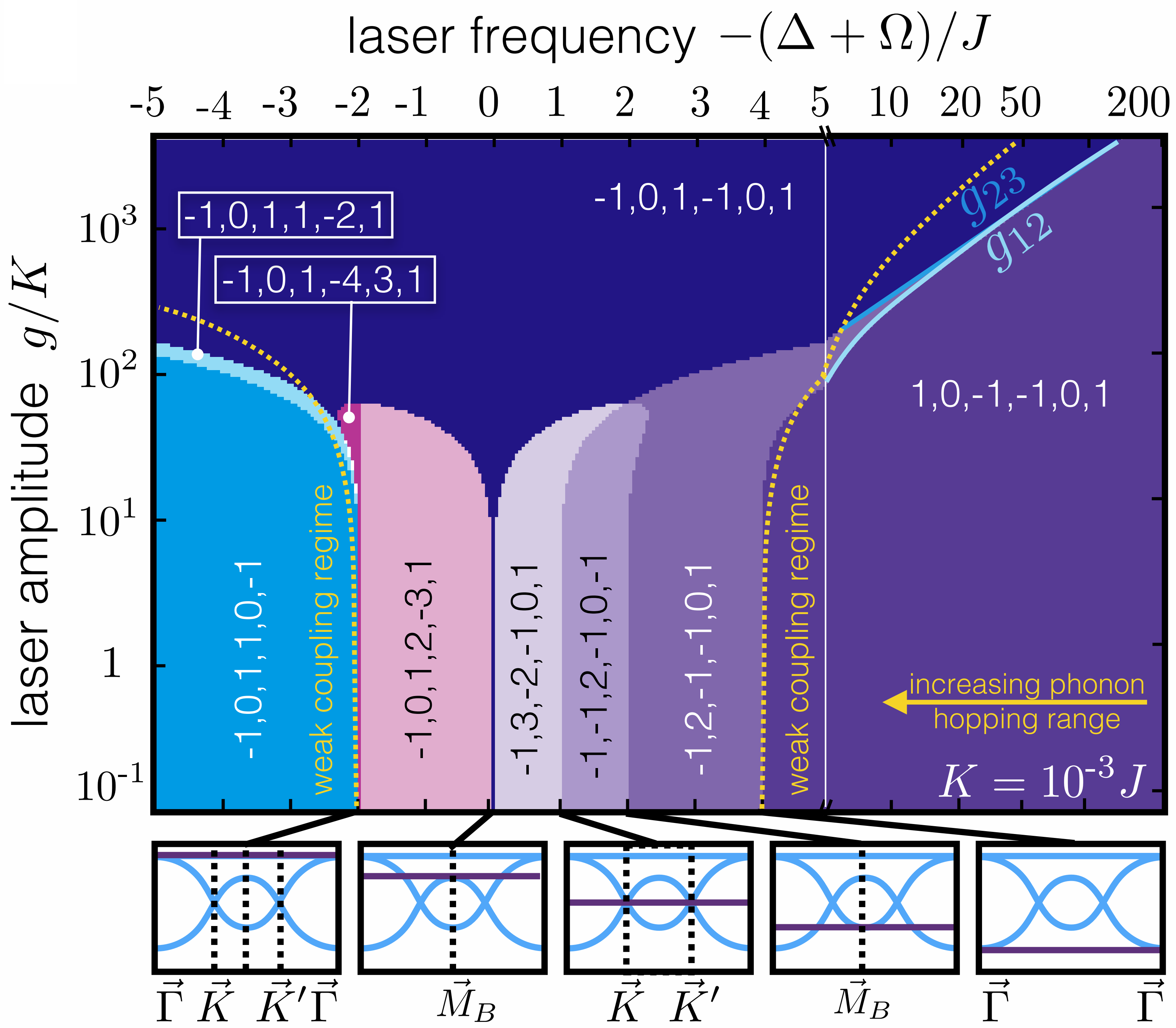
Vittorio Peano, Christian Brendel, Michael Schmidt, and Florian Marquardt, PRX 2015



a "weak coupling": light field modifies phonon hopping
b "strong coupling": photon and phonon bands mix

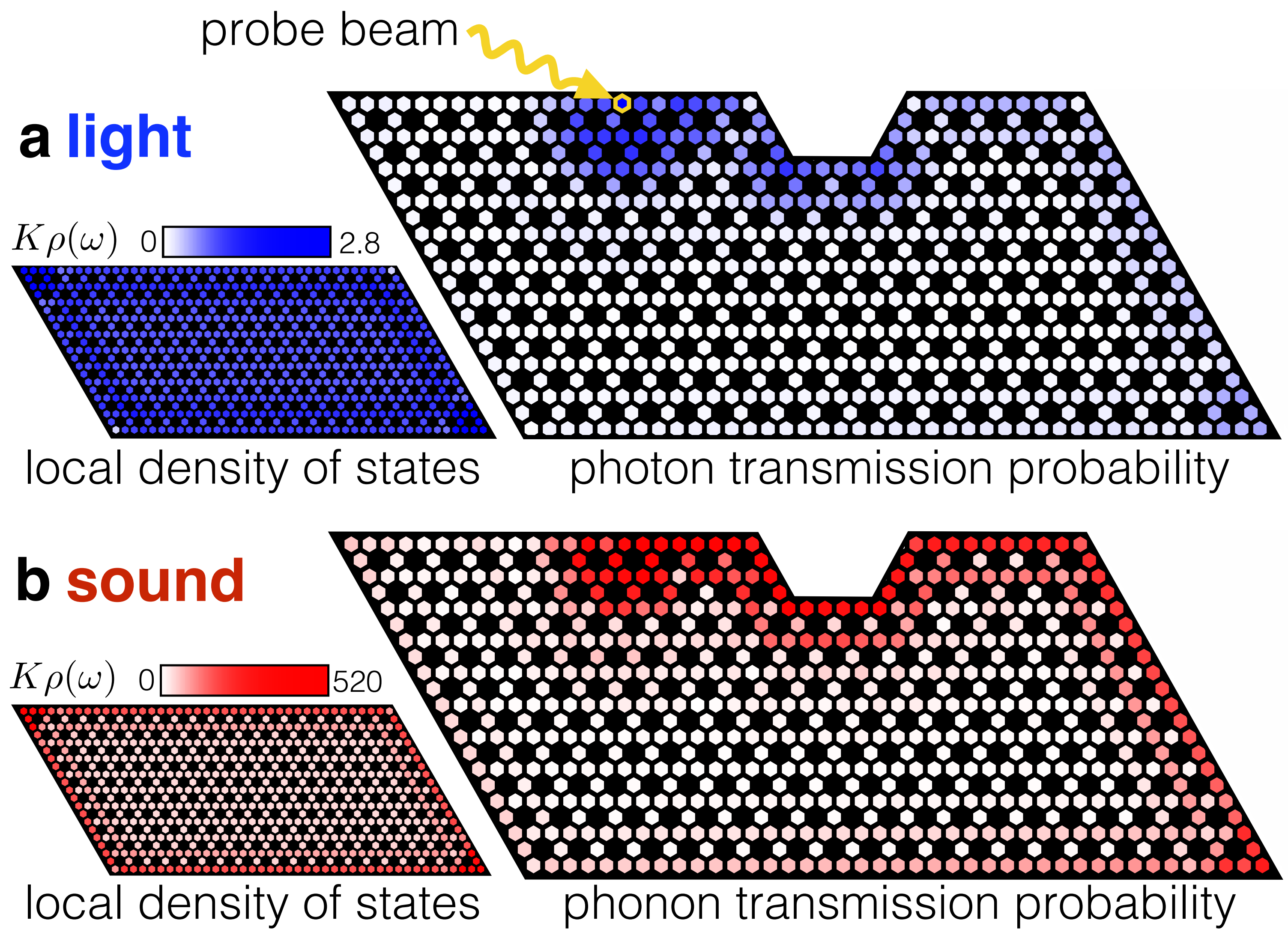
Topological Phases of Sound and Light in an Optomechanical Array

Topological Phase Diagram



[Chern numbers of bands]

Robust chiral transport of phonons



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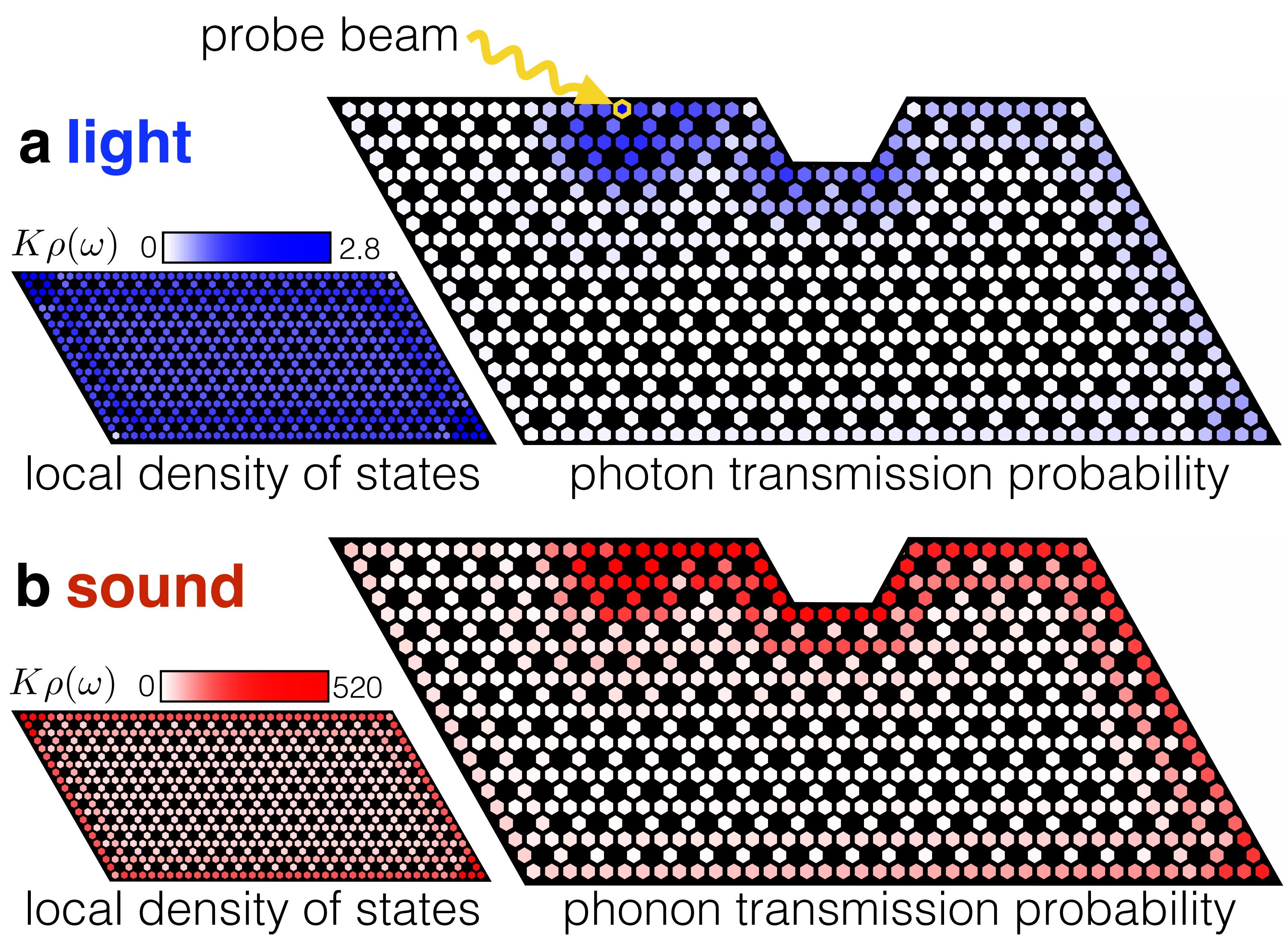


Challenges (for optomechanical crystals)

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)

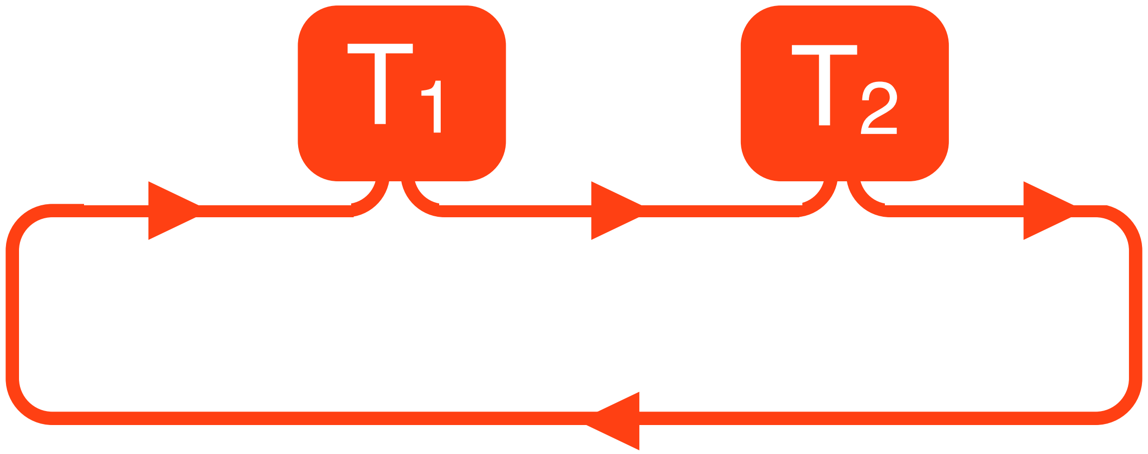
Features

- Topologically protected transport of phonons in the solid state

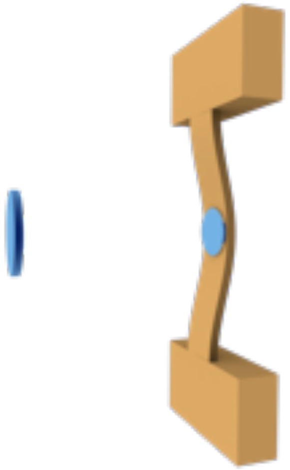
compare... coupled pendula
Süssstrunk, Huber Science '15
coupled gyroscopes
Nash,...,Irvine, arXiv:1504.03362

- Here: nanostructure, tuneable
- Full optical control and readout
- Arbitrary domains

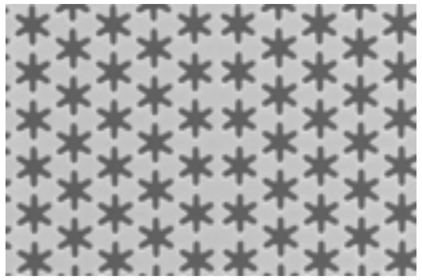
Features



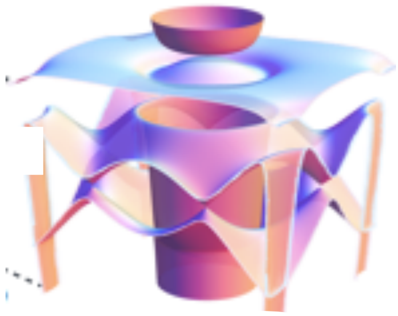
- study one-way phonon transport
- Time-dependent control: quenches, dynamical reconfiguration of edge states
- Photon/phonon polariton transport
- Classical nonlinear dynamics
- Thermalization in chiral edge states
- Quantum nonlinear dynamics: for larger g_0



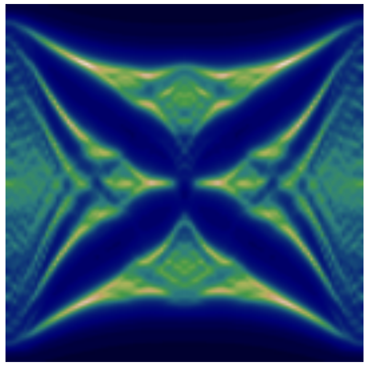
Cavity Optomechanics



Optomechanical Arrays



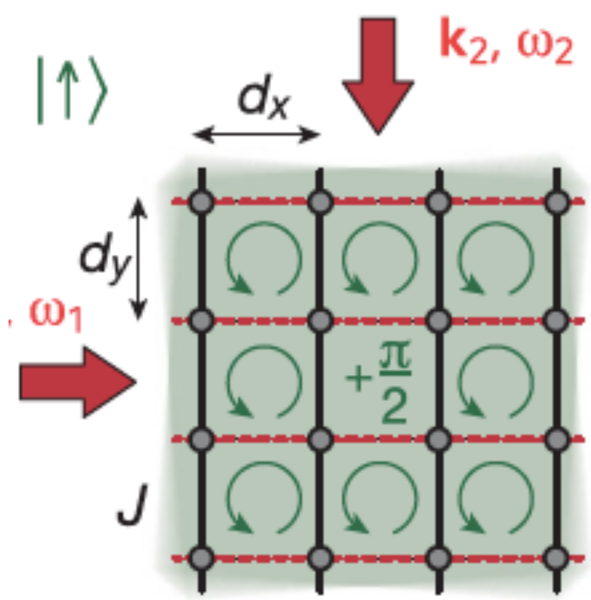
Topological Phases of Sound (and Light)



Dynamical Gauge Fields for the photons

Synthetic magnetic fields

neutral atoms



cold atom realizations:
Aidelsburger et al (Bloch group) 2013,
Miyake et al (Ketterle group) 2013

photons

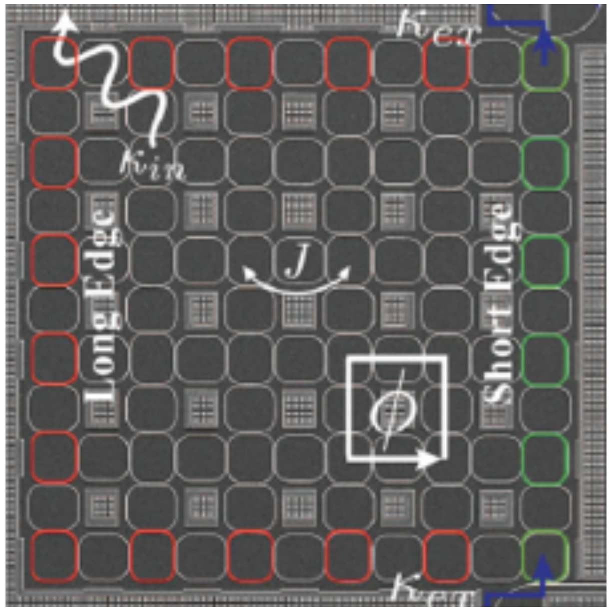
proposals:

Umucalilar and Carusotto, PRA 2011
circularly refractive medium

Hafezi, Demler, Lukin, Taylor, Nature Physics 2011

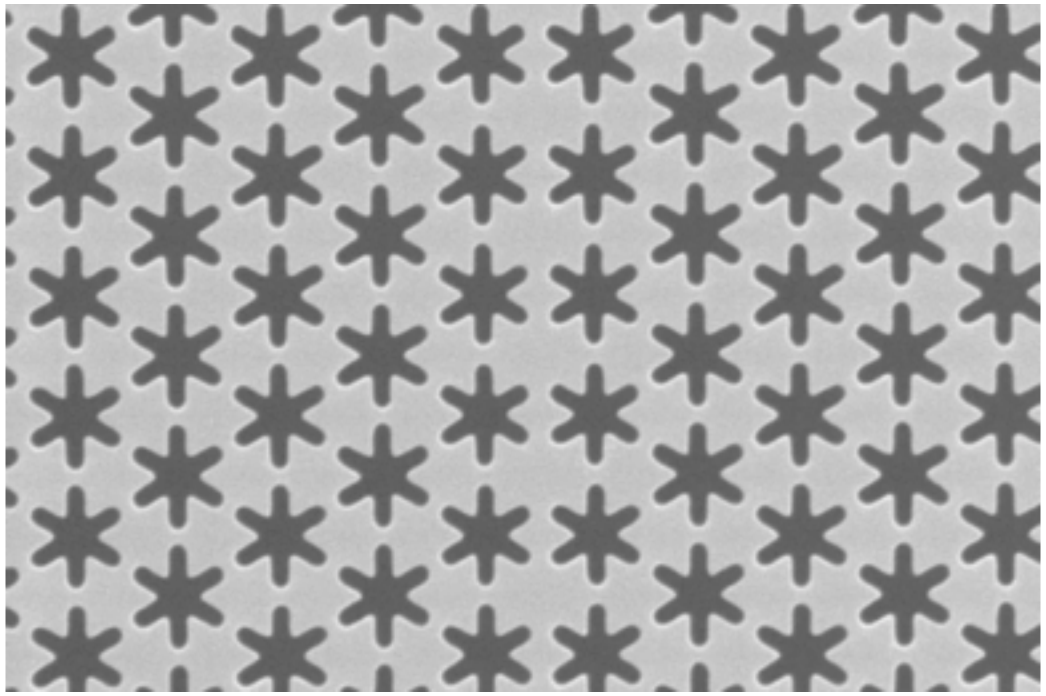
tuneable: Fang, Yu, Fan Nature Photonics 2012; proposed electrical modulation of refractive index

Mittal, ... , Hafezi PRL 2014
coupled ring resonators



Artificial magnetic fields for photons

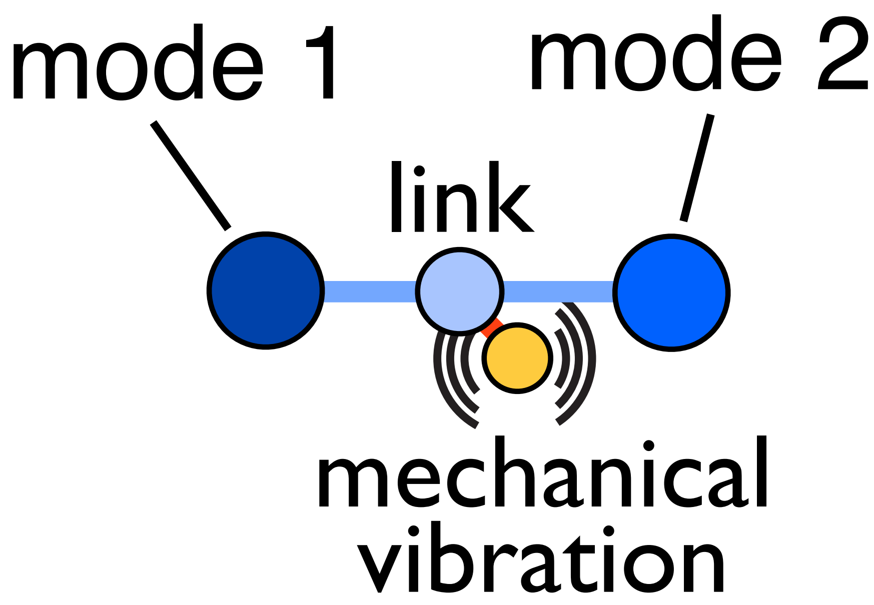
Need:



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

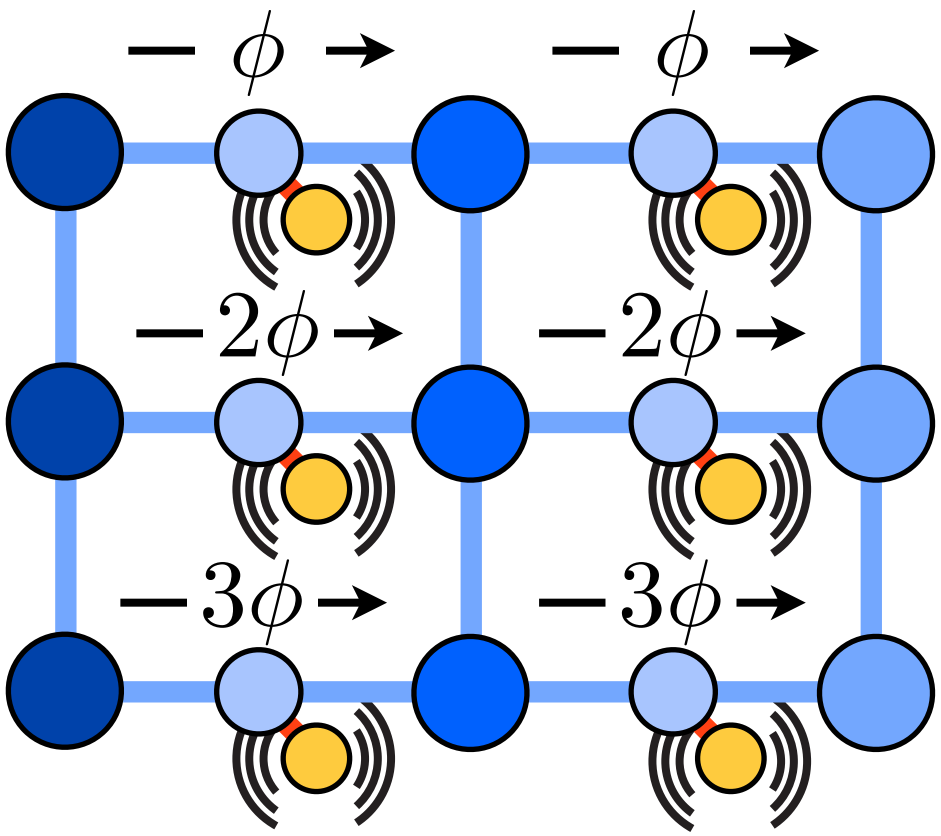
$$\omega = \omega_2 - \omega_1$$

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

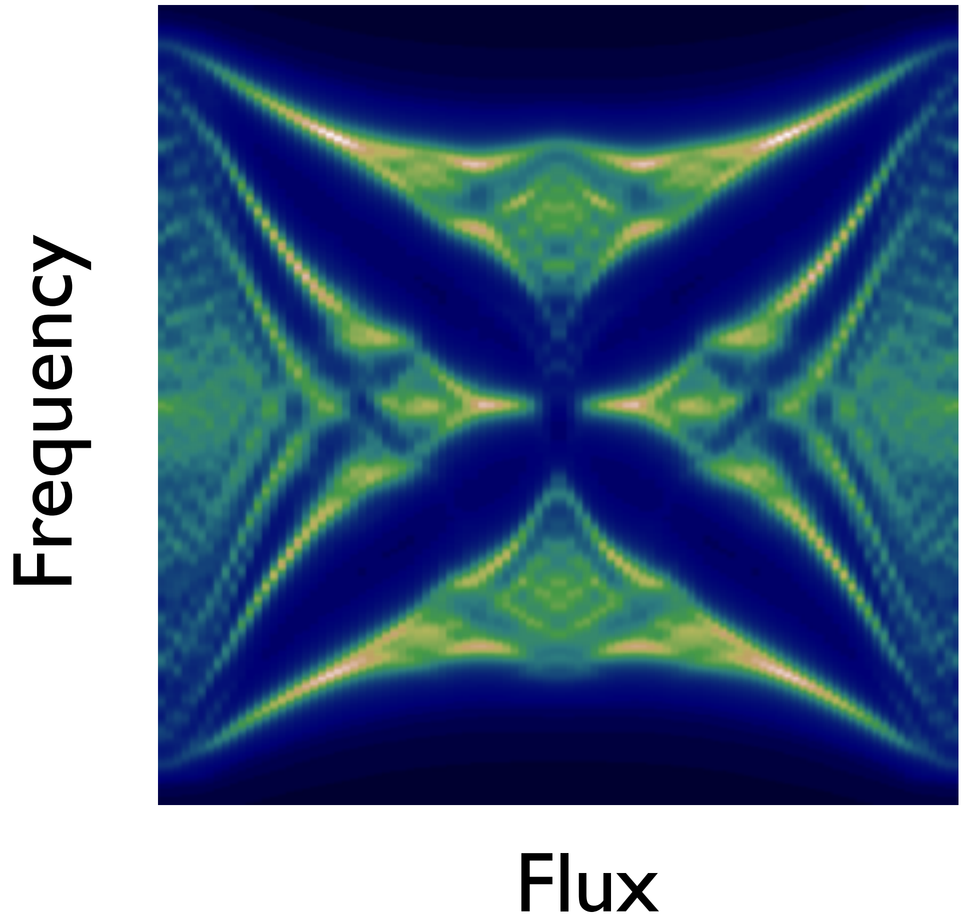
non-reciprocal phase!

(similar to Fan group proposal, but mechanical vibration instead of electrical modulation)

Artificial magnetic fields for photons



Hofstadter butterfly spectrum



arbitrary optical re-configuration of magnetic field distribution

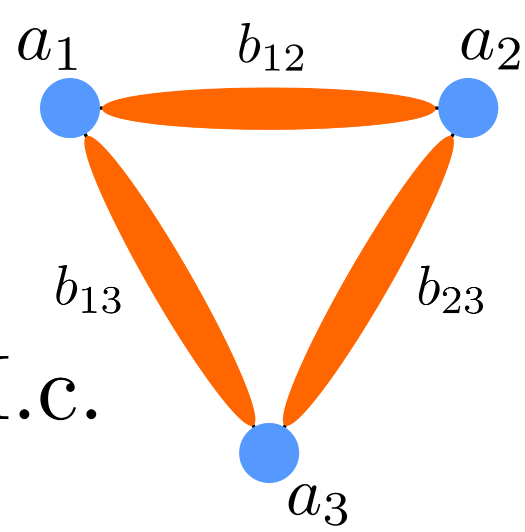
M. Schmidt, S. Keßler, V. Peano, O. Painter, F. Marquardt Optica 2015

Dynamical Gauge Fields

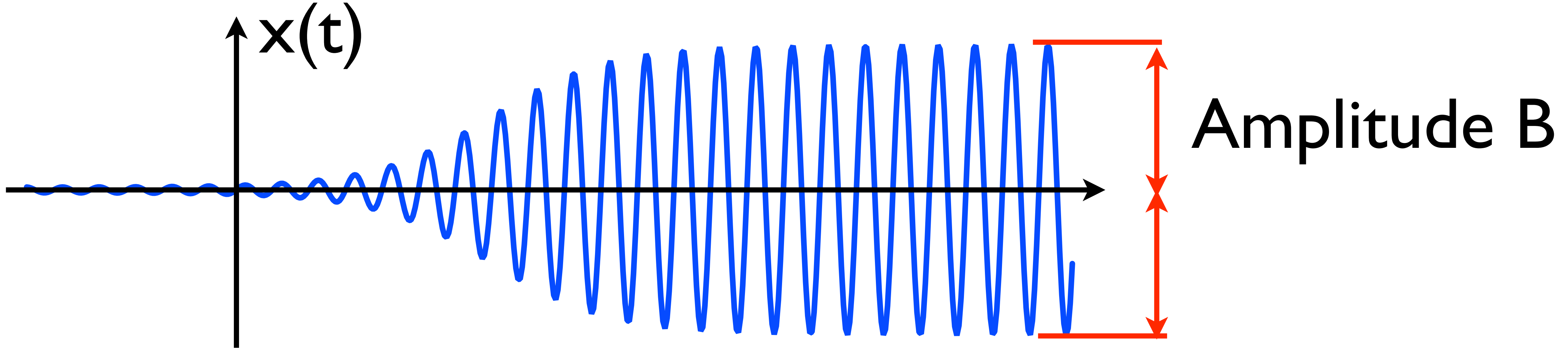
Optomechanical Hamiltonian:

phonon-assisted photon hopping

$$H = \sum_j \nu_j a_j^\dagger a_j + \sum_l \omega_l b_l^\dagger b_l + \sum_{\langle i,j \rangle} J_{i,j} b_{i,j} a_j^\dagger a_i + \text{H.c.}$$

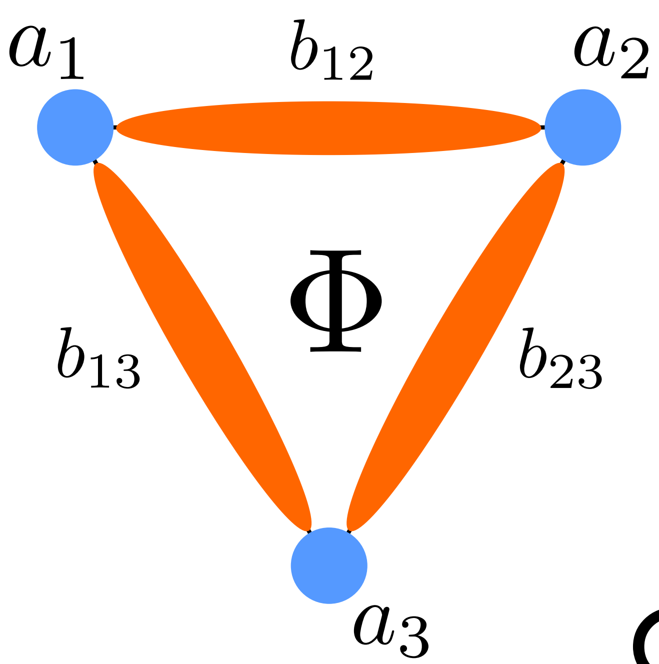


Mechanical oscillation: now self-oscillations (pumped by blue-detuned laser), instead of externally driven



S. Walter and FM, in preparation

Gauge-invariant dynamics



amplitude and phase:

$$a_j = A_j e^{i\theta_j} \qquad b_{ij} = B \; e^{i\phi_{ij}}$$

gauge-invariant flux (seen by the photons)

$$\Phi = \phi_{13} + \phi_{21} + \phi_{32}$$

Classical nonlinear dynamics:

mechanical phase dynamics

$$\dot{\phi}_{ij} = -\omega_{ij} - \frac{J_{ij}}{B_{ij}} A_i A_j \cos(\phi_{ij} + \theta_{ij})$$

optical phase dynamics

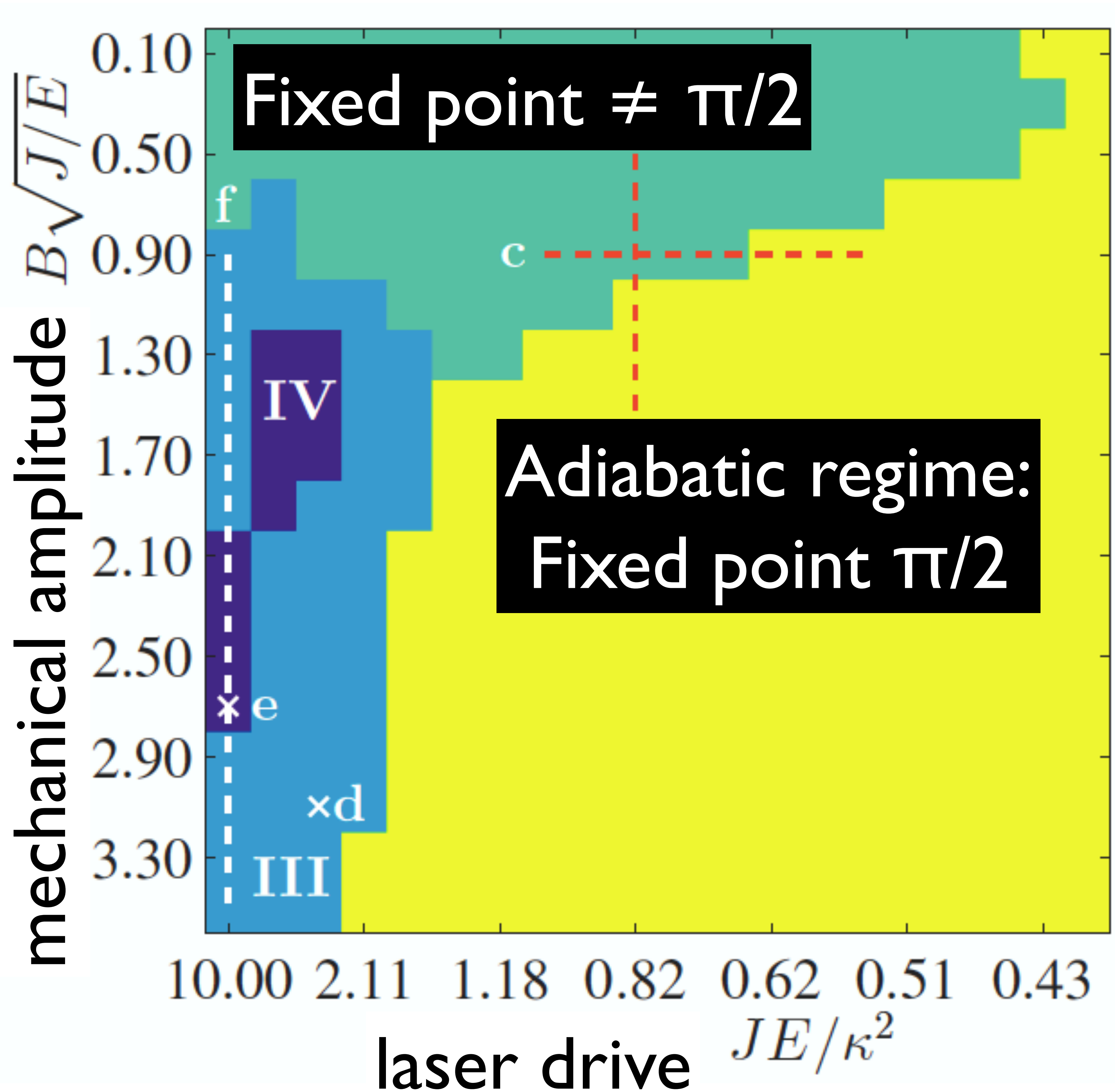
$$\dot{\theta}_i = -\nu_i - \sum_{j \neq i} J_{ij} B_{ij} \frac{A_j}{A_i} \cos(\phi_{ij} + \theta_{ij})$$

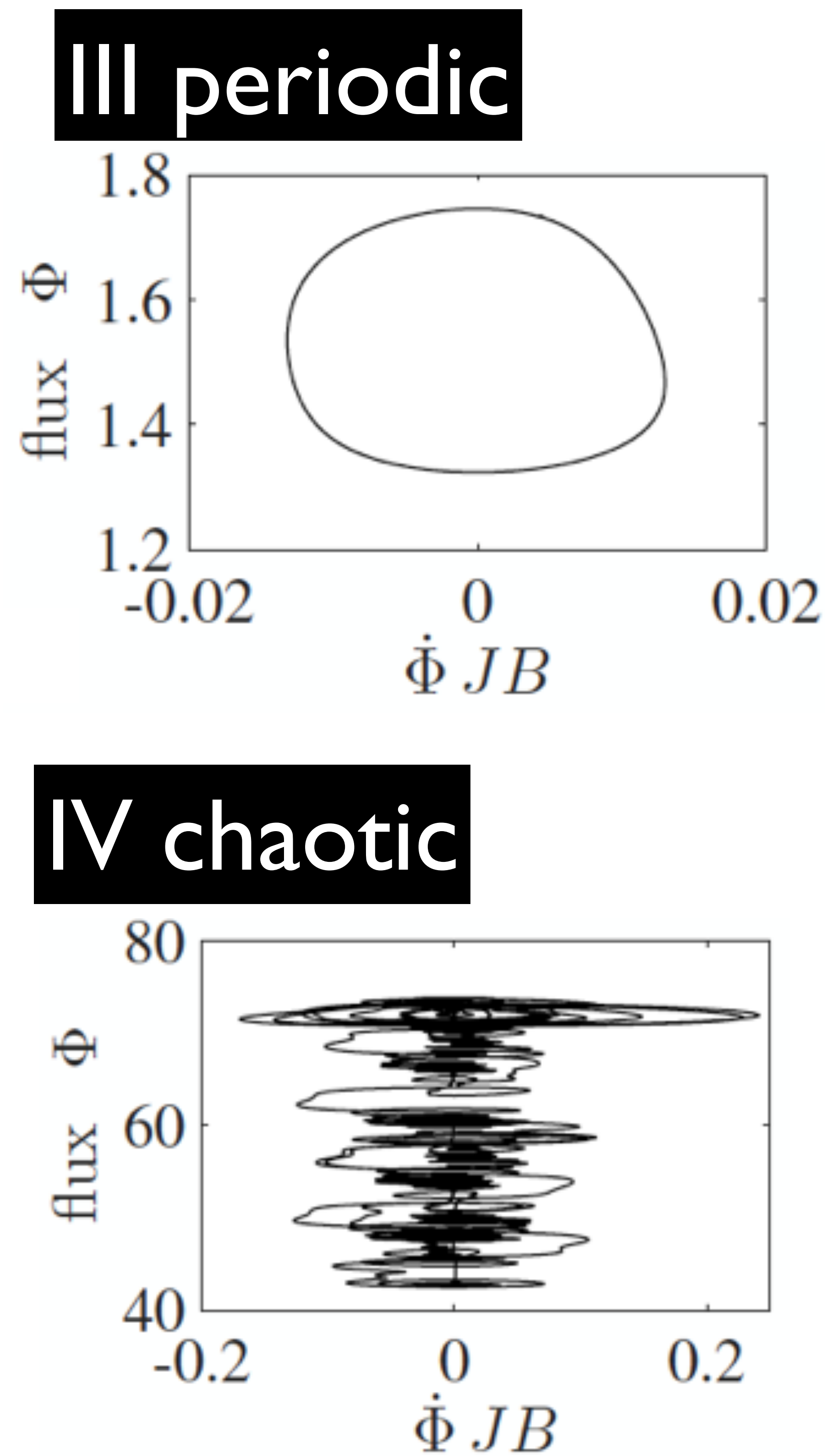
gauge transformation

$$\phi'_{ij} = \phi_{ij} + (\chi_j - \chi_i)$$

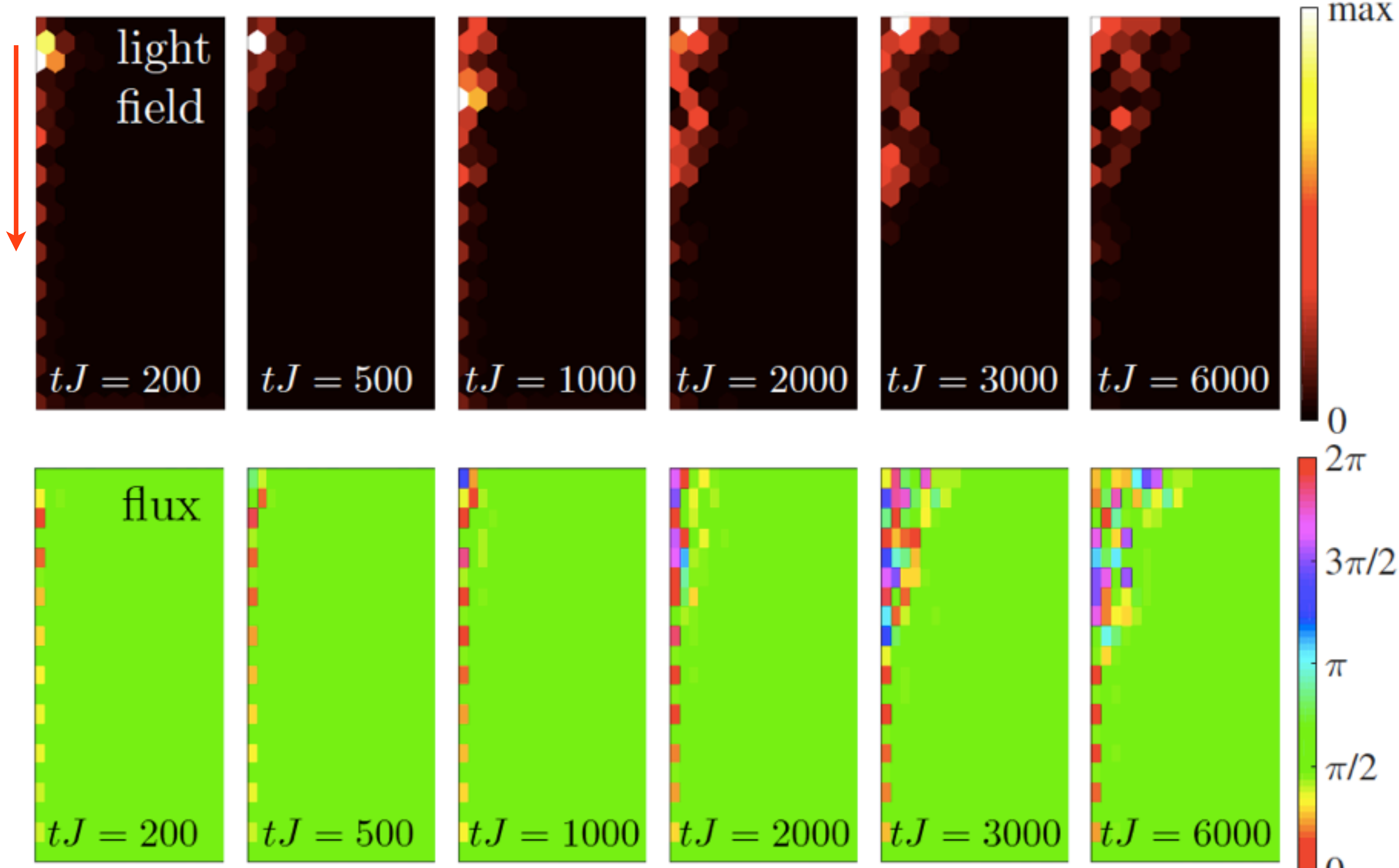
$$\theta'_i = \theta_i + \chi_i$$

Flux dynamics (3-site model)





Lattice: Photon flow reshapes flux



S. Walter and FM, in preparation

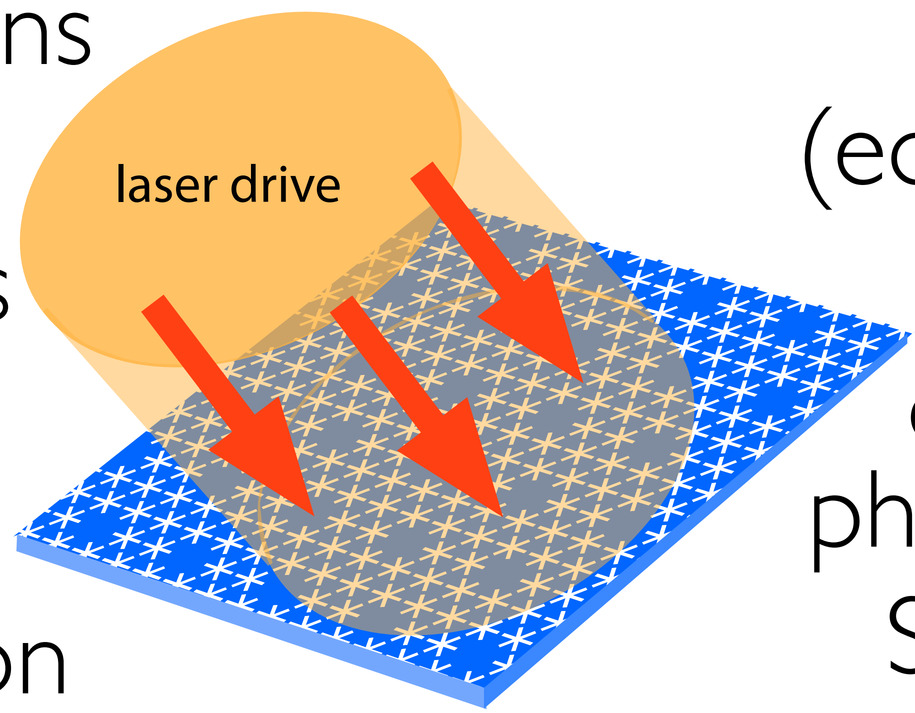
Optomechanical Arrays: Future possibilities

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)

more: see Oskar Painter's talk this afternoon!