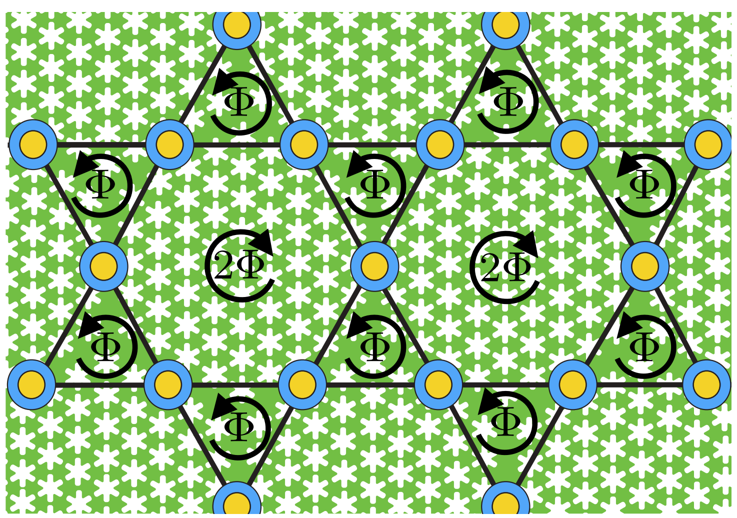
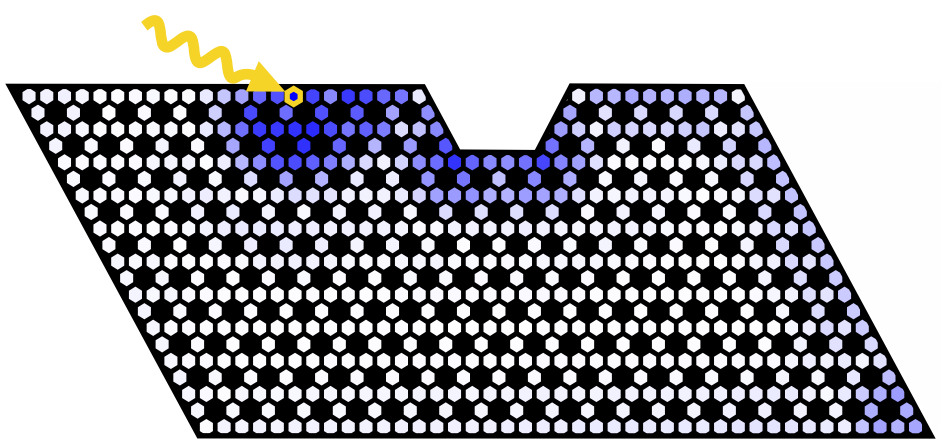
Tailoring the flow of of sound and light in an optomechanical array

Vittorio Peano, Christian Brendel, Michael Schmidt, Florian Marquardt
Friedrich-Alexander-Universität Erlangen-Nürnberg





transmission

Olomouc, Photons beyond qubits 2015

Johannes Kepler
De Cometis, 1619

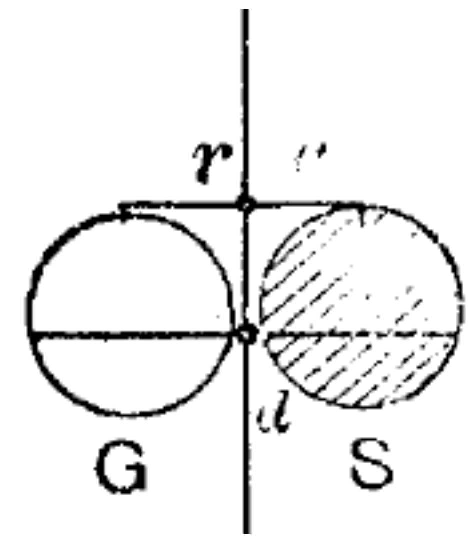
(Comet Hale-Bopp; by Robert Allevo)

Nichols and Hull, 1901
Lebedev, 1901

A PRELIMINARY COMMUNICATION ON THE PRESSURE OF HEAT AND LIGHT RADIATION.

BY E. F. NICHOLS AND G. F. HULL.

MAXWELL,[1] dealing mathematically with the stresses in an electro-magnetic field, reached the conclusion that "in a medium in which waves are propagated there is a pressure normal to the waves and numerically equal to the energy in unit volume."

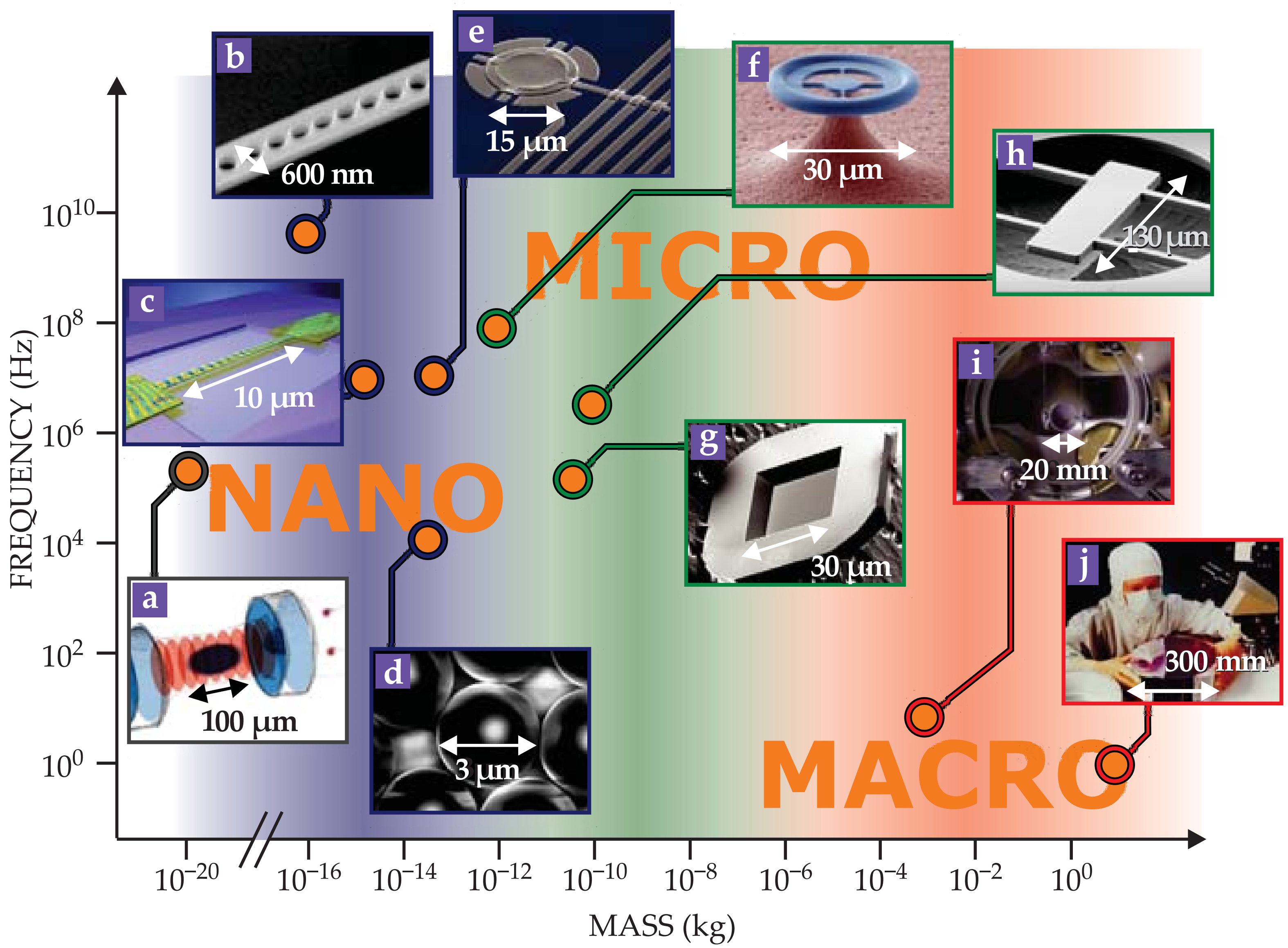


$$F = \frac{2I}{c}$$

Nichols and Hull, Physical Review **13**, 307 (1901)

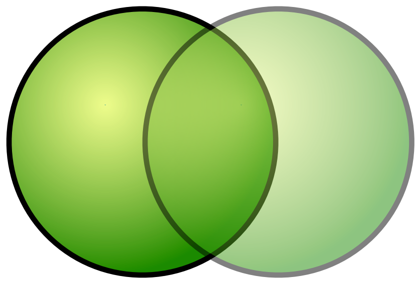
Optomechanics:

Interaction between photons and phonons is enhanced and can be tuned in situ by a laser

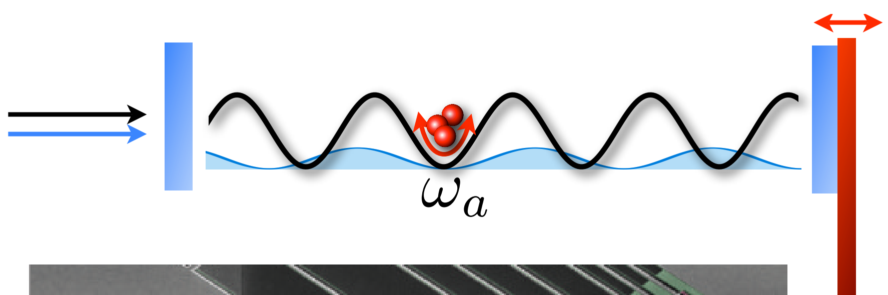


Aspelmeyer, Physics Today

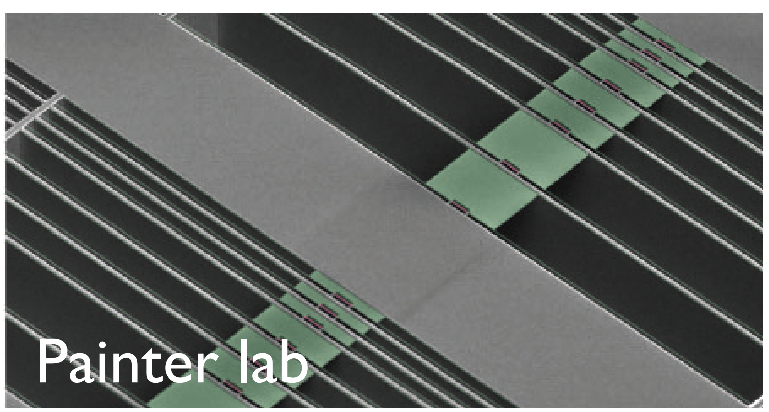
Optomechanics overlook:



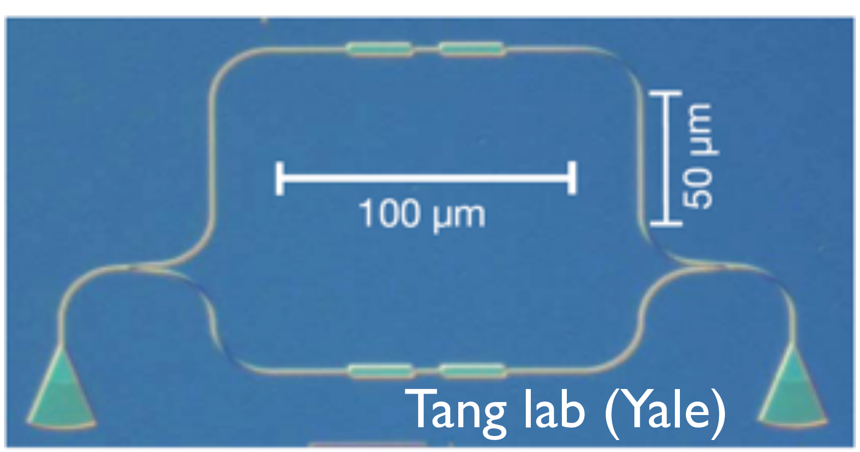
Fundamental tests of quantum mechanics in a new regime: entanglement with ‘macroscopic’ objects, unconventional decoherence? [e.g.: gravitationally induced?]



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



Precision measurements
small displacements, masses, forces, and accelerations



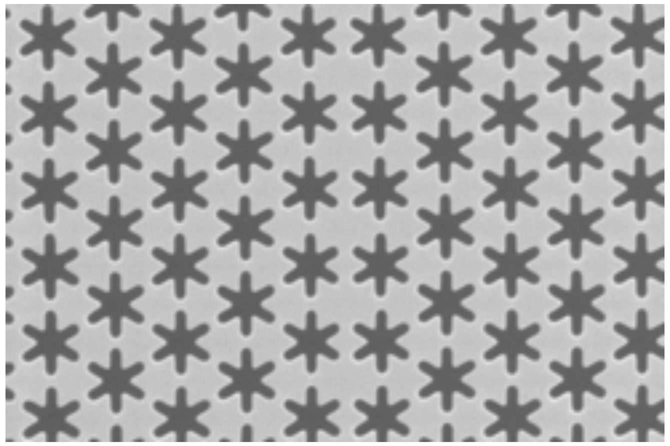
Optomechanical circuits & arrays
Exploit nonlinearities for classical and quantum information processing, storage, and amplification; study collective dynamics in arrays

VP, C. Brendel, M. Schmidt, and F. Marquardt, arXiv:1409.5375 (2014)

A topological state of sound and light

VP, C. Brendel, M. Schmidt, and F. Marquardt, arXiv:1409.5375 (2014)

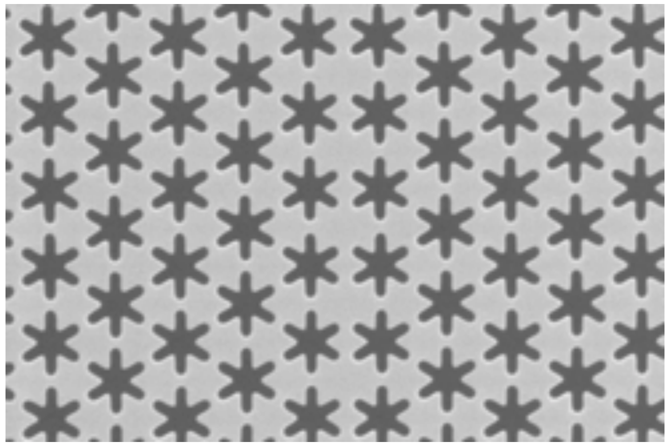
A topological state of sound and light



Dielectric (with the right pattern of holes)

a laser (with the right pattern of phases)

A topological state of sound and light



Dielectric (with the right pattern of holes)

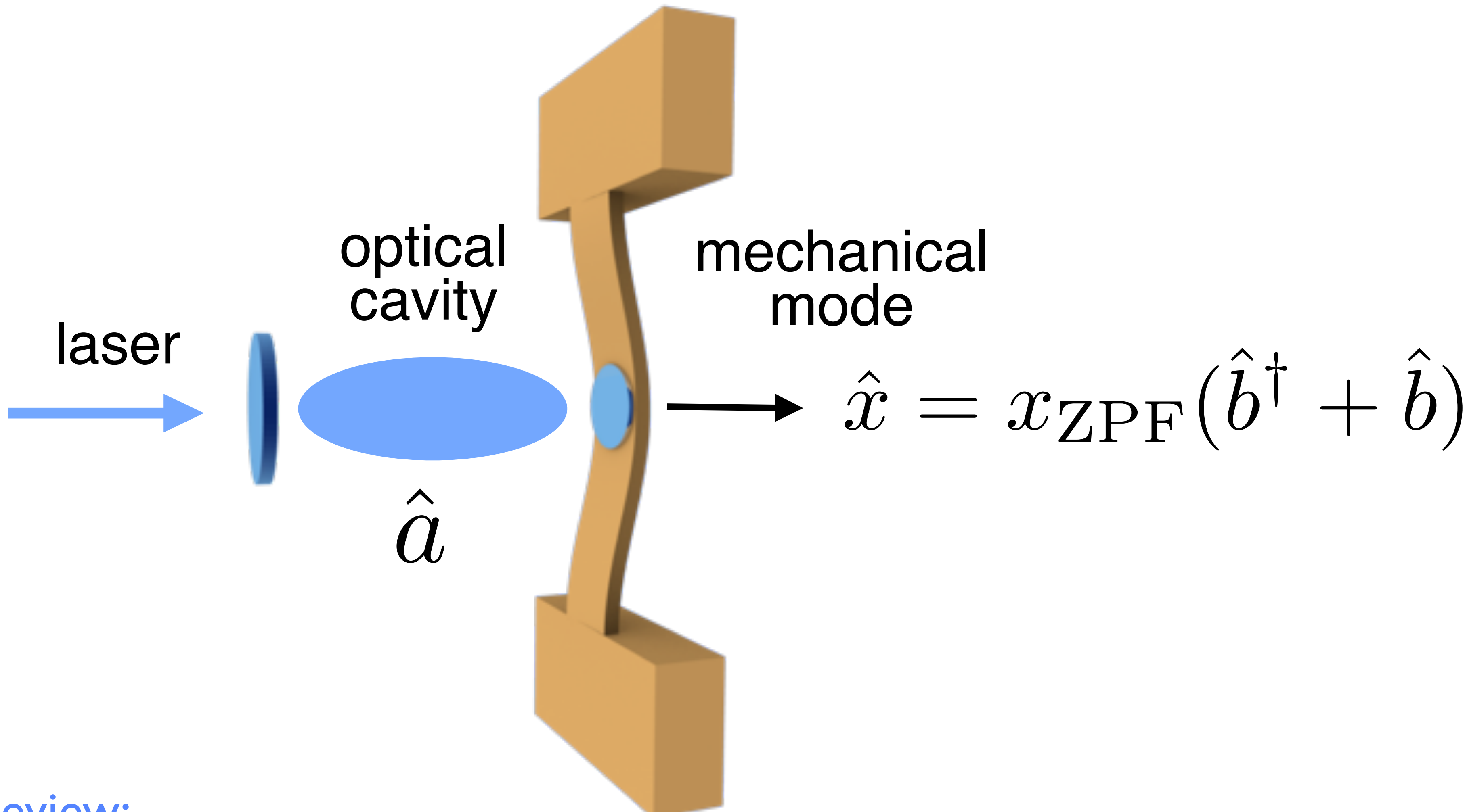
+

a laser (with the right pattern of phases)

nontrivial topology (a Chern insulator) created by the optomechanical interaction.

Basics of optomechanics

one mechanical mode and one optical mode interacting by radiation pressure



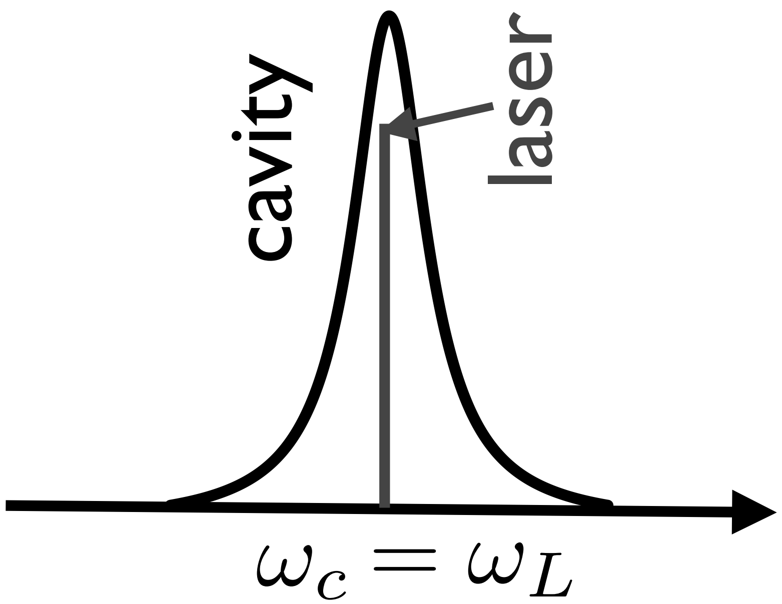
Review:
Aspelmeyer et. al RMP (2015)

Cavity resonant frequency depends on oscillator position

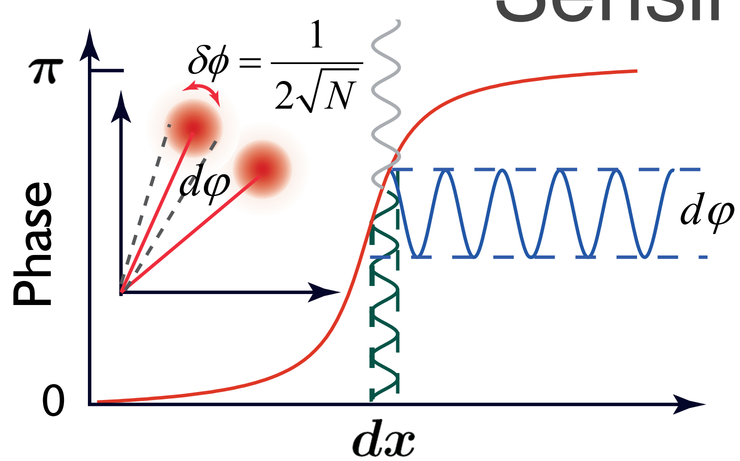
$$\hat{H} = \hbar\omega_c(1 - \hat{x}/L)a^\dagger a + \hbar\Omega b^\dagger b$$

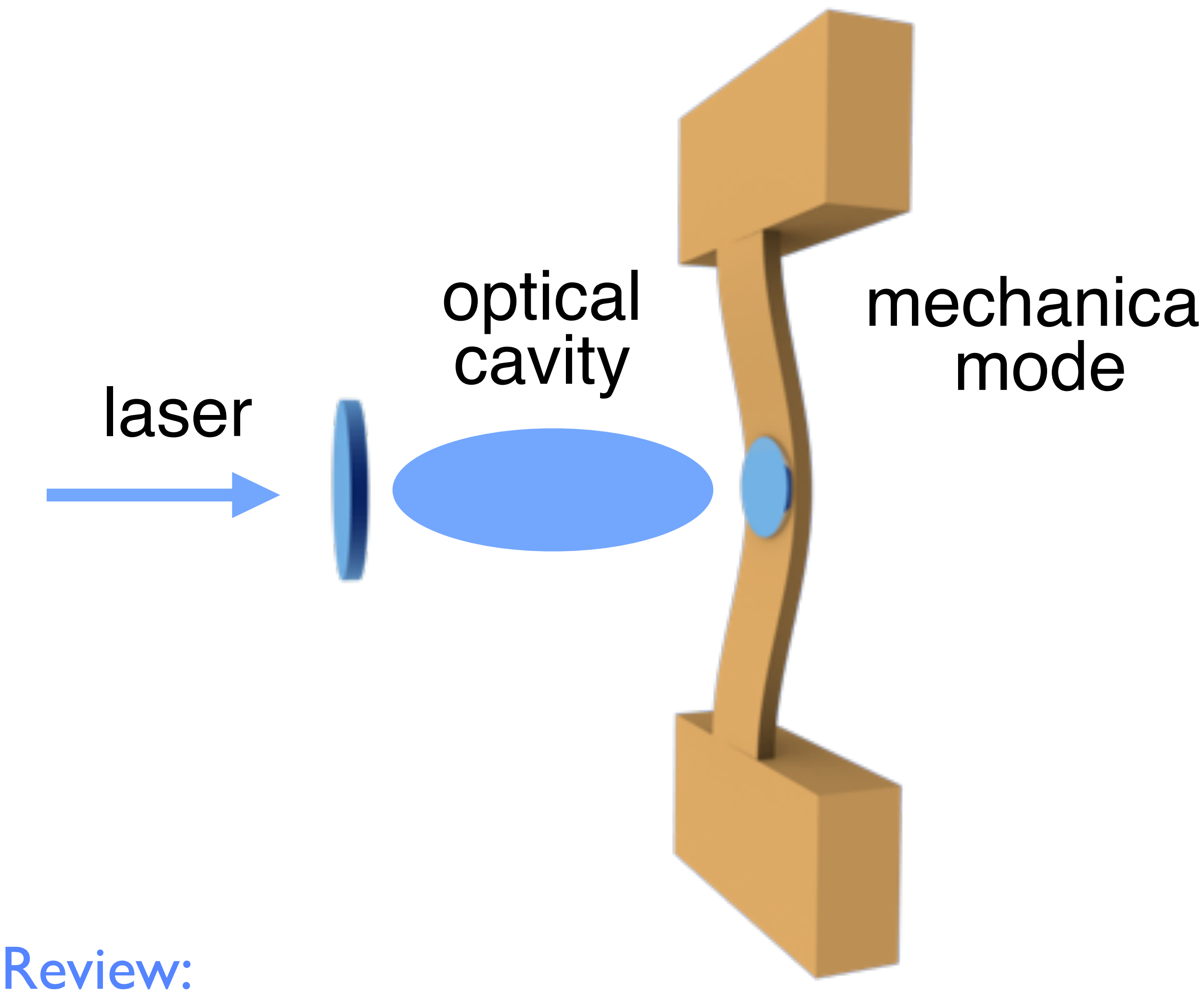
Single mode optomechanics

one mechanical mode and one optical mode interacting by radiation pressure



Sensing





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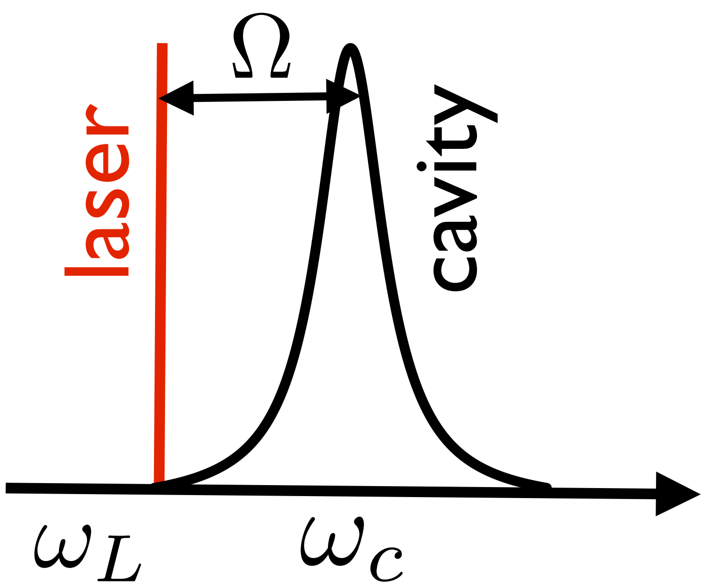
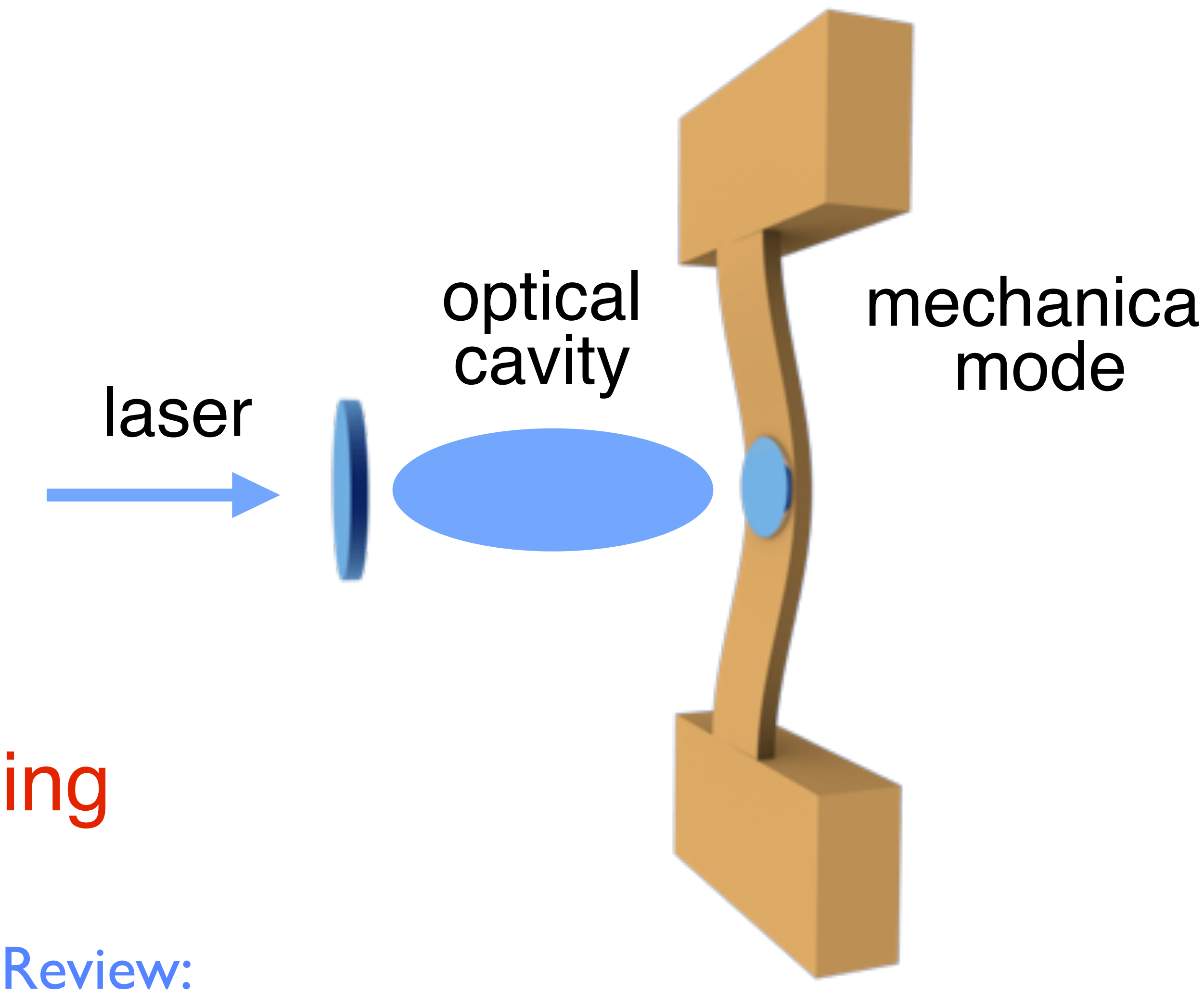
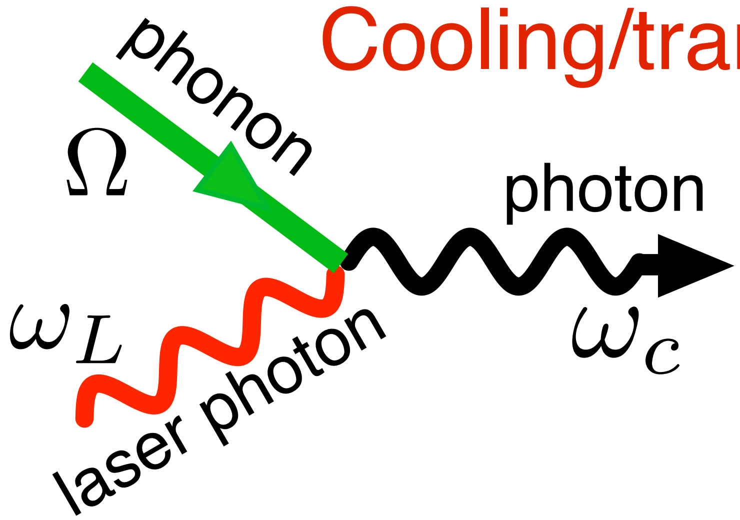




Cooling/transducing



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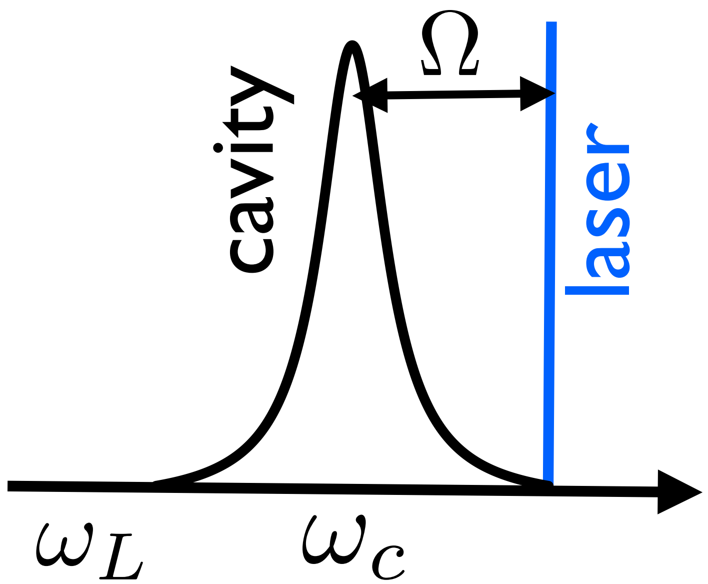
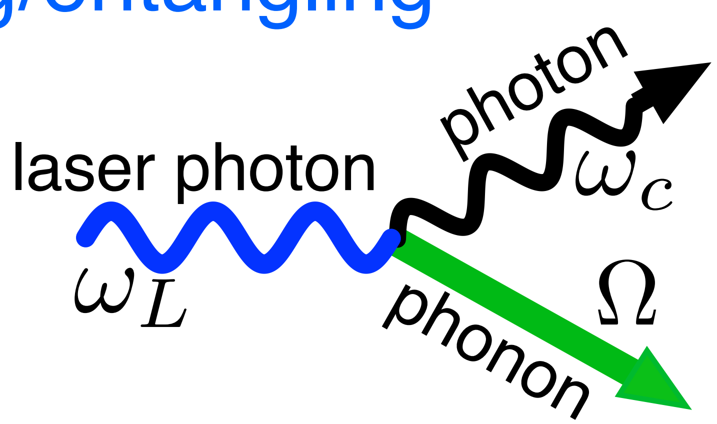
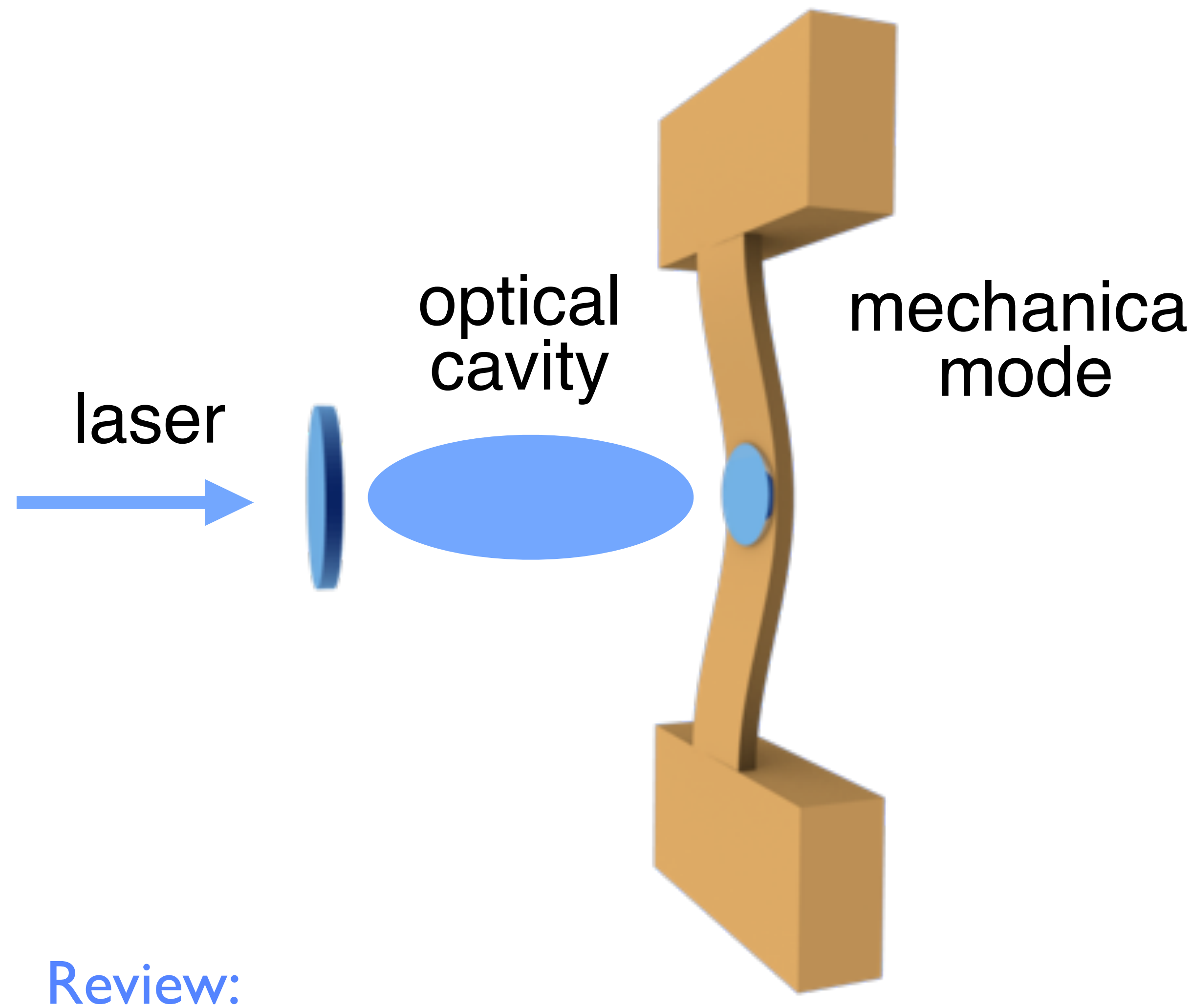


lasing/entangling





Review:
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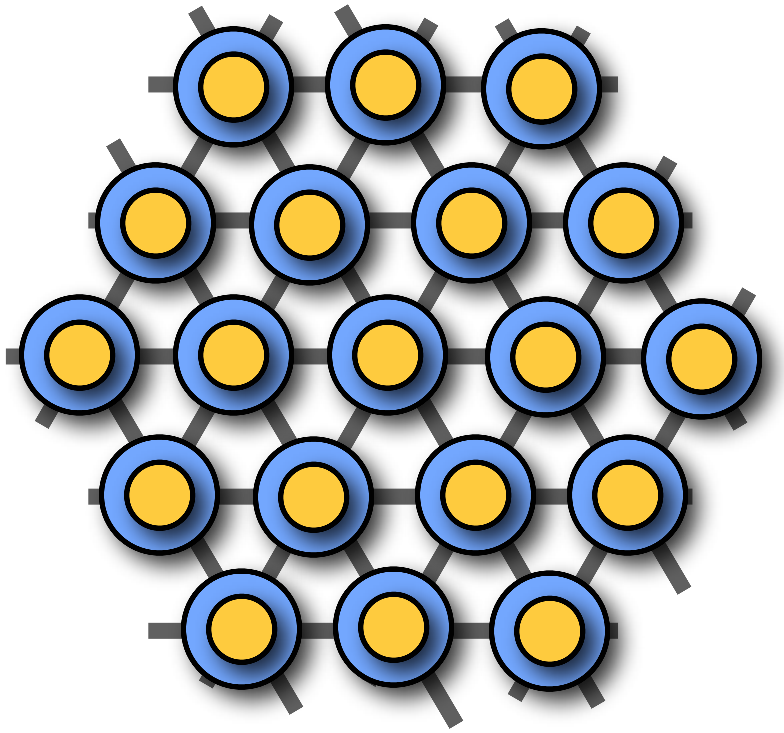
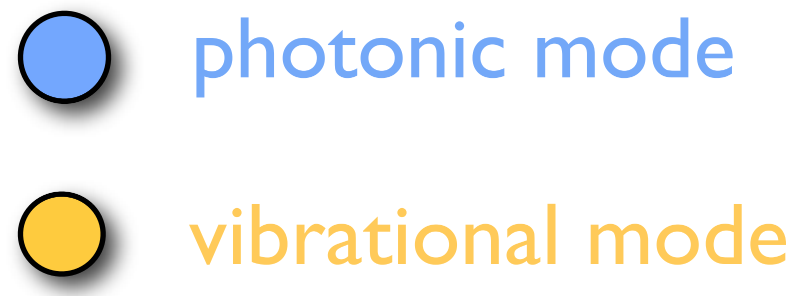
Optomechanical arrays

a periodic arrangement of optomechanical modes





photons and phonons hop between different sites as the localized modes have an evanescent coupling

Properties and functionalities determined by the geometry but also by driving fields!

Flow of photons and phonon tailored by laser drive

Optomechanical arrays would combine advantages of photonics

[excitations can be injected and read off locally (or momentum resolved) allowing stationary transport situations]

...and tunability rivaling cold atoms in optical lattices

laser wavefront engineering allows to tune phase and amplitude of OM coupling to realize

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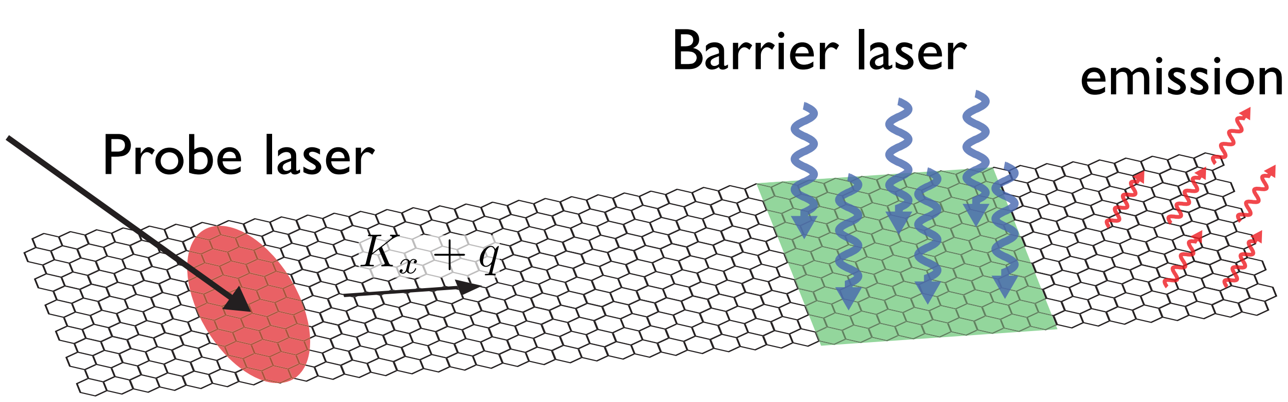
e. g. Klein tunneling for photons and phonons



M. Schmidt, VP, and F. Marquardt, NJP (2015)

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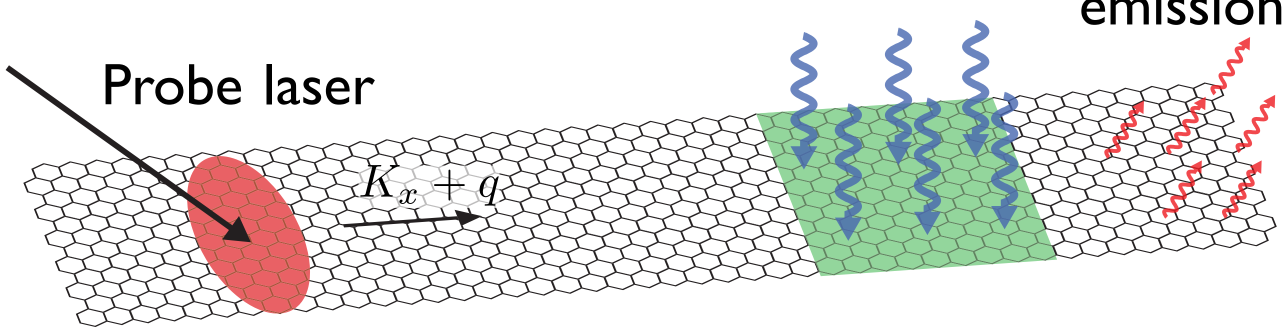
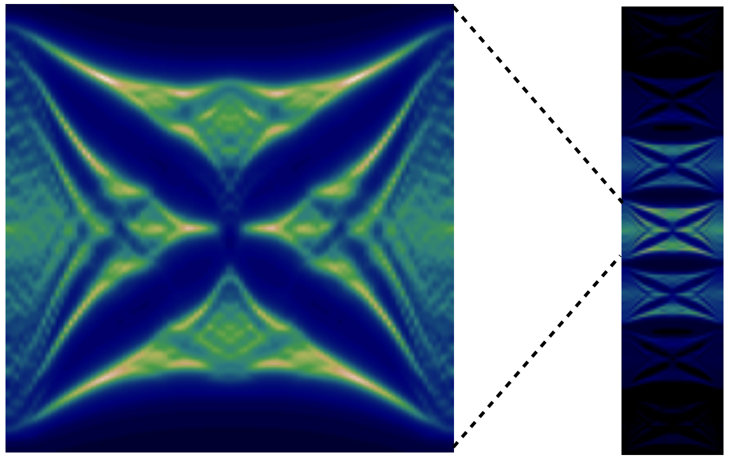


M. Schmidt, VP, and F. Marquardt, NJP (2015)

- nontrivial topologies/ synthetic gauge fields



M. Schmidt, S. Kessler, VP, O. Painter, and F. Marquardt, arXiv:1502.0764

VP, C. Brendel, M. Schmidt, and F. Marquardt, arXiv:1409.5375 (2014)

A topological state of sound and light?

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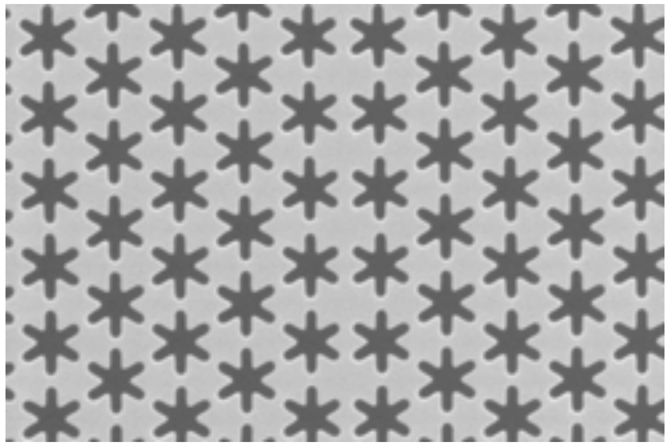

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a laser (with the right pattern of phases)

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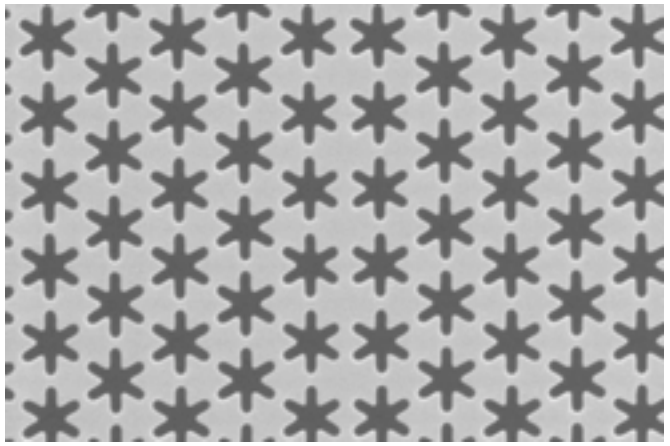


Dielectric (with the right pattern of holes)

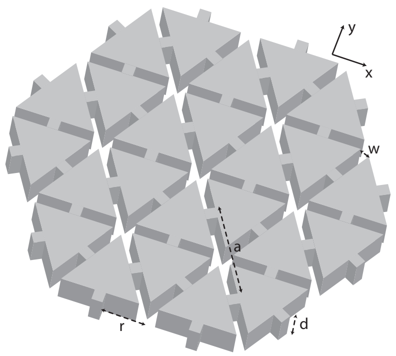
+

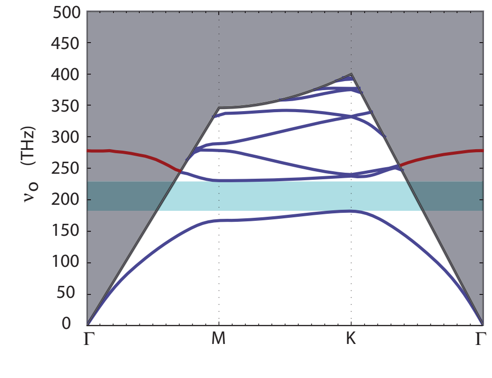
a laser (with the right pattern of phases)

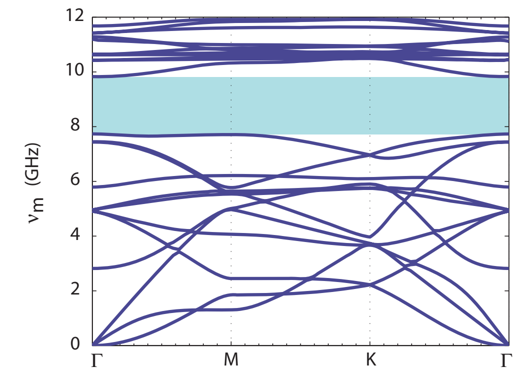
nontrivial topology (a Chern insulator) created by the optomechanical interaction.

An optomechanical array
based on an optomechanical crystal

Patterned dielectric slab (e.g. silicon) with coexisting optical and mechanical band gap forms an OM crystal

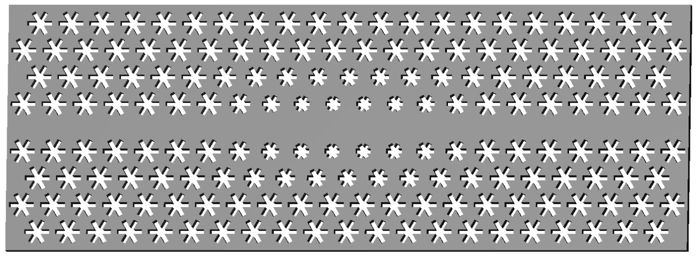


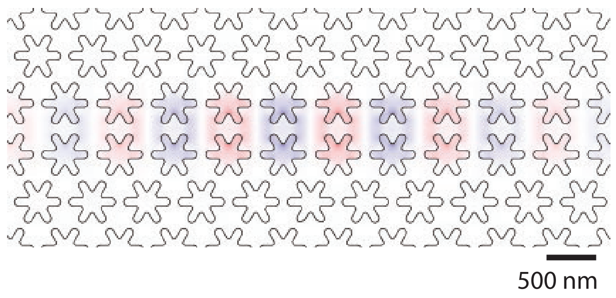




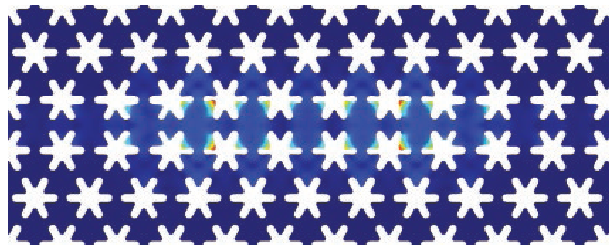
A defect creates optomechanical building block: a pair of co-localized optical and vibrational modes

Naeini et. al., PRL (2014)





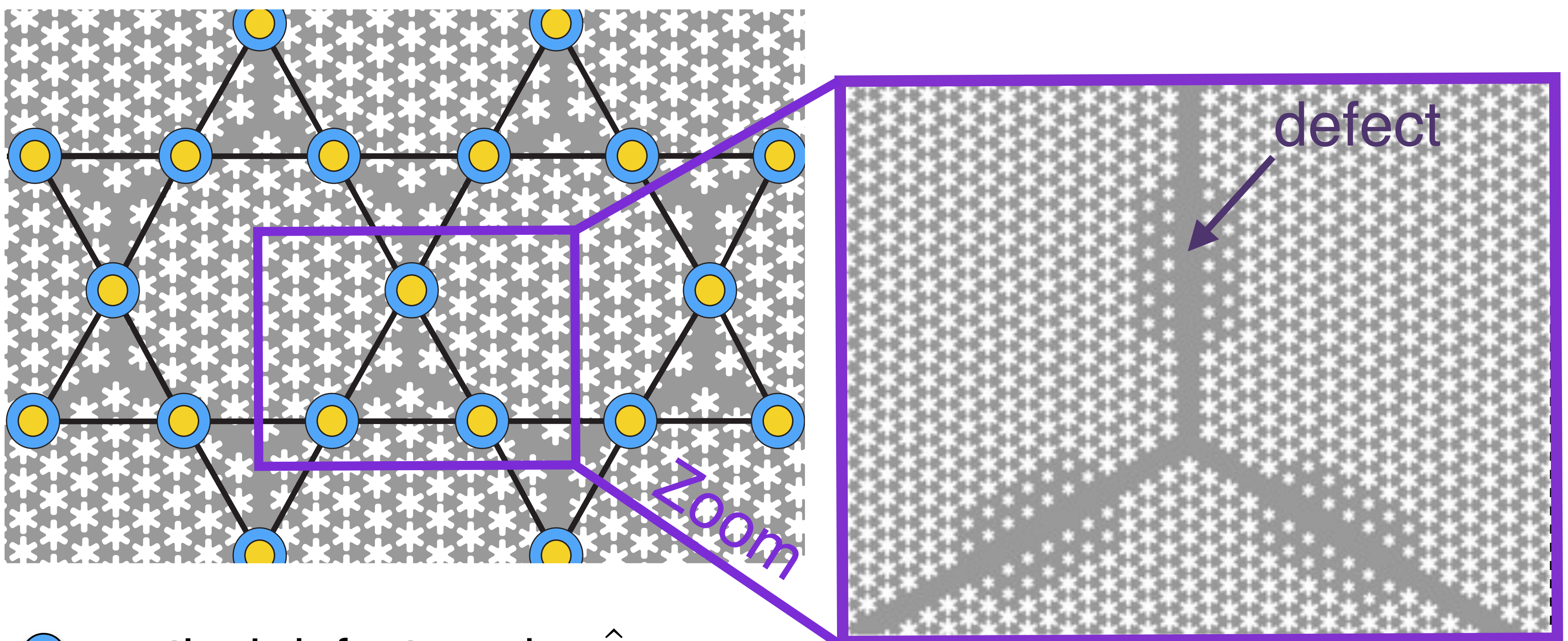
Optical defect mode



Mechanical defect mode

A periodic arrangement of defects forms an optomechanical array

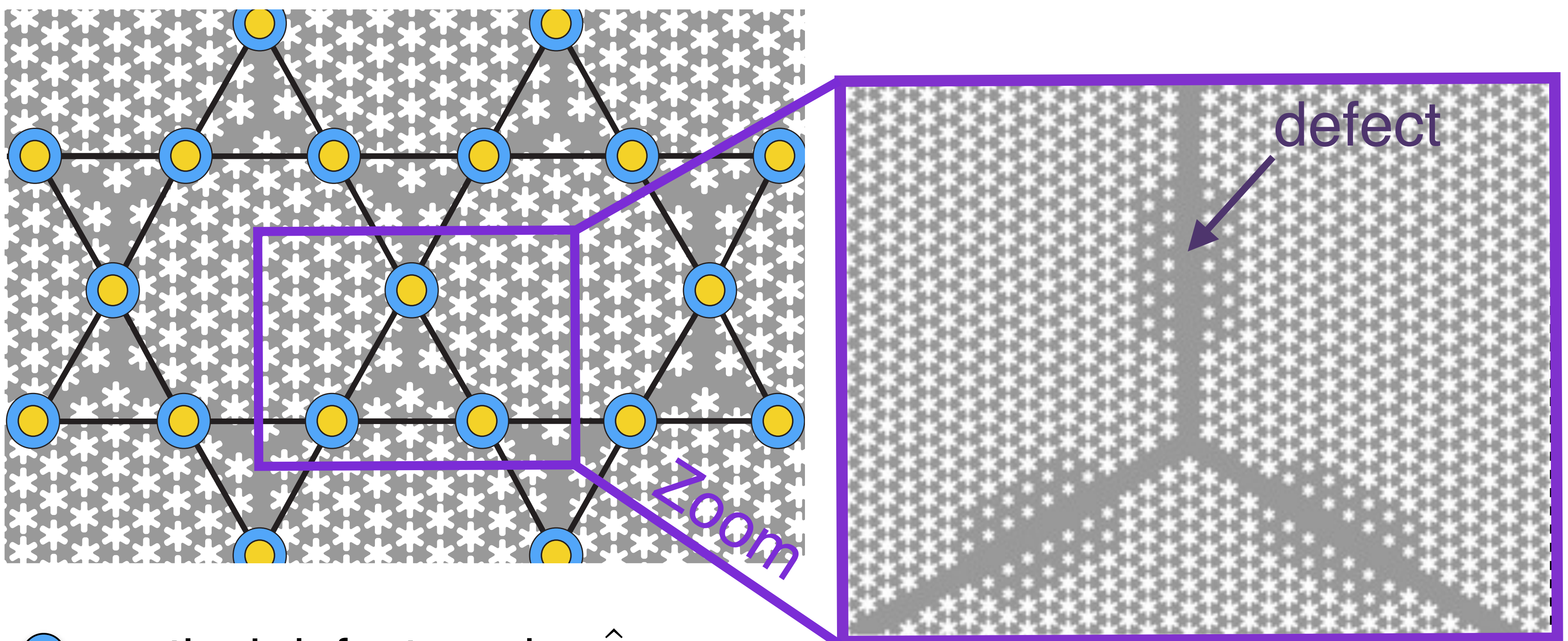
Optomechanical arrays



optical defect mode $\hat{a}_j$

mechanical defect mode $\hat{b}_j$

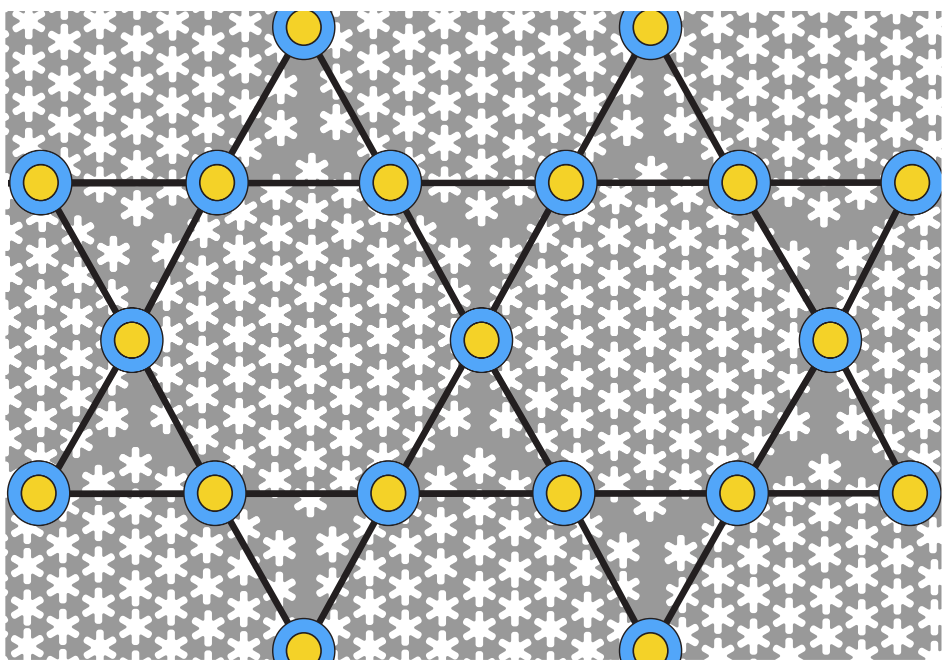
Optomechanical arrays



optical defect mode $\hat{a}_j$
mechanical defect mode $\hat{b}_j$

- photons and phonons hop between different sites as the local *Wannier* modes have an evanescent coupling

Optomechanical arrays



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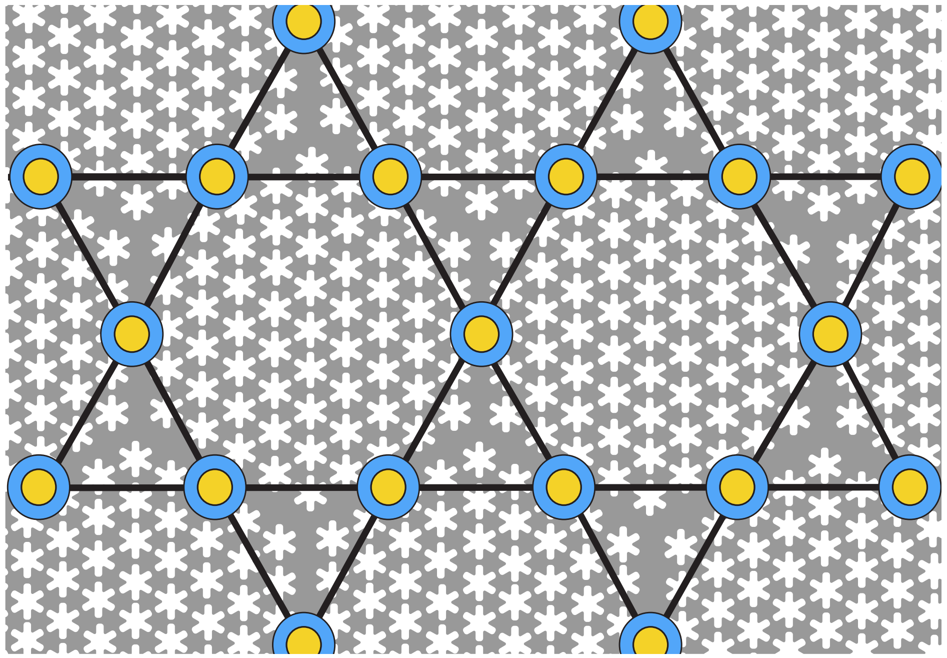

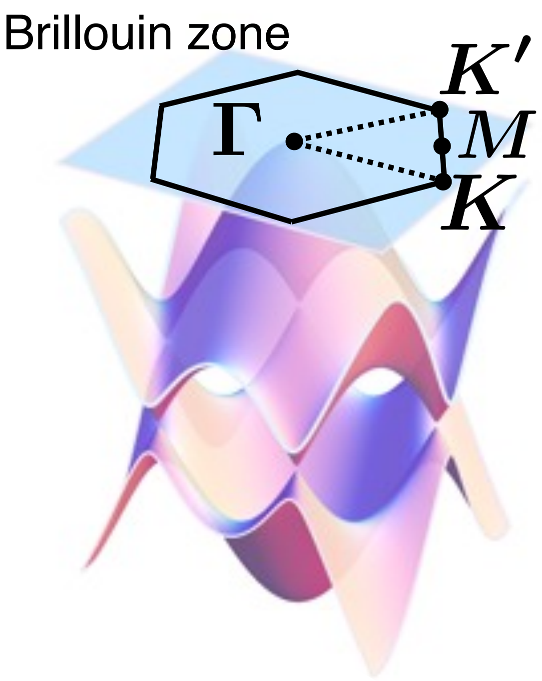

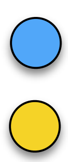

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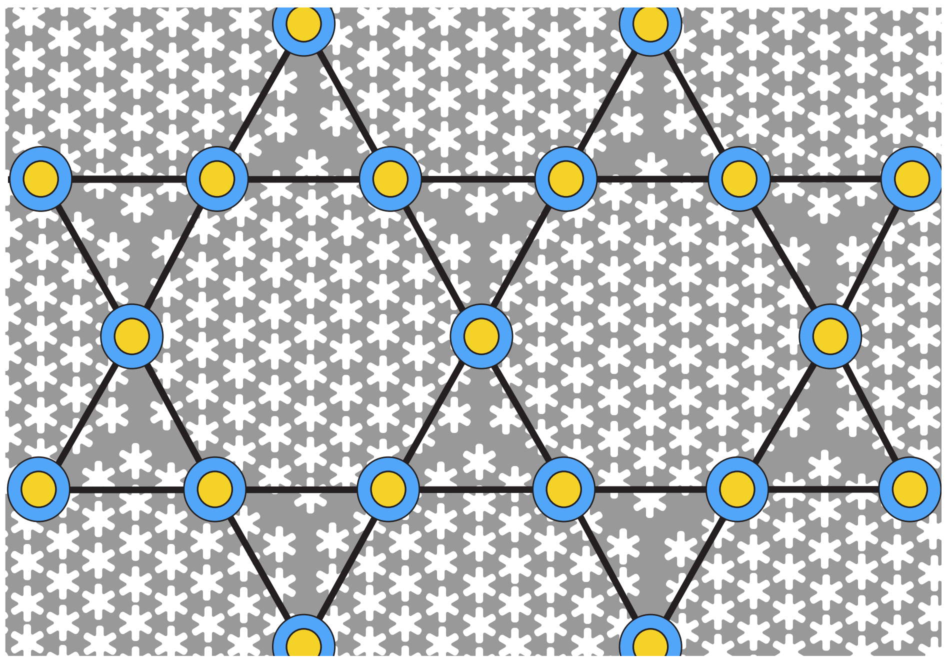
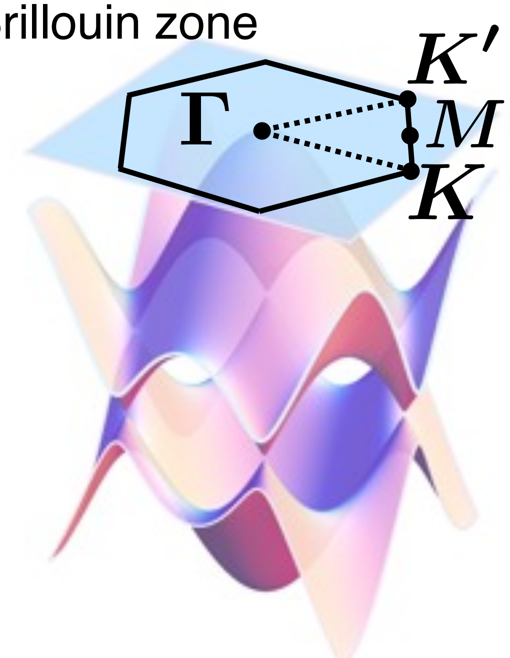
- symmetry: optical and mechanical band strucures have Dirac cones

Optomechanical arrays



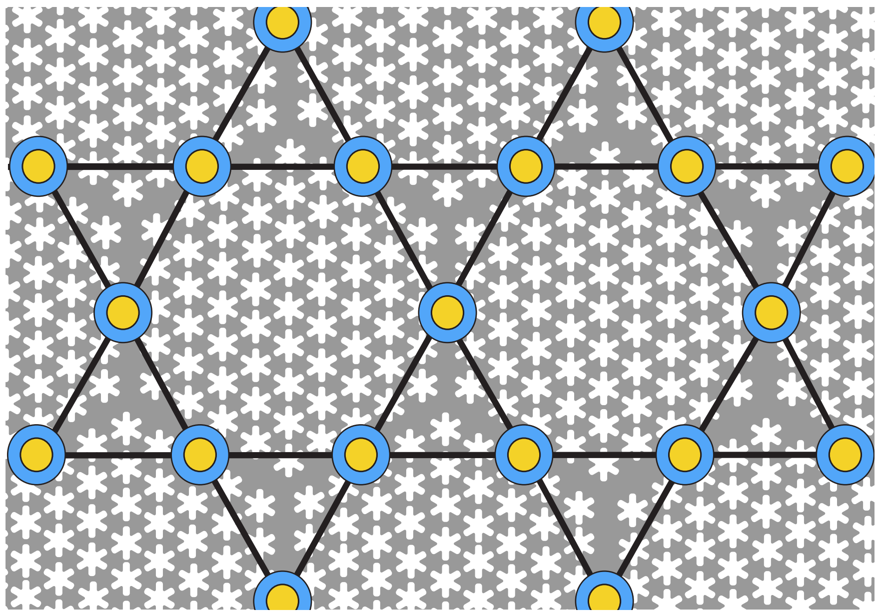


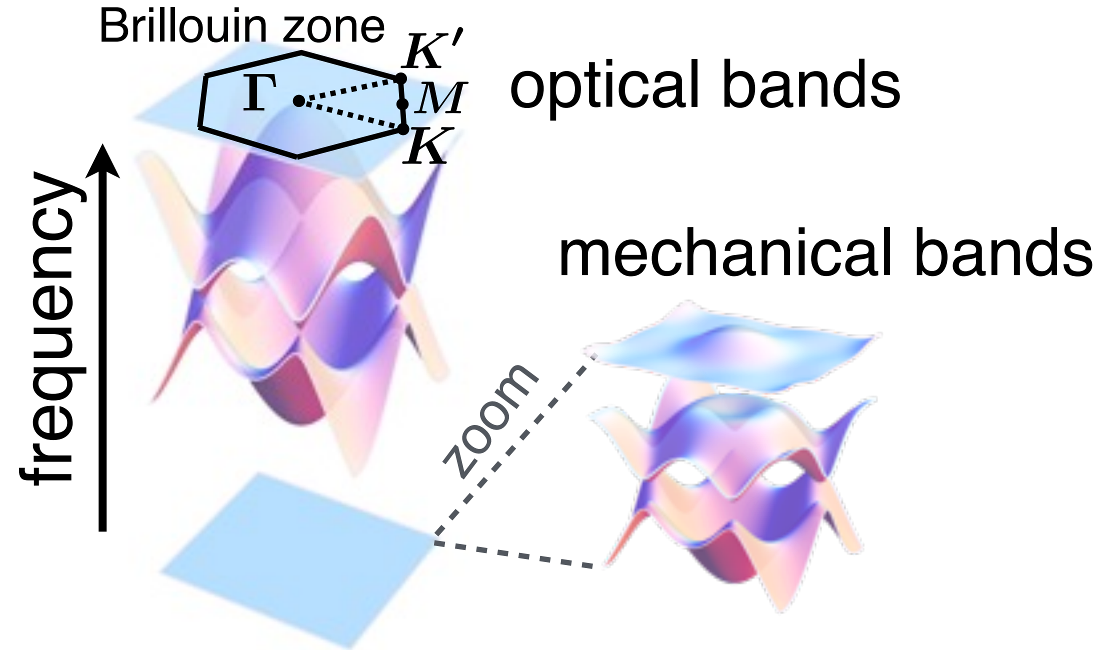
- optical defect mode $\hat{a}_j$
- mechanical defect mode $\hat{b}_j$

- photons and phonons hop between different sites as the local *Wannier* modes have an evanescent coupling
- symmetry: optical and mechanical band strucures have Dirac cones
- onsite radiation pressure interaction between photons and phonons

$$\hat{H}_{\mathrm{OM}} = \hbar g_0 \hat{a}_j^\dagger \hat{a}_j (\hat{b}_j + \hat{b}_j^\dagger)$$

Optomechanical arrays



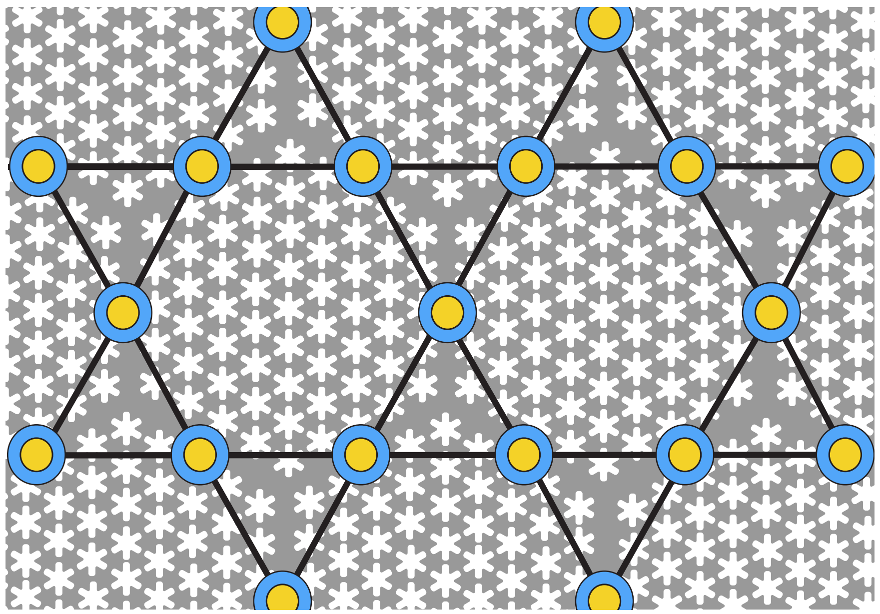


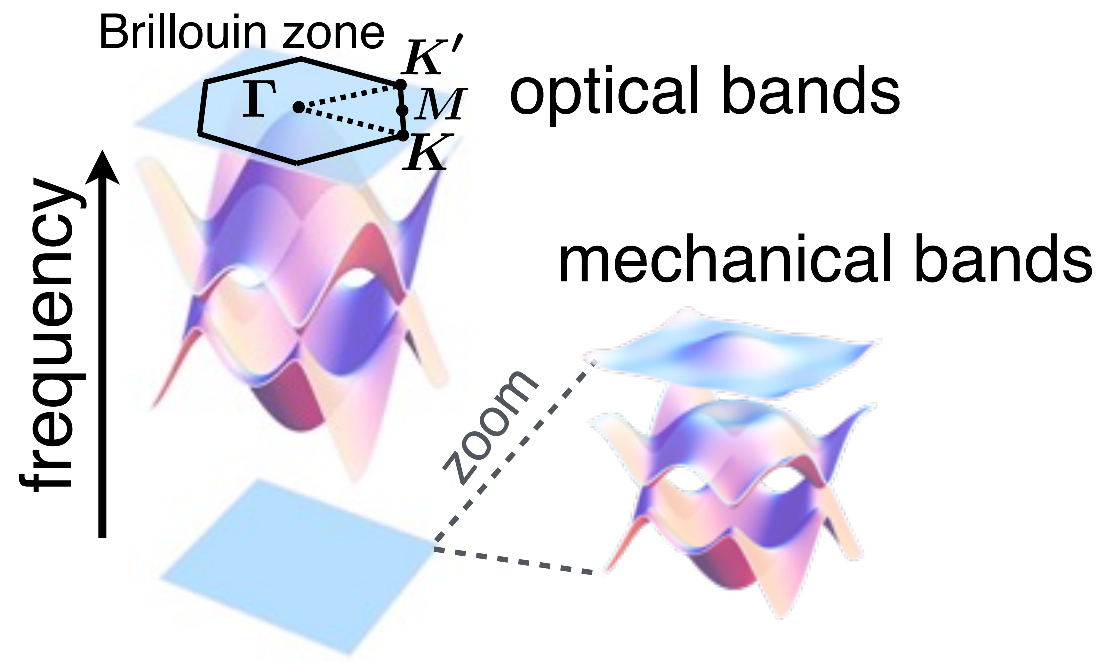
optical defect mode $\hat{a}_j = \alpha_j + \delta\hat{a}_j$

mechanical defect mode $\hat{b}_j = \beta_j + \delta\hat{b}_j$

with a laser: steady light amplitudes α_j and radiation pressure induced mechanical displacements β_j

Optomechanical arrays





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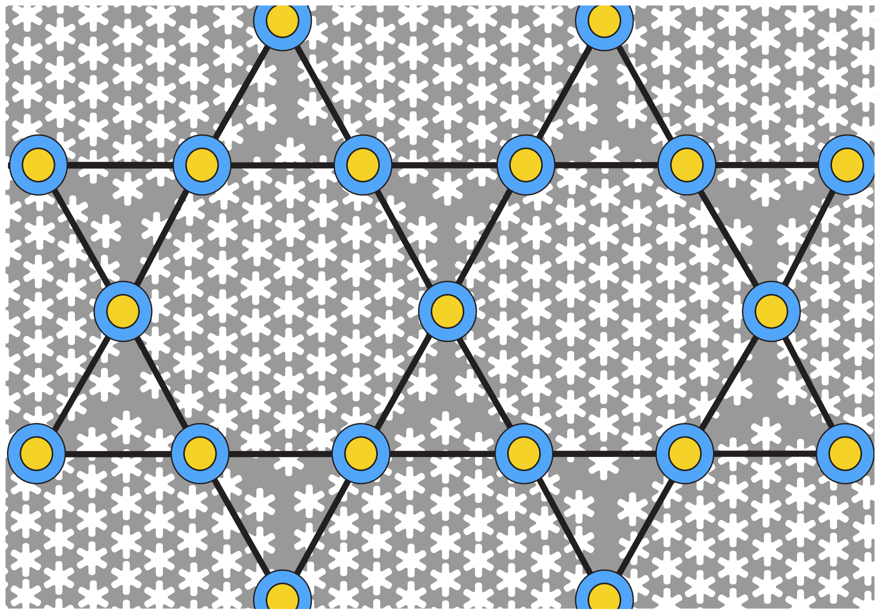
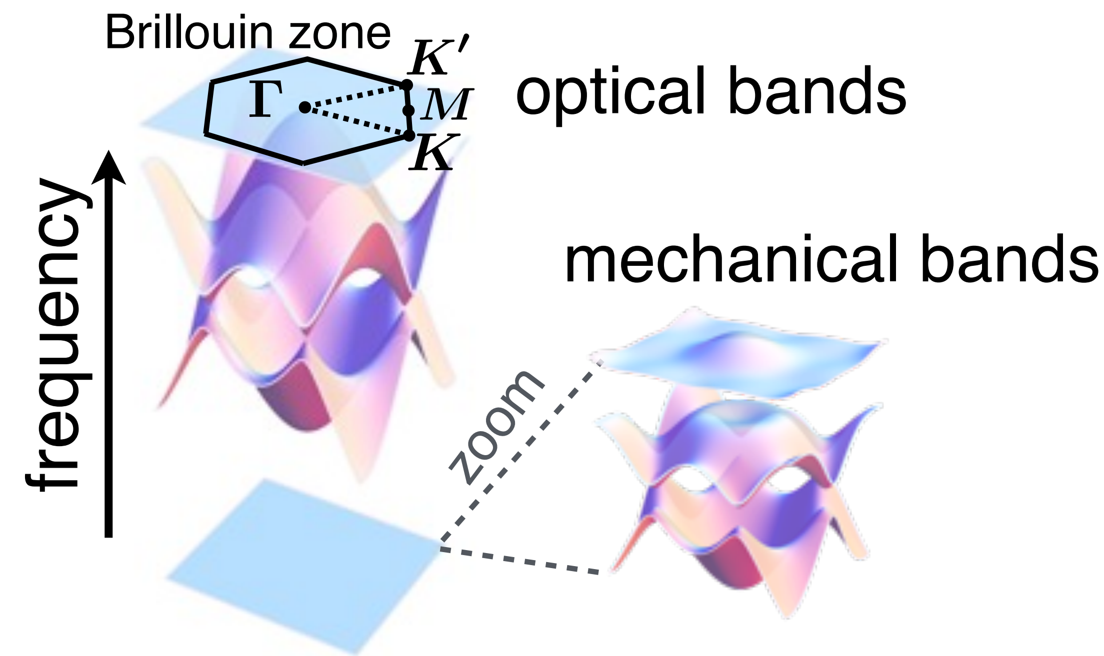
$g_j = g_0\alpha_j$

linearized OM interaction: $\hat{H}_{\mathrm{OM}} \approx \hbar(g_j\delta\hat{a}_j^\dagger\delta\hat{b}_j + g_j\delta\hat{a}_j^\dagger\delta\hat{b}_j^\dagger + h.c.)$

Optomechanical arrays





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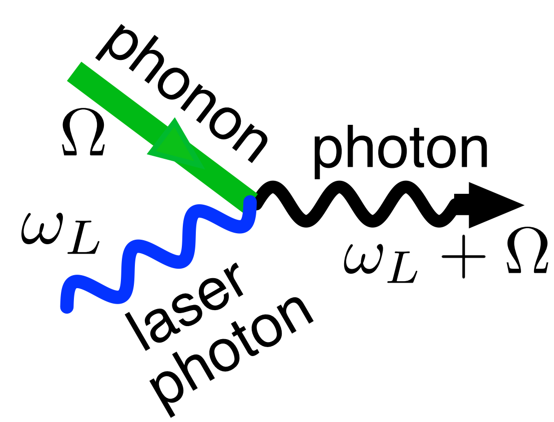
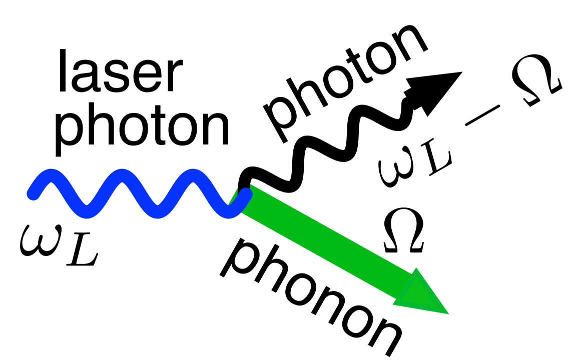
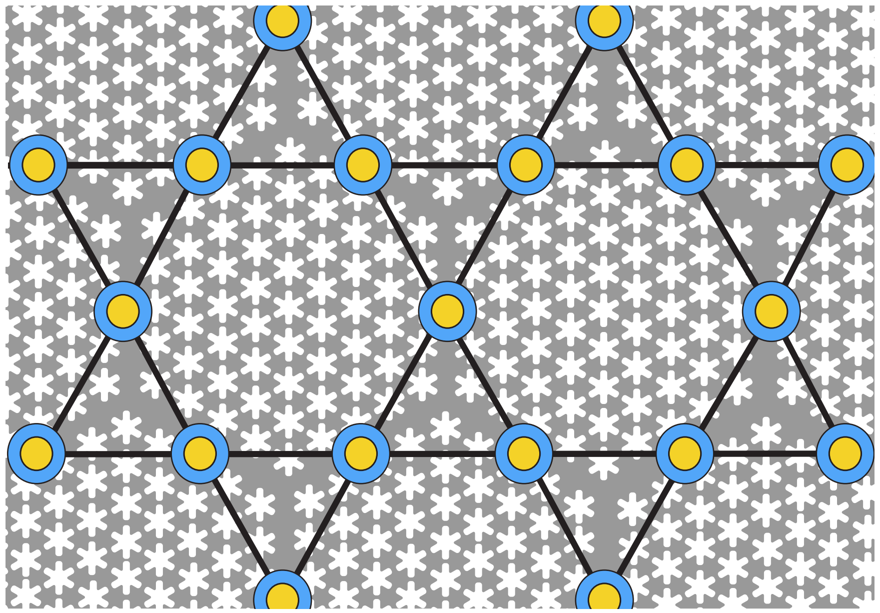
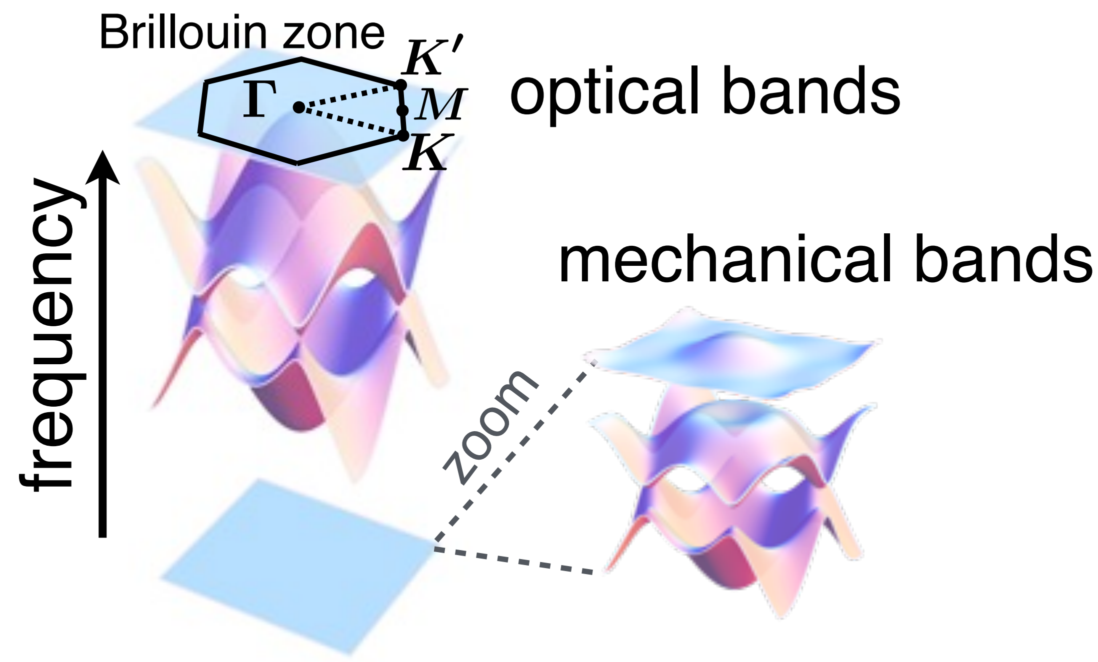
Raman scattering:





Optomechanical arrays





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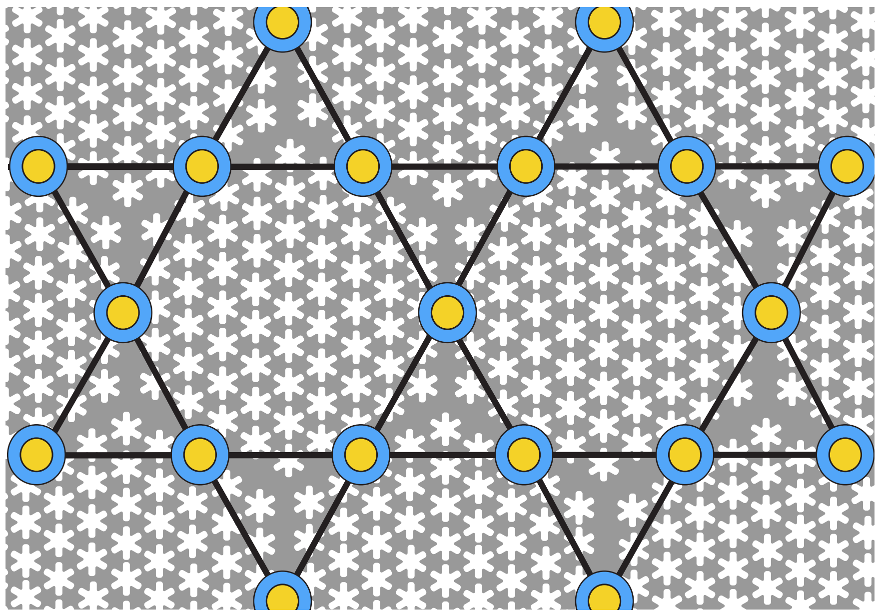
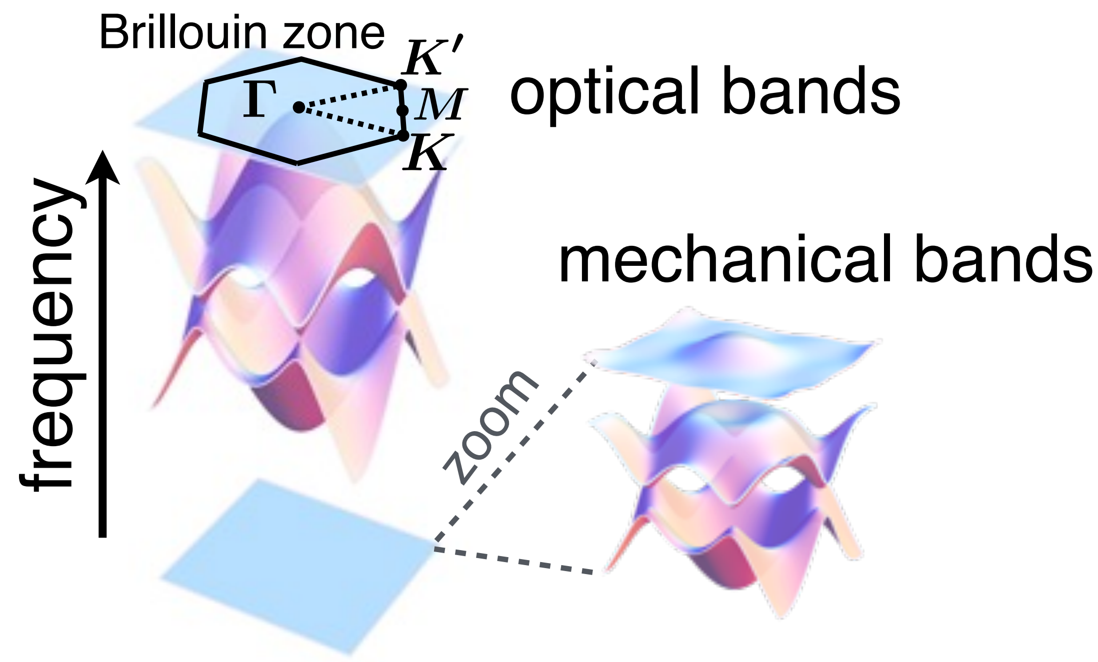
Optomechanical arrays





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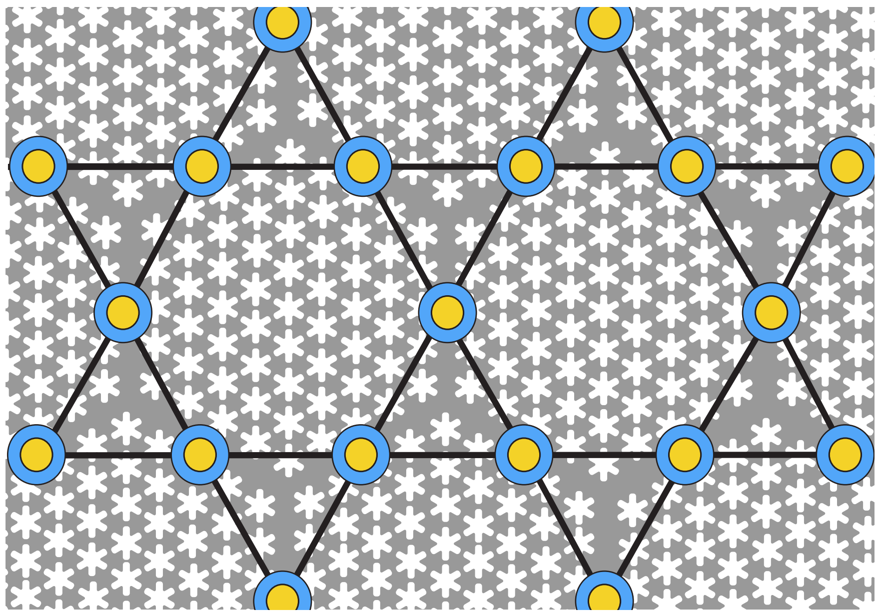
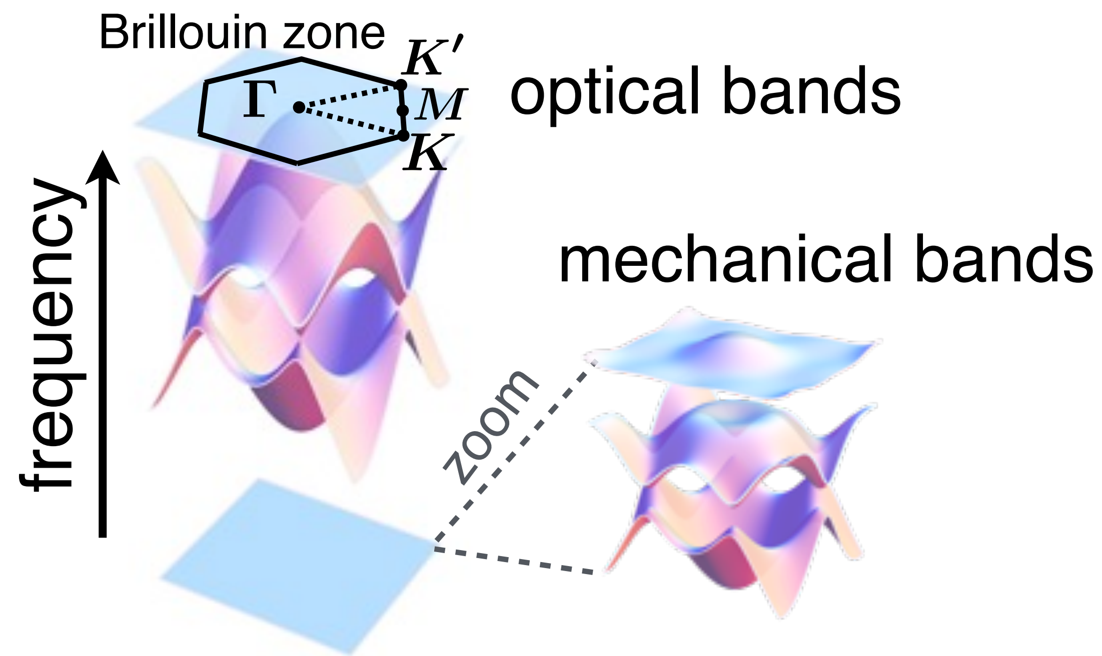
Non-trivial topology induced by OM coupling with a pattern of phases imprinted by the laser $g_j = ge^{i\phi_j}$

Optomechanical arrays





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with a laser: steady light amplitudes α_j and radiation pressure induced mechanical displacements β_j

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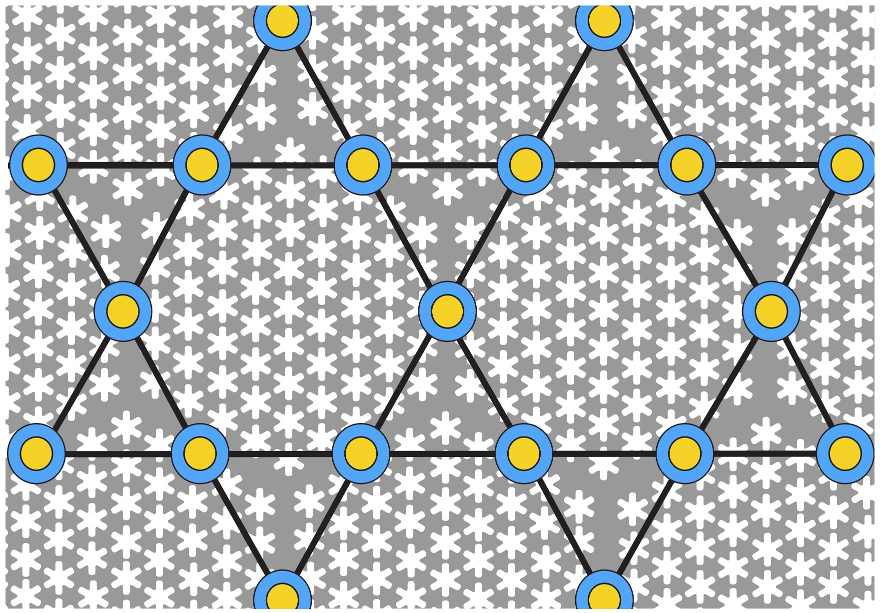

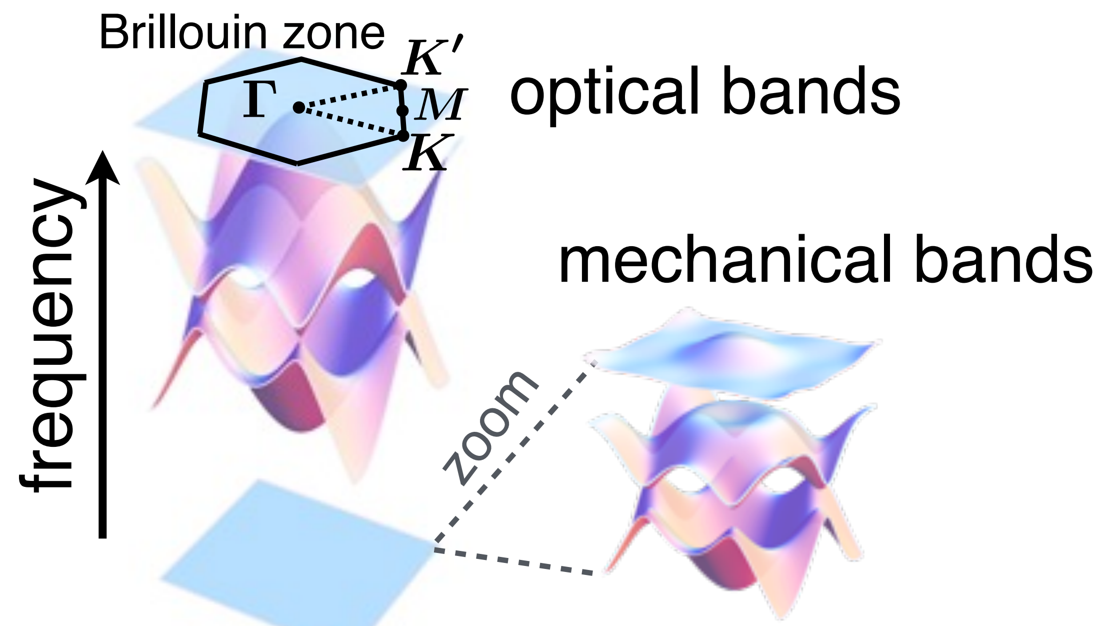

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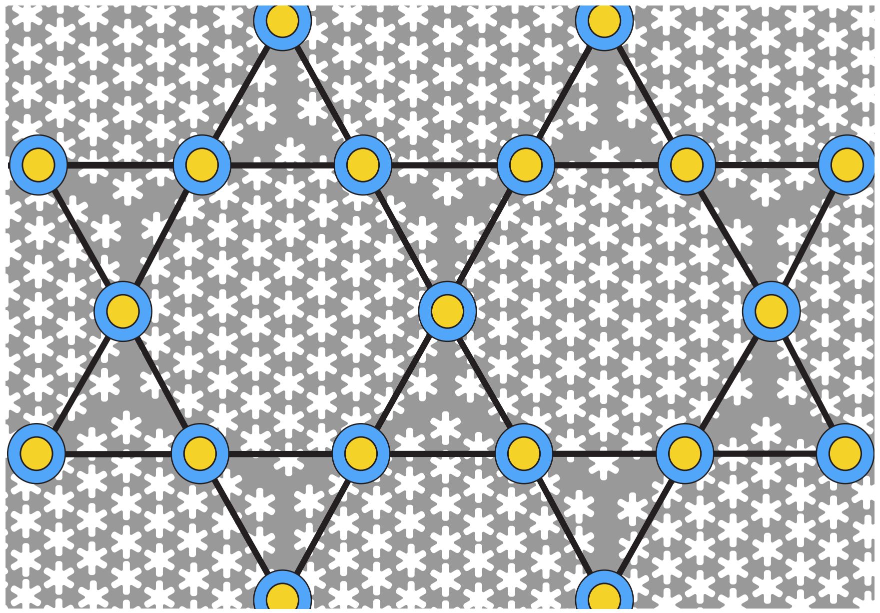

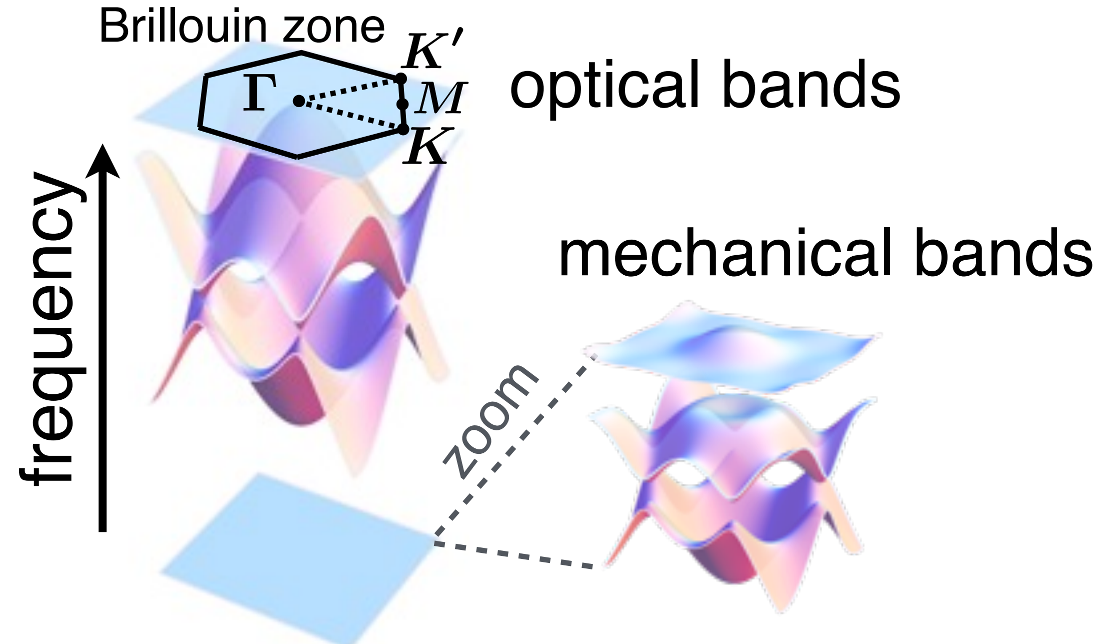

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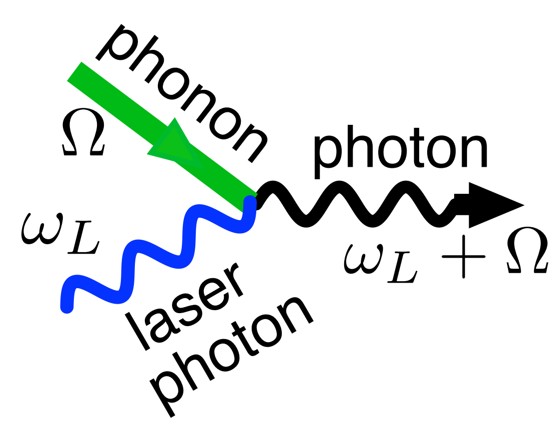
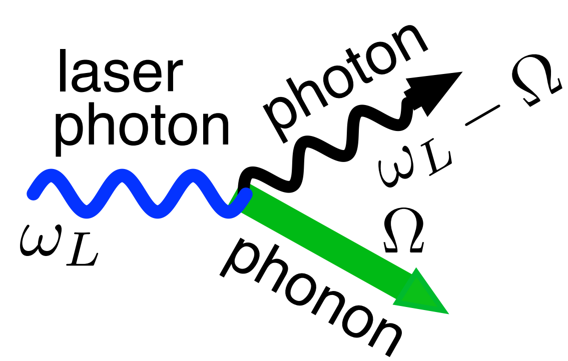
Raman scattering:





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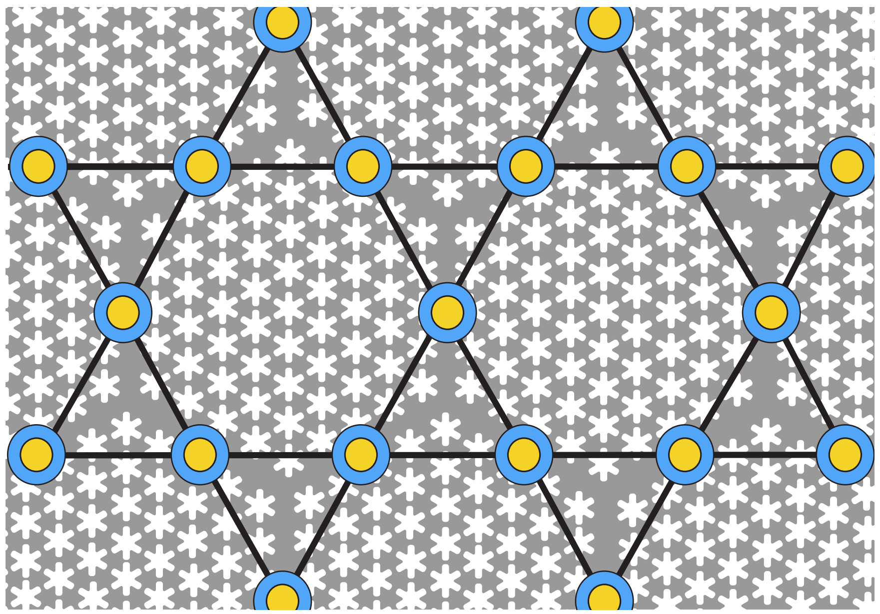

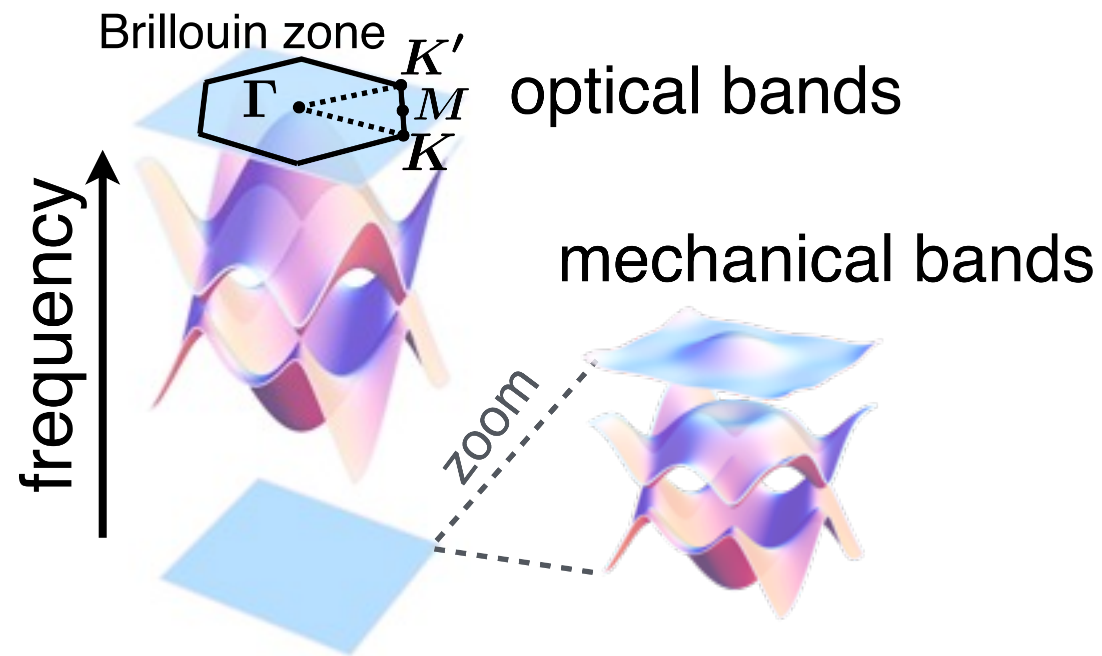

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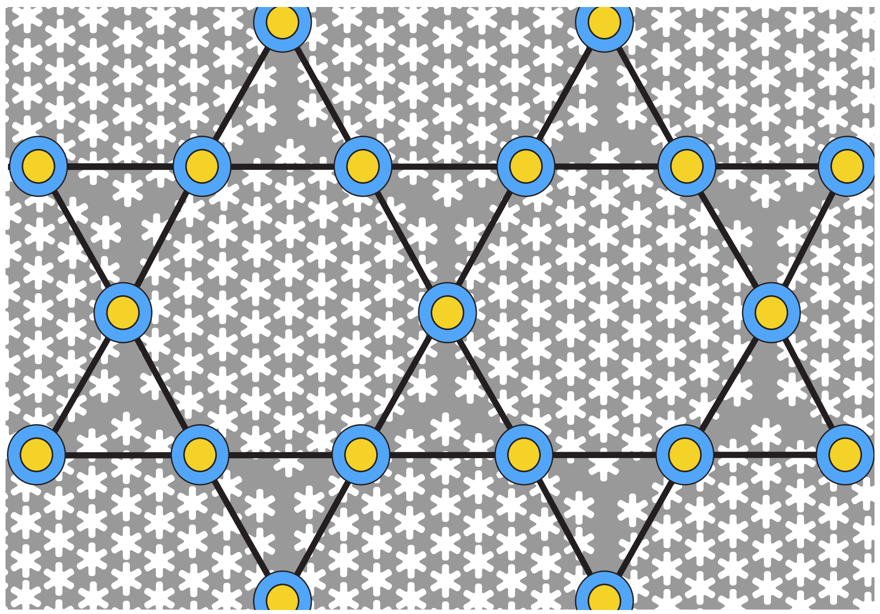

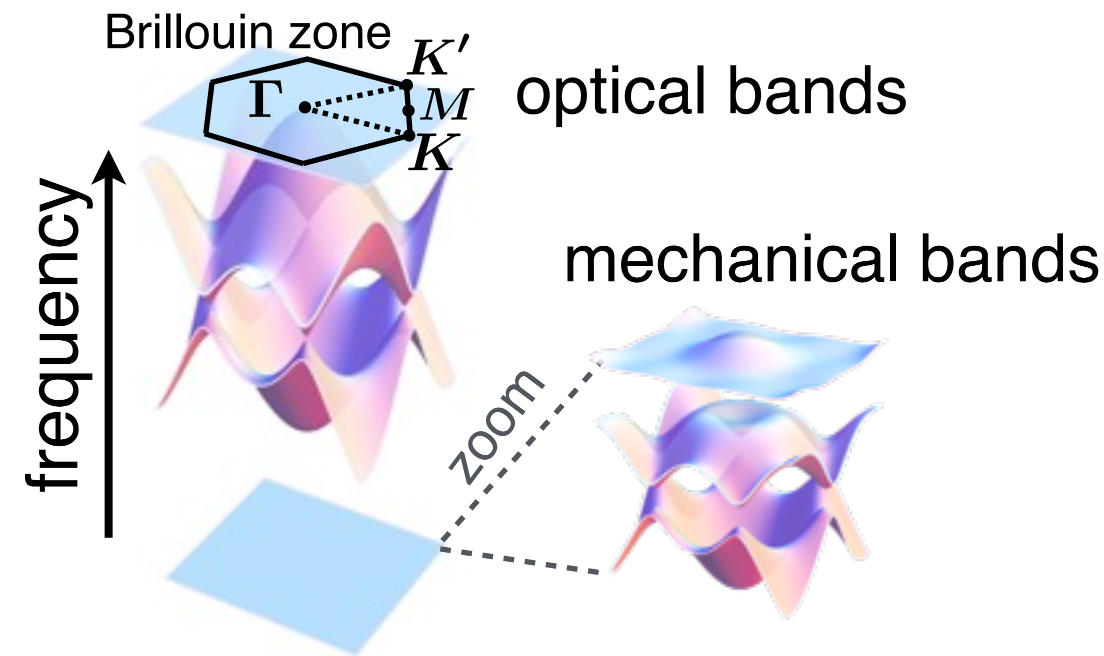

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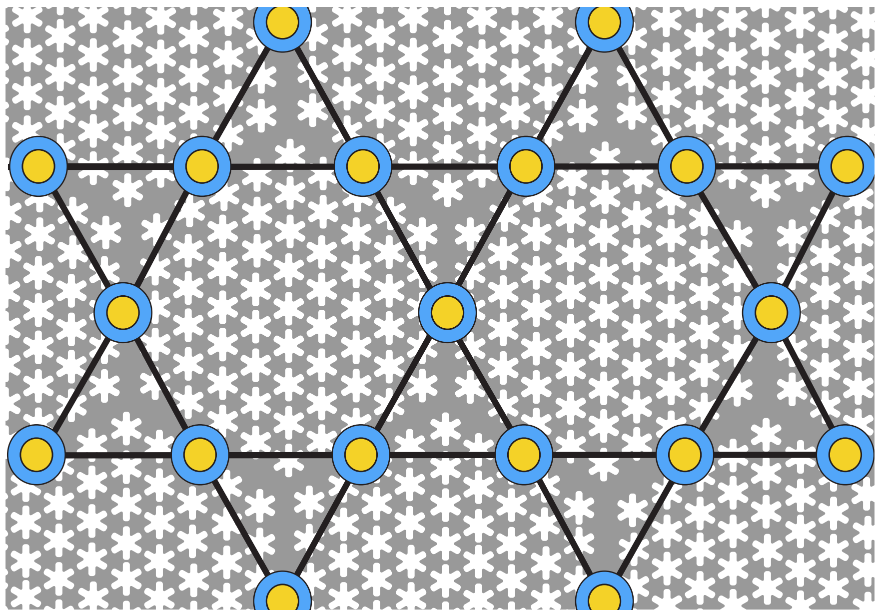

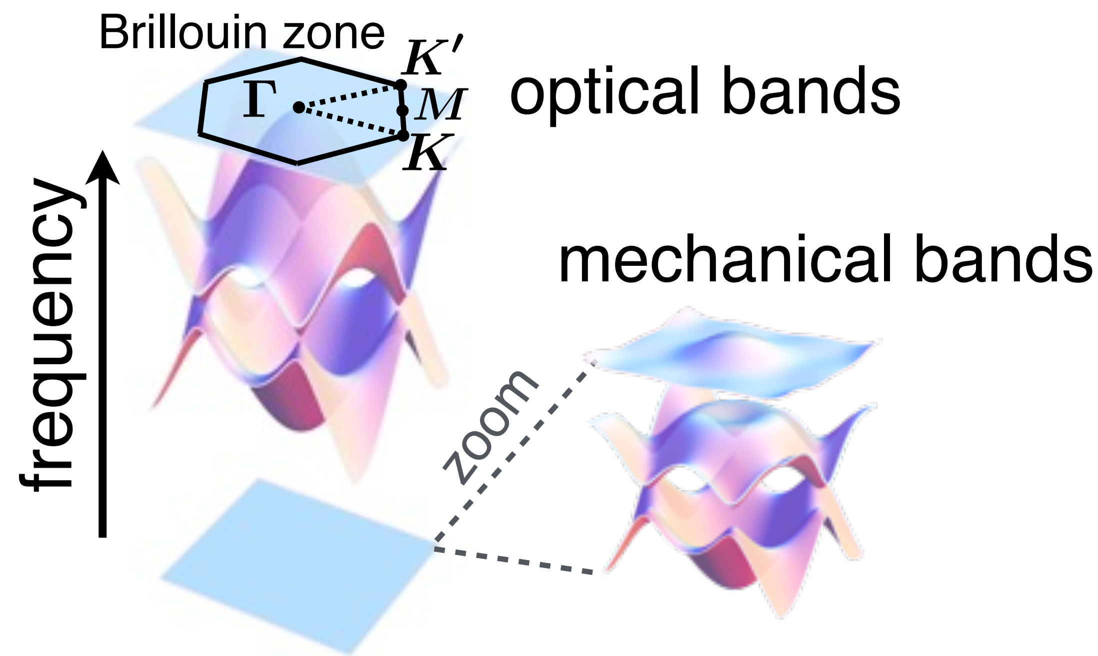

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with a laser: steady light amplitudes α_j and radiation pressure induced mechanical displacements β_j

$$\hat{H}/\hbar = \sum_j \Omega \delta\hat{b}_j^\dagger \delta\hat{b}_j - \Delta \delta\hat{a}_j^\dagger \delta\hat{a}_j + \sum_{lj} J_{lj} \delta\hat{a}_l^\dagger \delta\hat{a}_j + K_{jl} \delta\hat{b}_l^\dagger \delta\hat{b}_j + \hat{H}_{OM}$$

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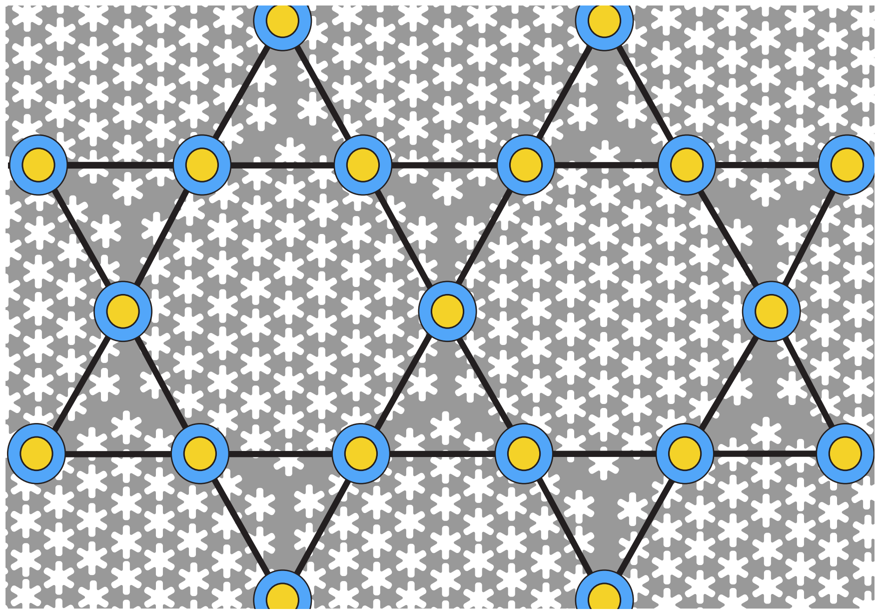

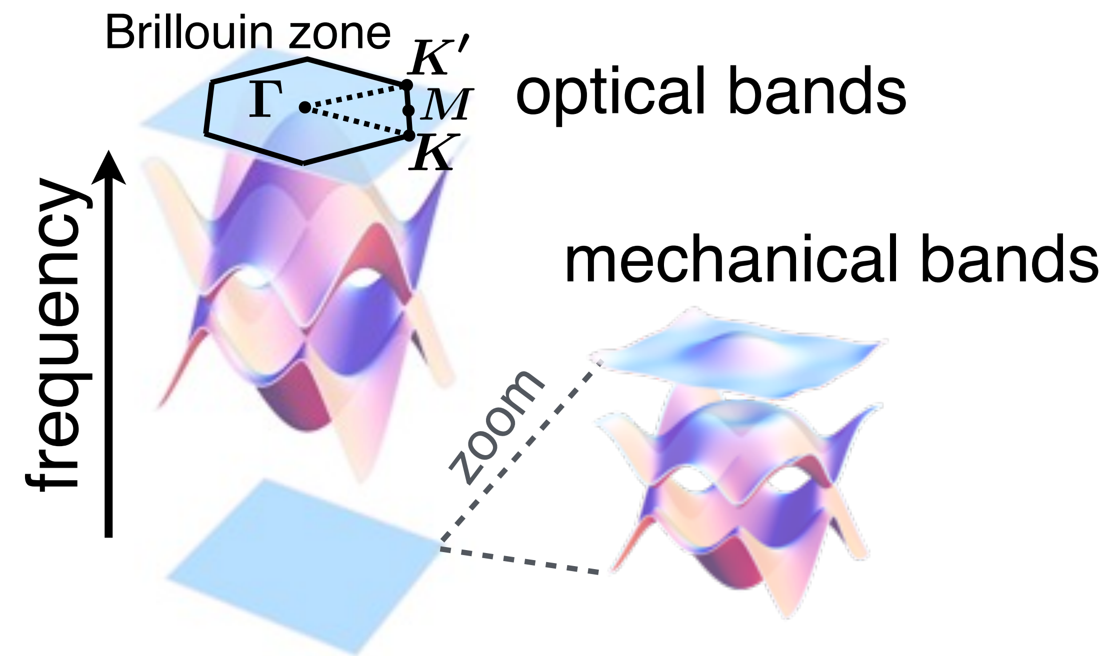

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Basic on topological band structures

Periodic table of topological band structures

	Symmetry			d							
AZ	Θ	Ξ	Π	1	2	3	4	5	6	7	8
A	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	1	0	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	1	1	1	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	−1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
AII	−1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
CII	−1	−1	1	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	−1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	1	−1	1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

Hasan and Kane, RMP (2010)

It classifies topological band structures based on symmetries (time reversal, chiral, particle-hole) and dimensionality.

It applies to fermionic insulators, superconductors but also non-interacting bosons if particle numbered is conserved.

Basic on topological band structures

Chern numbers

$$\hat{H}/\hbar = \sum_j \Omega \hat{b}_j^\dagger \hat{b}_j - \Delta \hat{a}_j^\dagger \hat{a}_j - \left(g_j \hat{a}_j^\dagger \hat{b}_j + h.c. \right) + \hat{H}_{\mathrm{hop}}$$

Rewrite Hamiltonian in momentum space

$$\hat{H}/\hbar = \sum_k \mathbf{c}_k^\dagger \hat{h}_k \mathbf{c}_k \qquad \mathbf{c}_k = (N)^{-1/2} \sum_j e^{-ik\cdot r_j} (\hat{a}_{jA}, \hat{a}_{jB}, \hat{a}_{jC}, \hat{b}_{jA}, \hat{b}_{jB}, \hat{b}_{jC})$$

$\hat{h}_k$ $\;6 \times 6$ single-particle Hamiltonian with eigenvectors $|\mathbf{k}_l\rangle$ band index

[excitations can be photons or phonons on sublattices A, B, or C]

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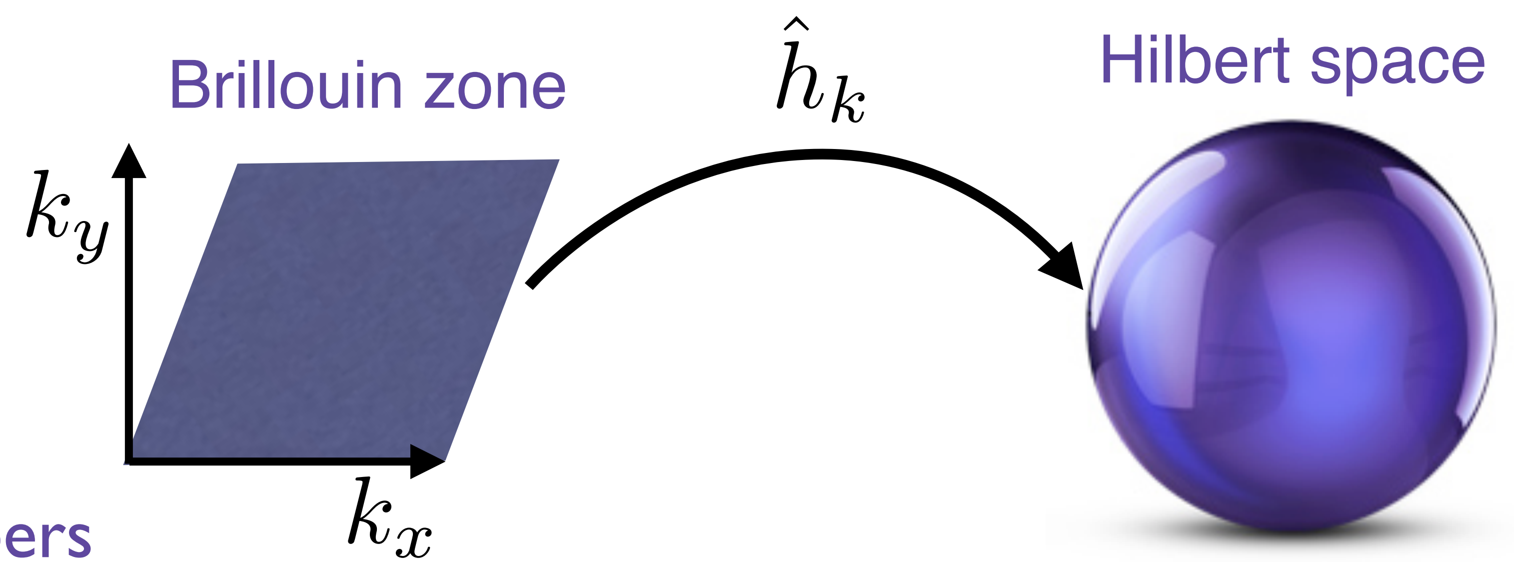

Chern numbers

$$C_l = -\frac{1}{2\pi} \int_{BZ} d^2k (\nabla_{\mathbf{k}} \times \mathcal{A}_{\mathbf{l}}(\mathbf{k})) \cdot \mathbf{e}_z \qquad \mathcal{A}_l = i \langle \mathbf{k}_l | \nabla_{\mathbf{k}} | \mathbf{k}_l \rangle$$

Berry connection

Basic on topological band structures

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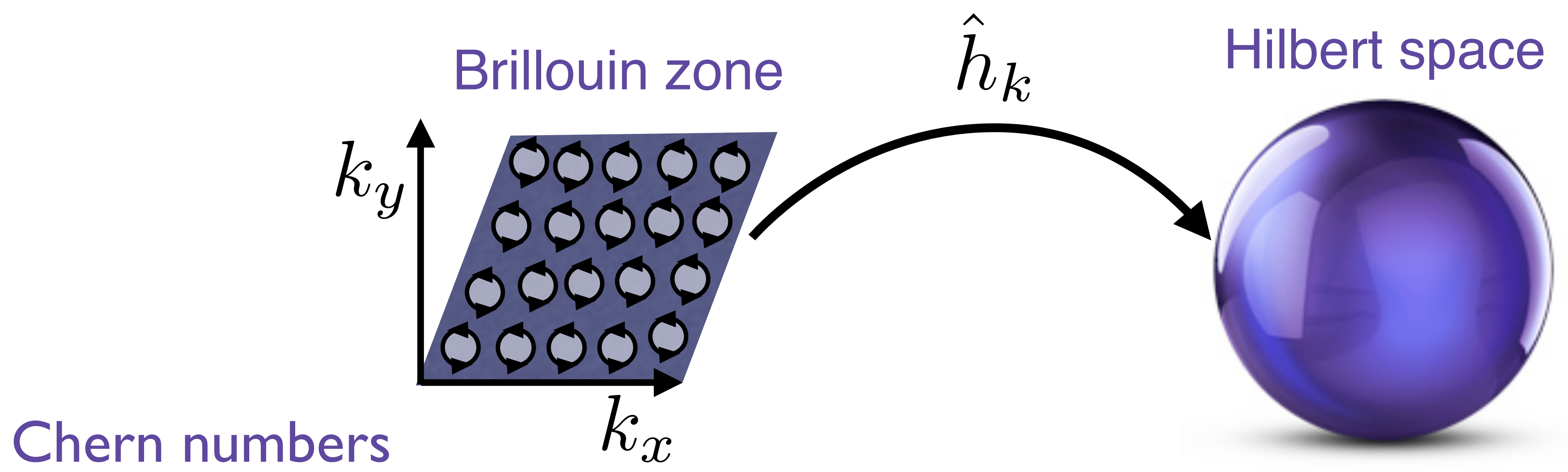

Chern number = (sum of Berry phases across Brillouin zone)/2π

Basic on topological band structures

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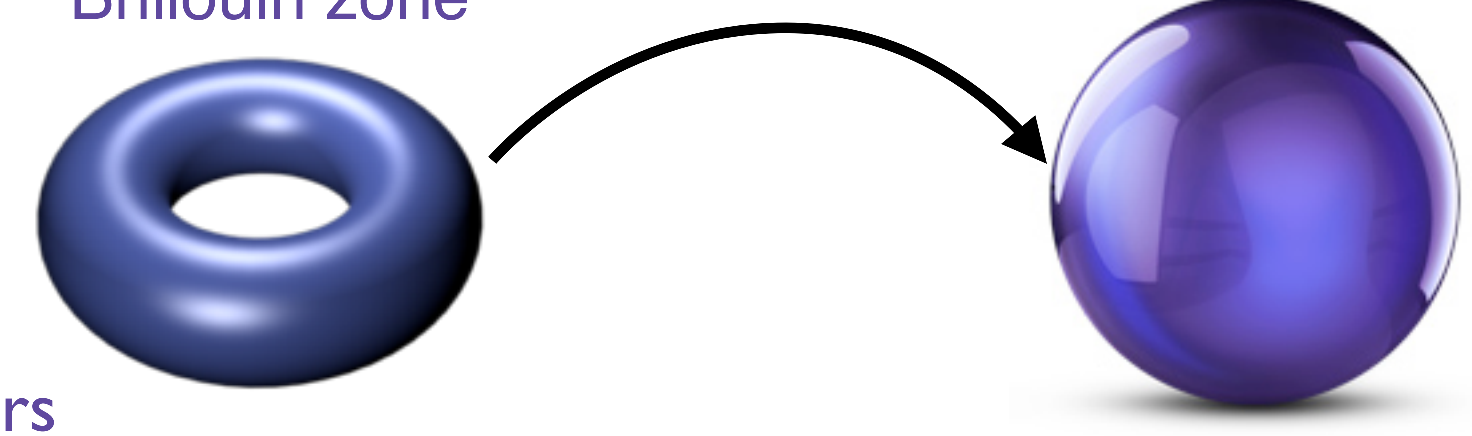

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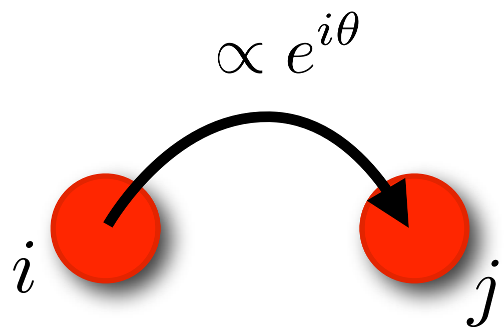
Berry connection

In a crystal: hopping with direction-dependent phase $=$ magnetic field



$$\theta = q \int_{r_i}^{r_j} \mathbf{A} \cdot d\mathbf{s}$$

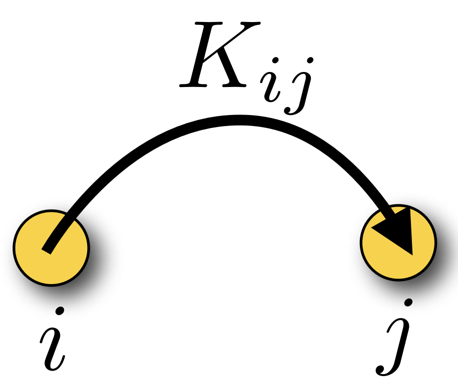
vector potential

Synthetic gauge fields for phonons

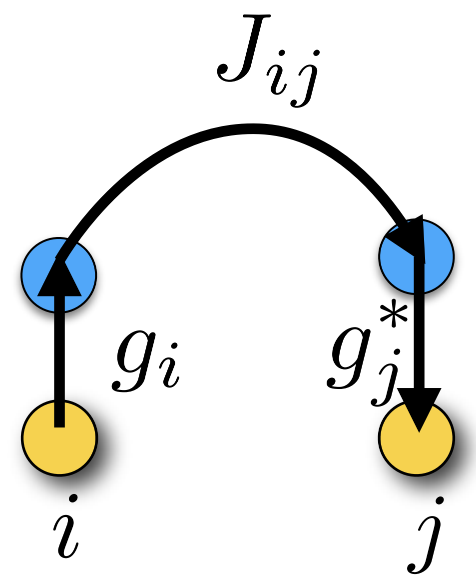
In OM arrays interference between mechanical and optical hopping creates synthetic (effective) gauge fields

Effective mechanical hopping

$K_{ij}^{(eff)} =$



$+$



$$K_{ij}^{(eff)} = K_{ij} + g_i g_j^* J_{ij} / (\Omega + \Delta)^2 = |K_{ij}^{(eff)}| e^{i\theta}$$

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

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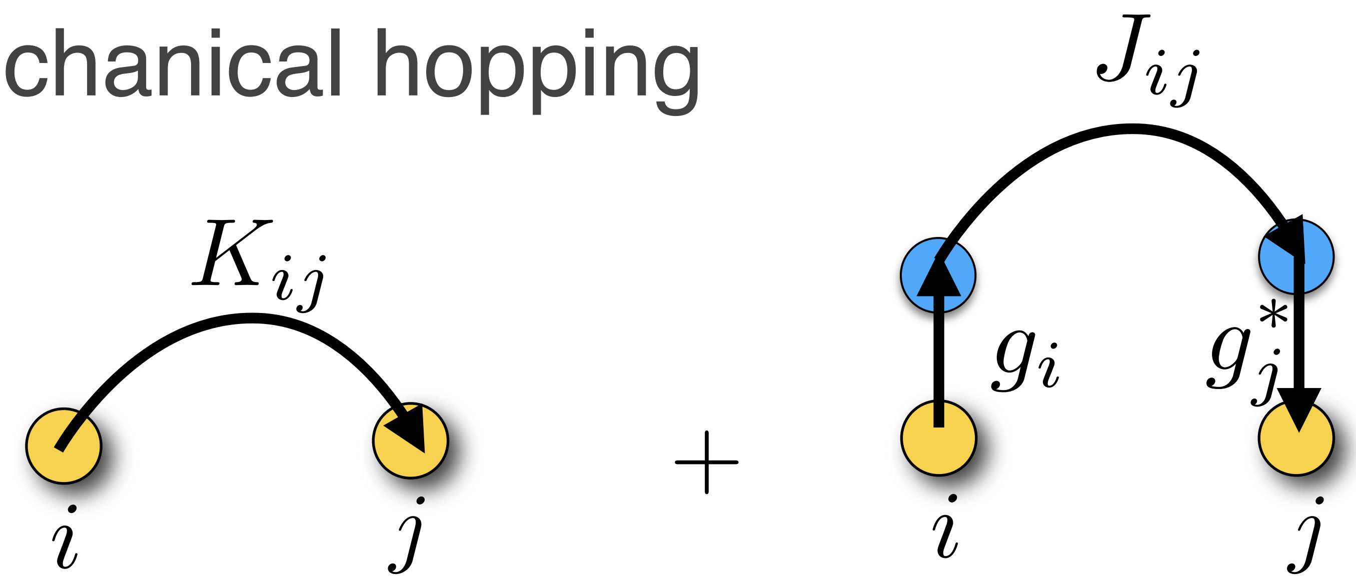

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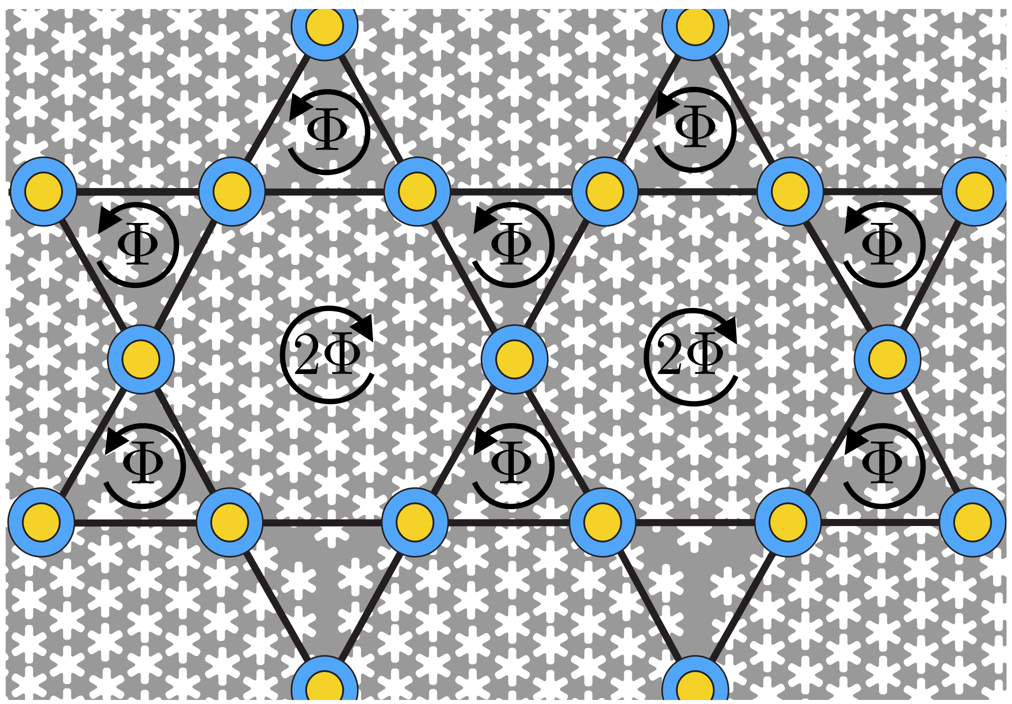
a small array of three sites form a “phonon circulator”,
Habraken et al., New Journal of Physics, 14, 115004 (2012)

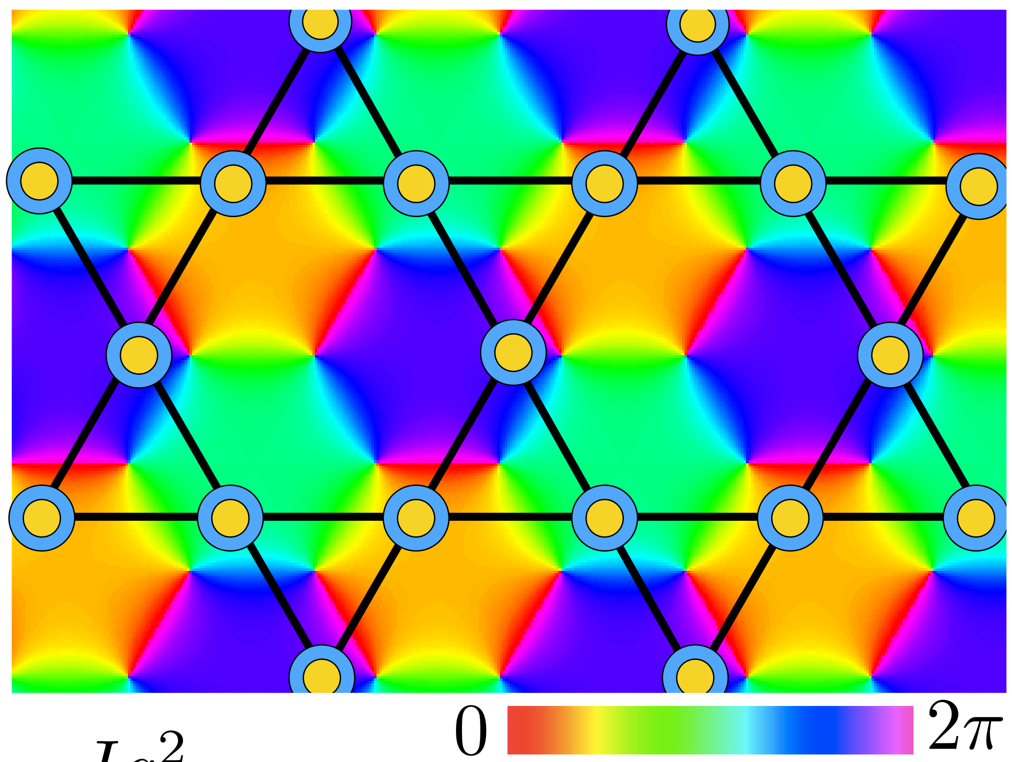
Anomalous Quantum Hall physics for phonons

In a Kagome array a driving with a pattern of phases creates a staggered synthetic field

phonon synthetic gauge field



phase pattern created by three lasers



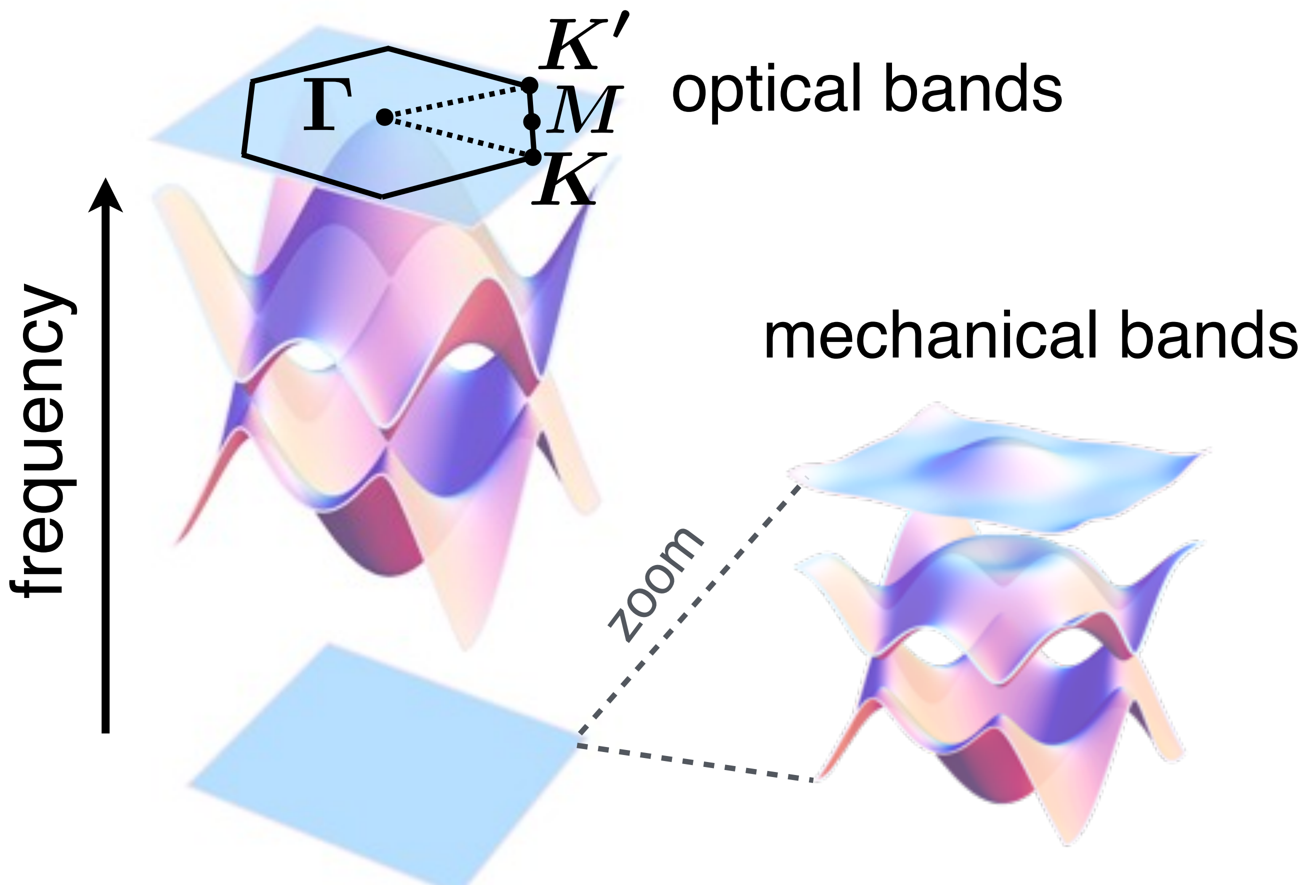
$$\Phi = \frac{3\pi}{2} - 3\arctan\frac{2K(\Delta+\Omega)^2 - Jg^2}{\sqrt{3}Jg^2}$$

Anomalous quantum Hall physics in a Kagome lattice,
Ohgushi, Murakami, Nagaosa, PRB, 14, 115004 (1988)

but here long range hopping possible....

Anomalous Quantum Hall physics for phonons

"weak coupling":
light field modifies phonon hopping



long range mechanical hopping possible

Anomalous Quantum Hall physics for phonons

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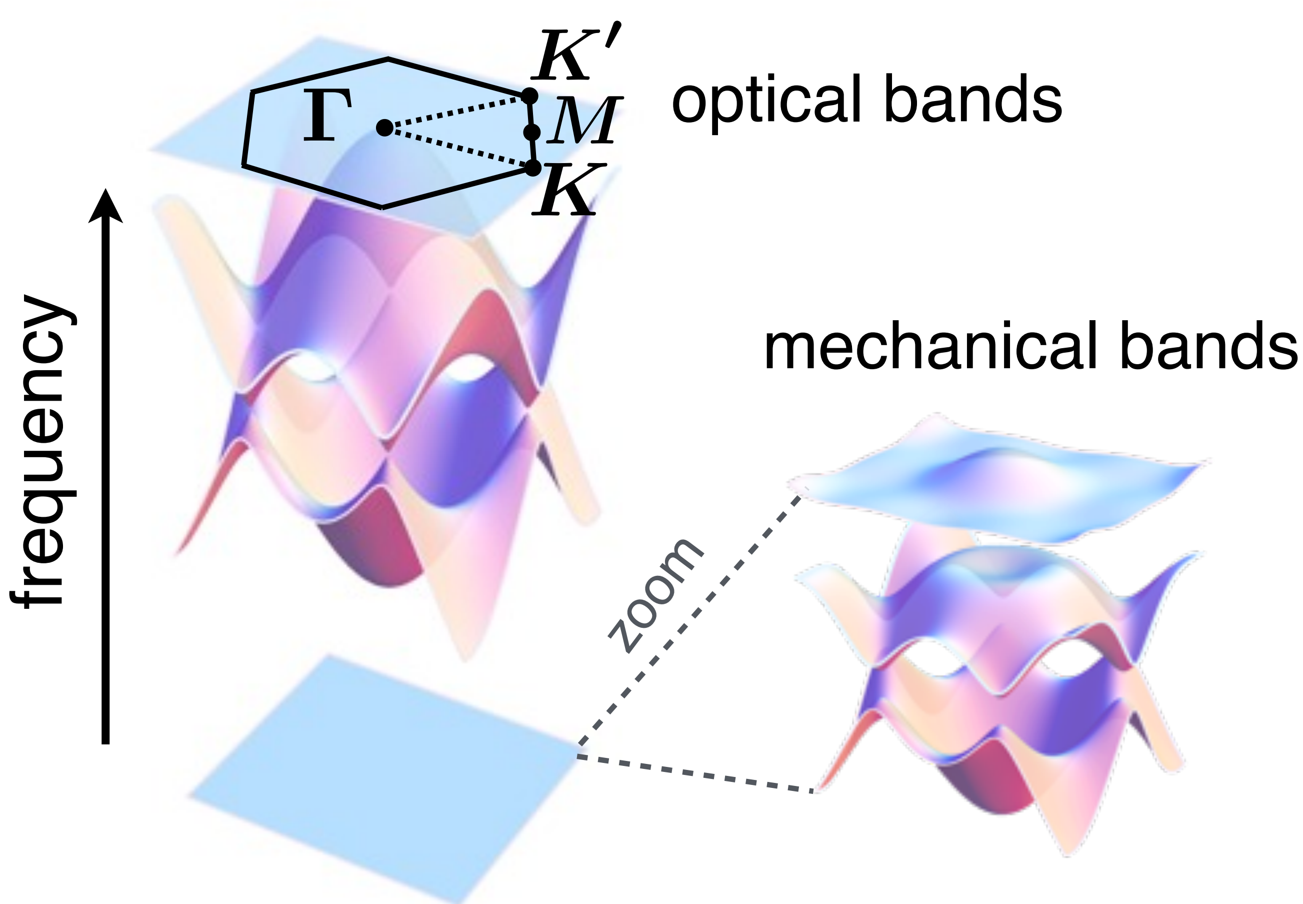

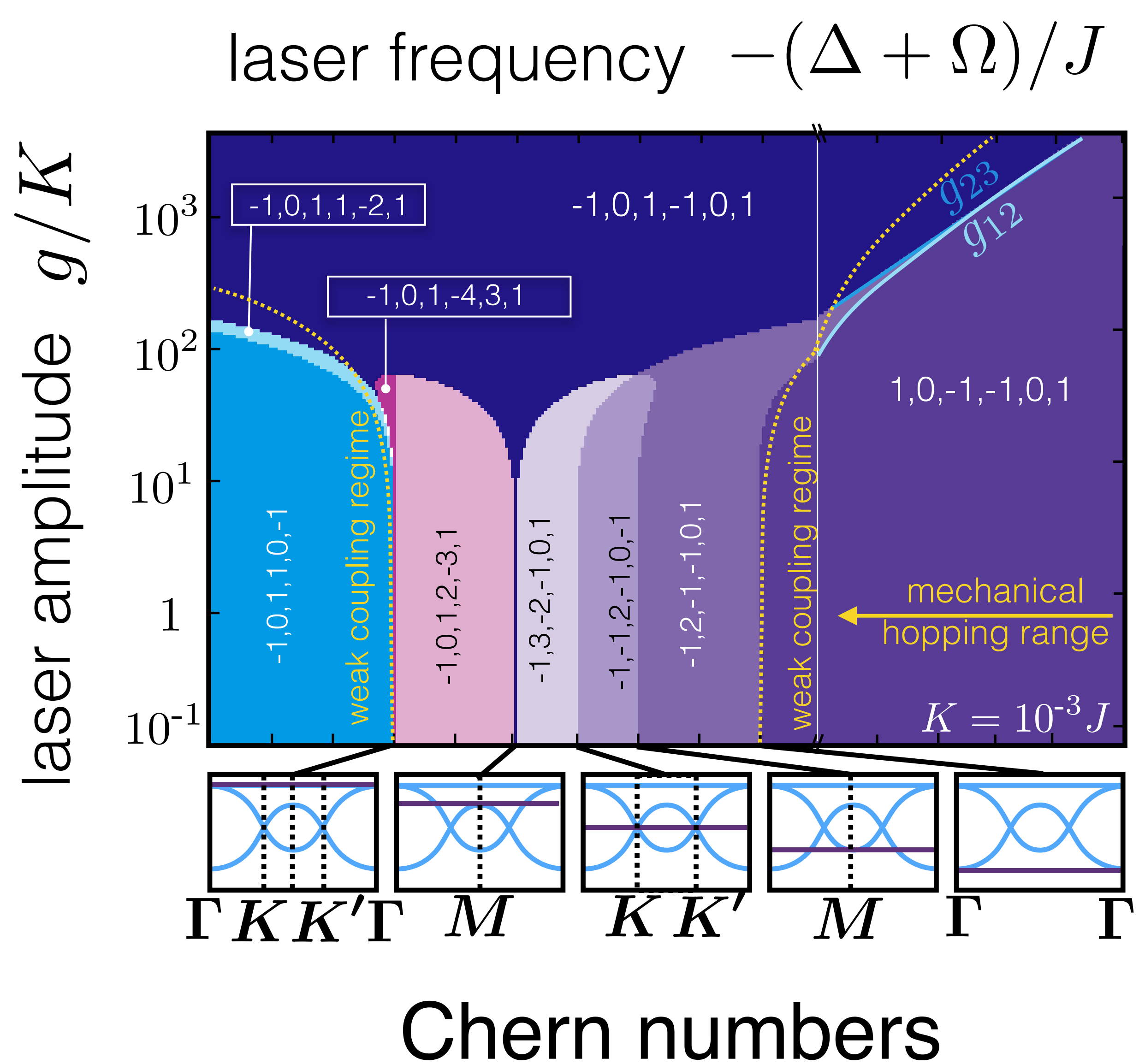

A Chern insulator of sound and light

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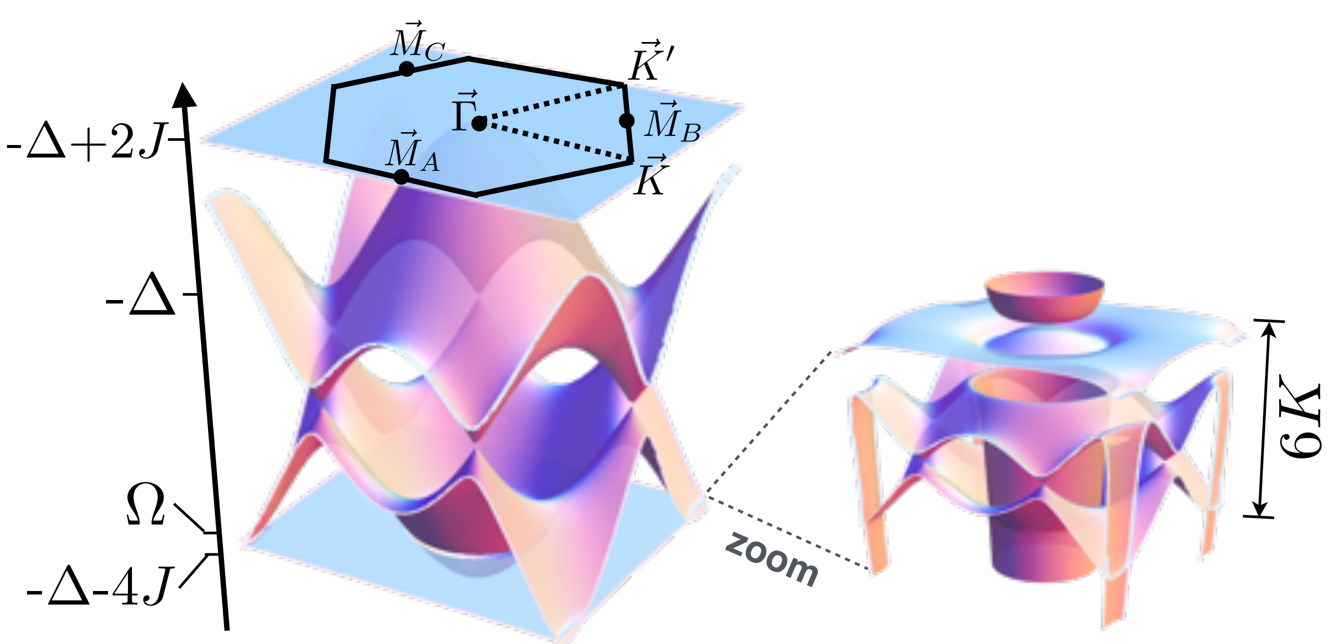
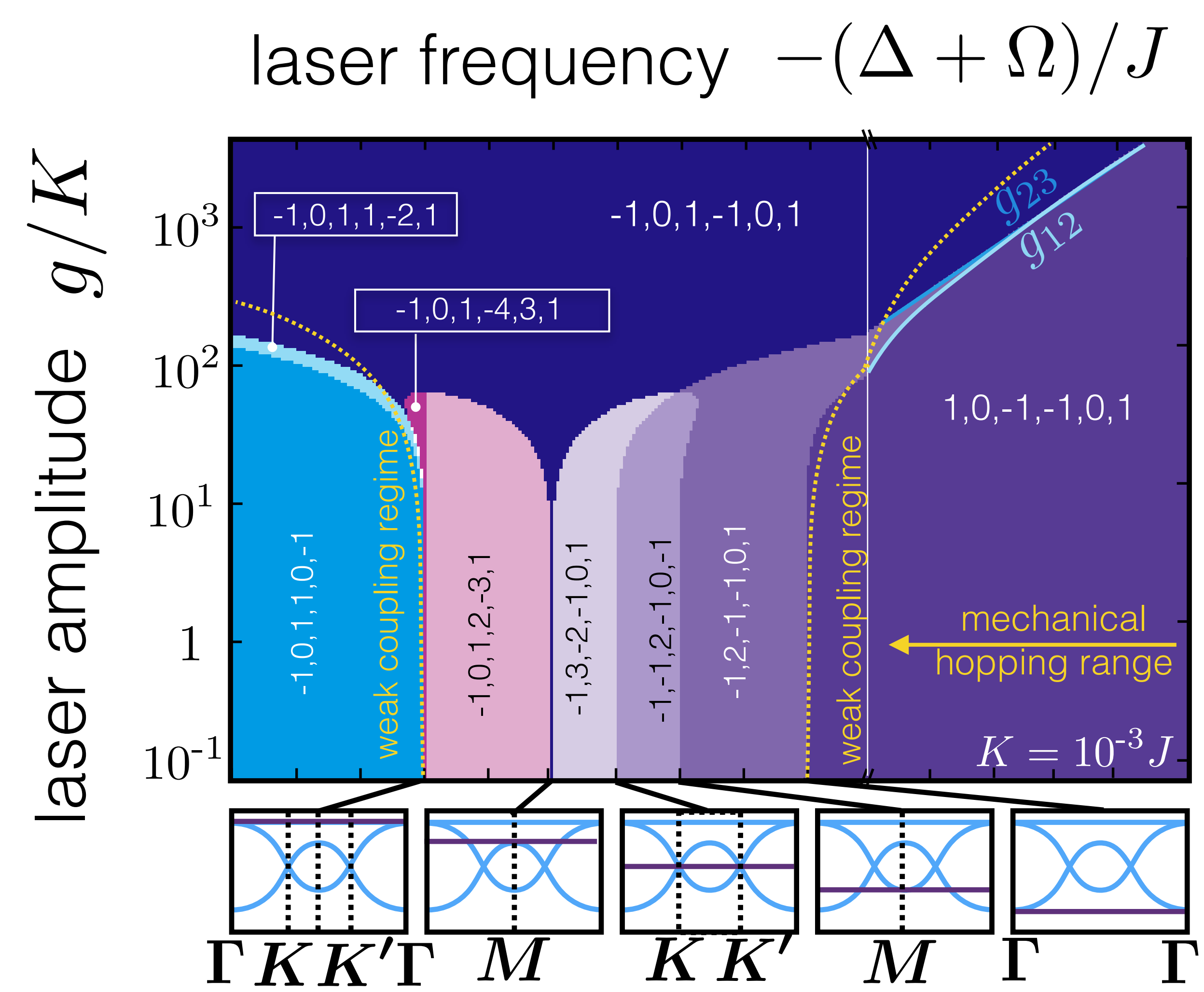
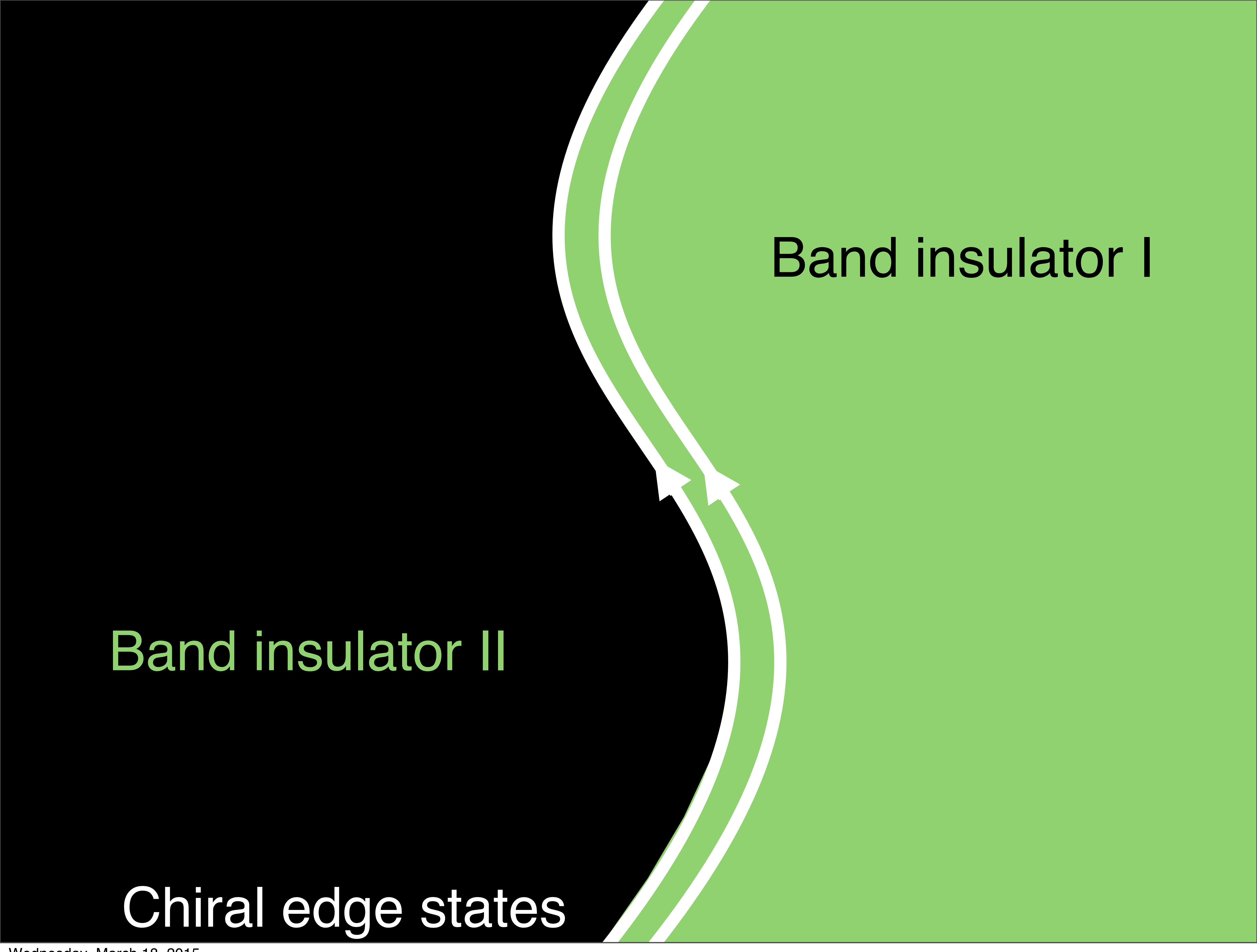
"Strong coupling":
photon and phonon bands mix





Chern numbers

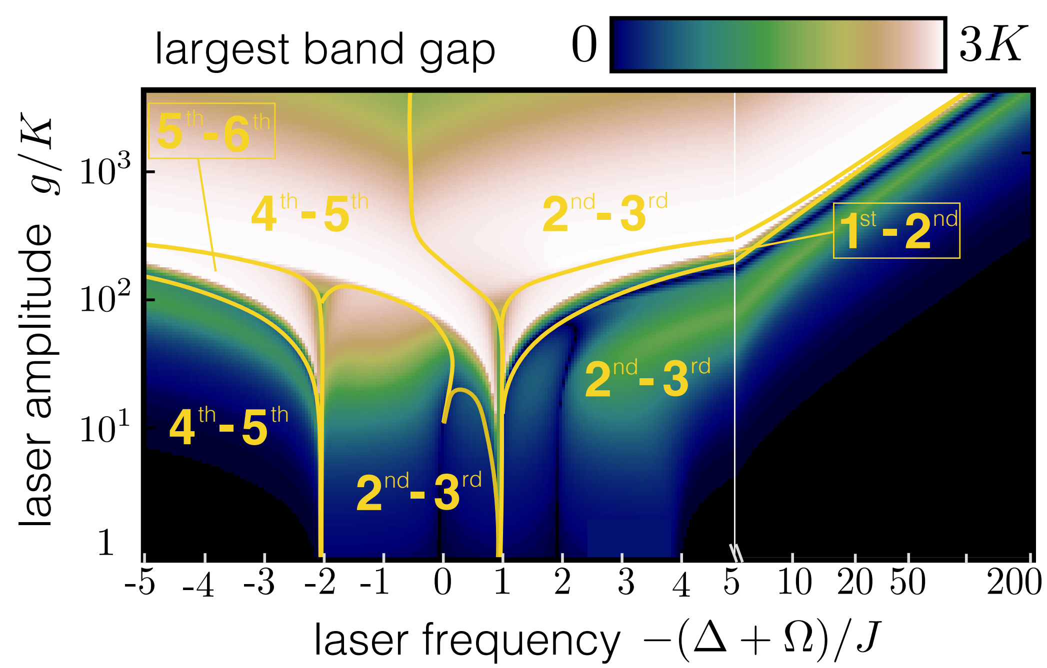

Band insulator I
Band insulator II
Chiral edge states

Is phonon transport topologically protected?

What could go wrong:

- Dissipation could smear the band gap:

For $J \gg K$ band gap is at most $\sim K$



does the band gap survive for large photon decay rates $\kappa \gg K$?

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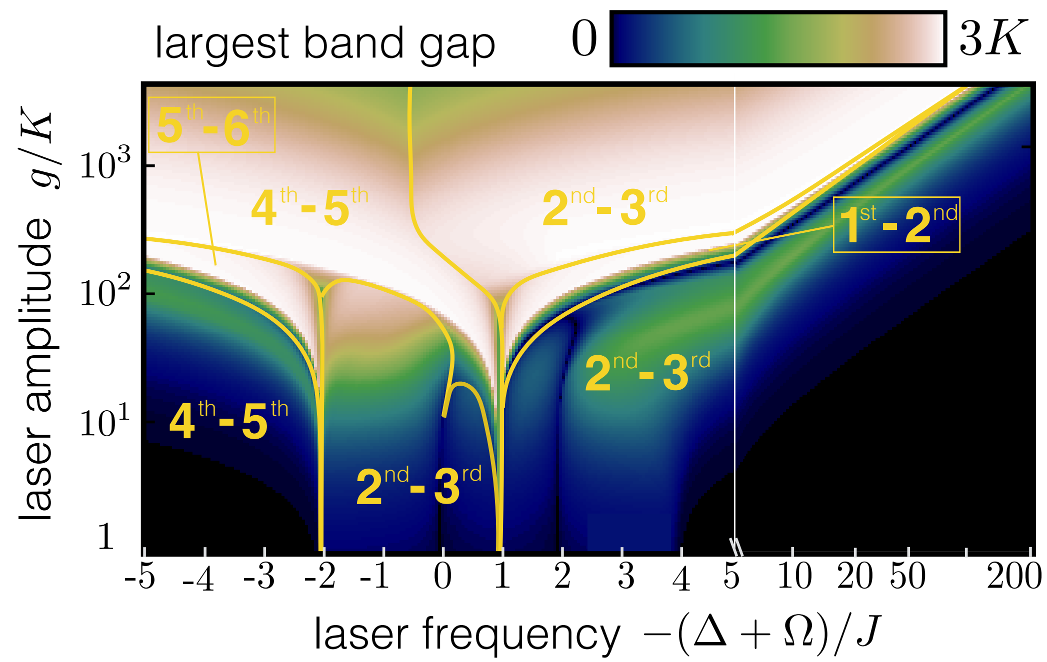
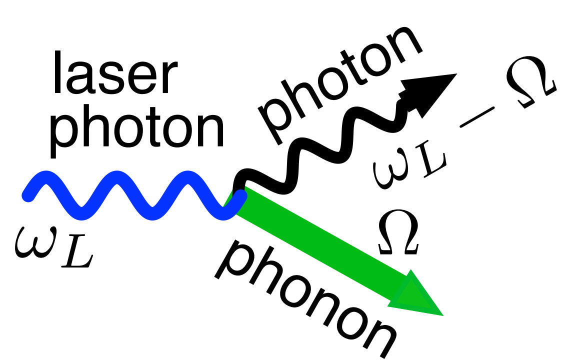


does the band gap survive for large photon decay rates $\kappa \gg K$?

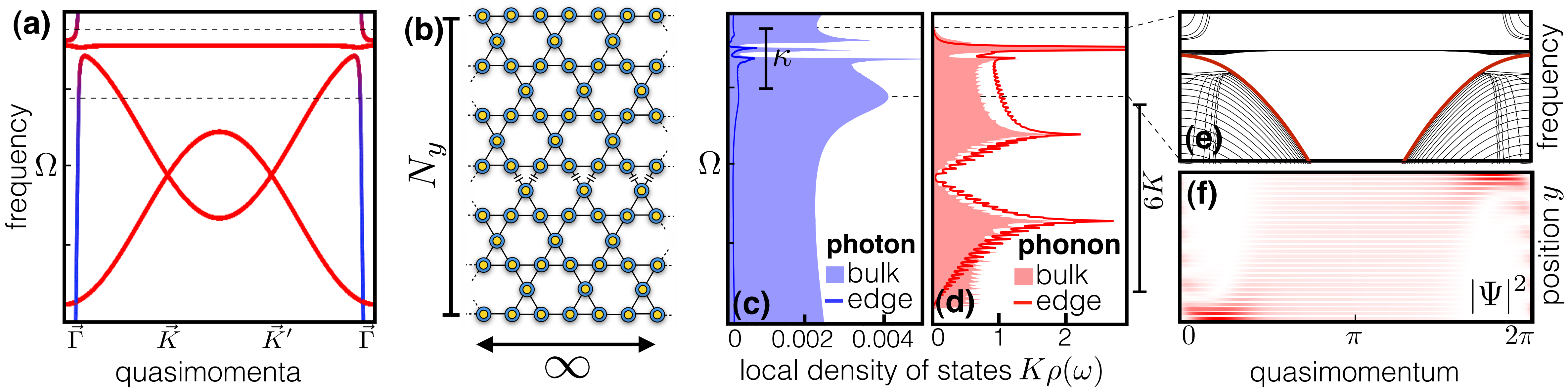
- Squeezing interaction could modify topological properties:

Topological invariant is defined only for particle-conserving bosonic Hamiltonians



Topological band gap is extraordinarily resilient to dissipation

Chern numbers [-1,2,-1,-1,0,1]



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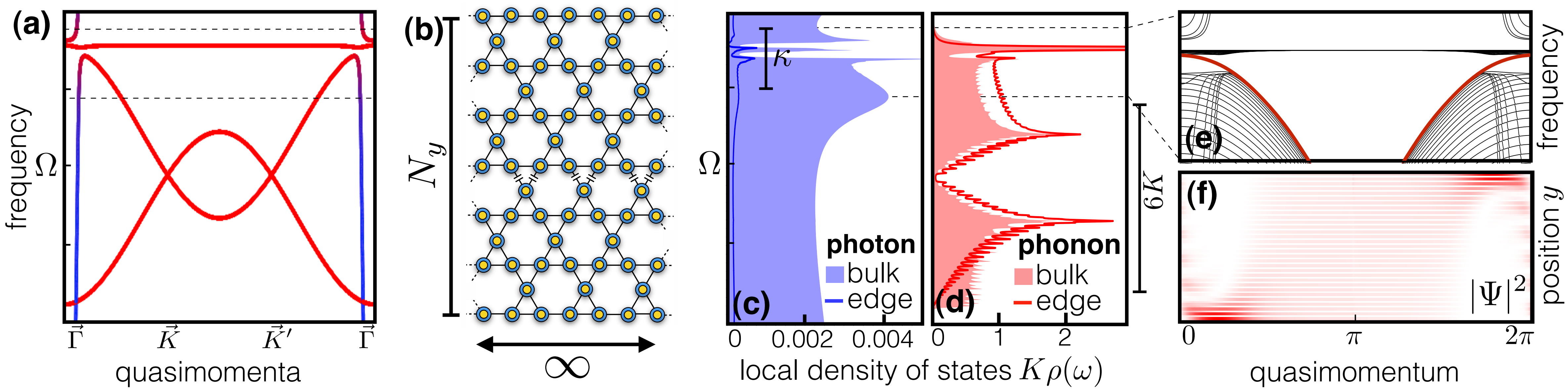
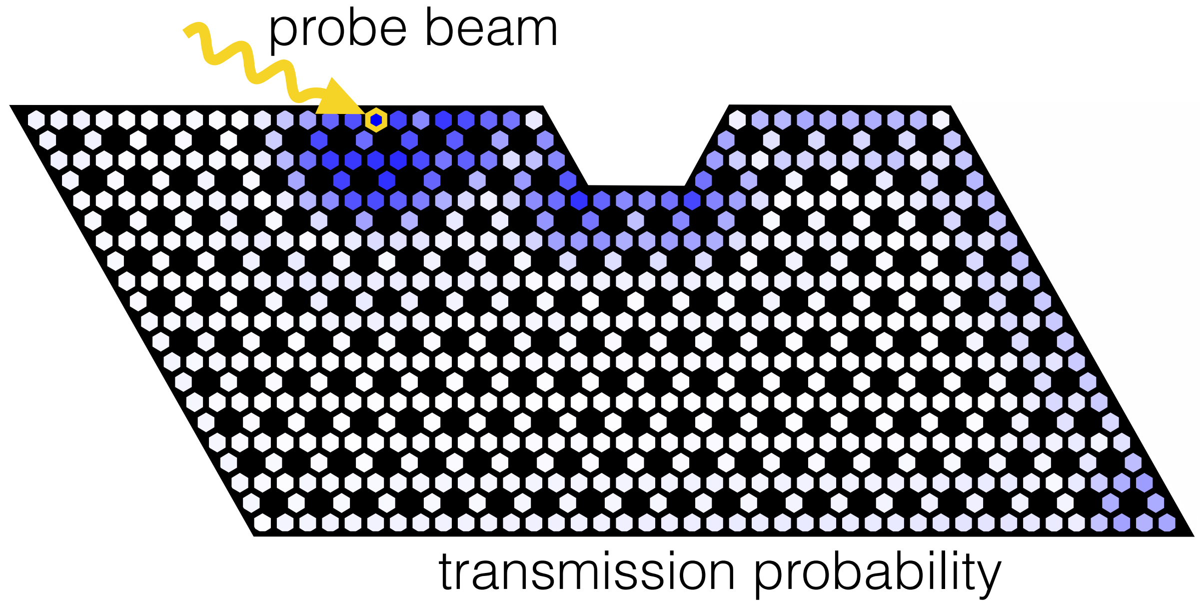
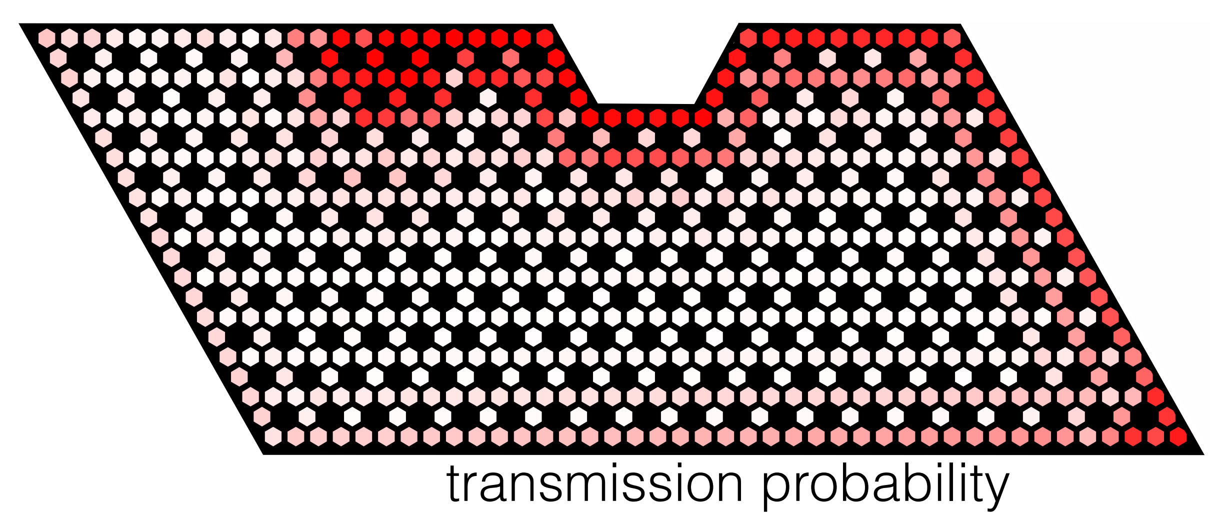


Phonon transport is very robust and can be probed optically

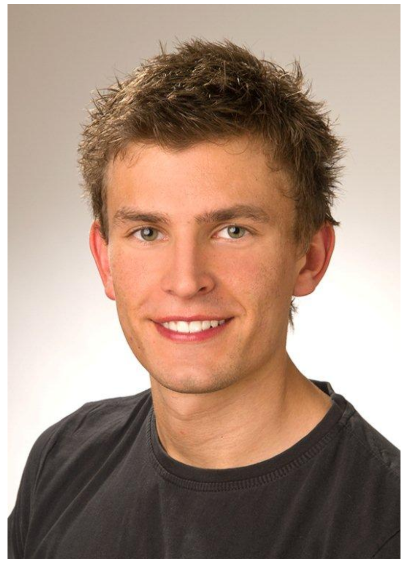




Conclusions and Outlook

VP, C. Brendel, M. Schmidt, and F. Marquardt, arXiv:1409.5375 (2014)

- Example of topological phases of phonons in the solid state (once realized in the experiment)
- Strong coupling regime: Two physically different particle species
- Full optical control and readout
- Create arbitrary domains using spatial laser profile, reconfigure edge states
- Time-dependent control: quenches of topological phases



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