Dynamically generated Synthetic Electric Fields for Photons

Petr Zapletal

Cavendish Laboratory

University of Cambridge

Joint work: Florian Marquardt, Andreas Nunnenkamp, Stefan Walter

P. Zapletal, S. Walter, F. Marquardt, arXiv:1806.08191 (2018)

Hybrid Optomechanical Technologies

EPSRC
Engineering and Physical Sciences Research Council

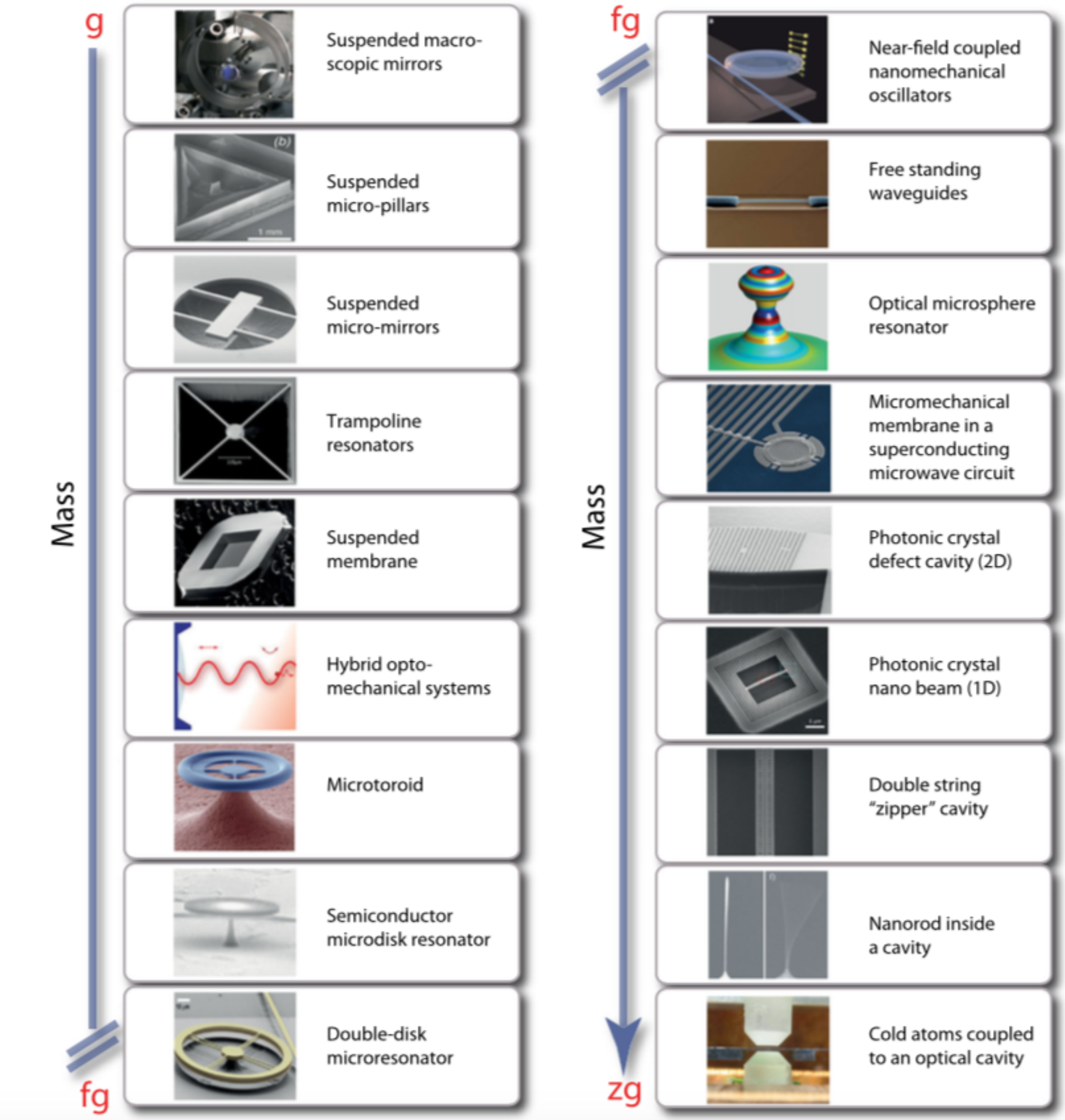
MAX PLANCK INSTITUTE
for the science of light

Cavity optomechanics

$$\hat{H}/\hbar = \nu\, \hat{a}^{\dagger}\hat{a} + \Omega\, \hat{b}^{\dagger}\hat{b} - J\, \hat{a}^{\dagger}\hat{a}\, (\hat{b}^{\dagger} + \hat{b})$$

- Ground state cooling
- Standard quantum limit
- Single phonon control
- Coherent state transfer

Multimode optomechanics

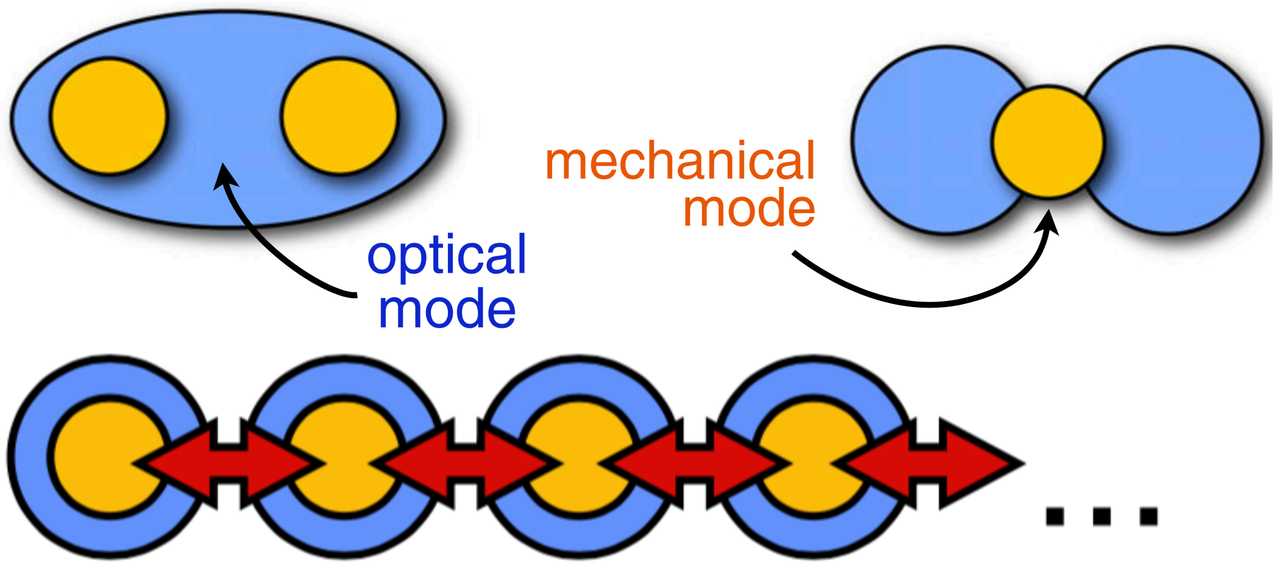


M. Aspelmeyer et al., Rev. Mod. Phys. **86**, 1391 (2014).

Outline

1. Optomechanical arrays
2. Synthetic gauge fields
3. Dynamical gauge fields $\Longrightarrow$ unidirectional transport
4. Dynamical gauge fields in the quantum regime

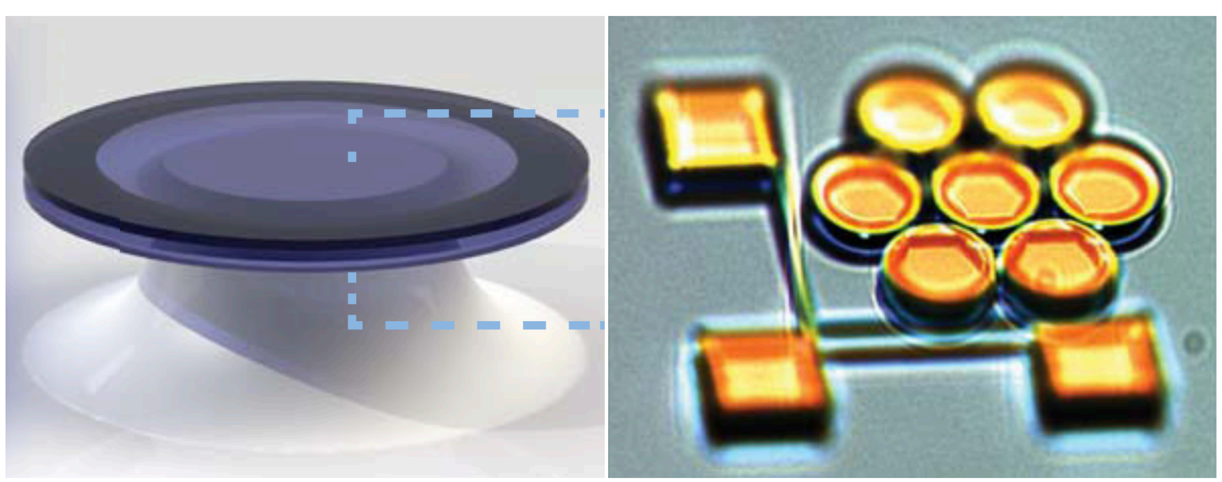
Optomechanical arrays



G. Heinrich et al., Phys. Rev. Lett. **107**, 043603 (2011)

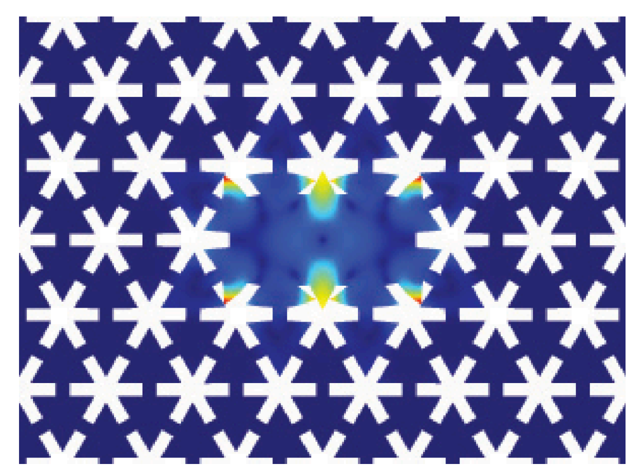
- Band structure
- Synchronization
- Topological phases
- Disorder

Resonator disks



M. Zhang et al., Phys. Rev. Lett. **115** 163902 (2015)

Photonic crystals



A. H. Safavi-Naeini et al., New J. Phys. **13**, 013017 (2011).

Gauge fields

Example: Electromagnetism

Maxwell equations

$$\vec{\nabla} \cdot \vec{\mathcal{E}} = \frac{\rho}{\epsilon_0}$$

$$\vec{\nabla} \cdot \vec{\mathcal{B}} = 0$$

$$\vec{\nabla} \times \vec{\mathcal{E}} = -\frac{\partial}{\partial t}\vec{\mathcal{B}}$$

$$\vec{\nabla} \times \vec{\mathcal{B}} = \mu_0 \left(\mathcal{J} + \epsilon_0 \frac{\partial}{\partial t}\vec{\mathcal{E}} \right)$$

Potentials

$$\vec{\mathcal{E}} = -\nabla\varphi - \frac{\partial}{\partial t}\vec{A}$$

$$\vec{\mathcal{B}} = \vec{\nabla} \times \vec{A}$$

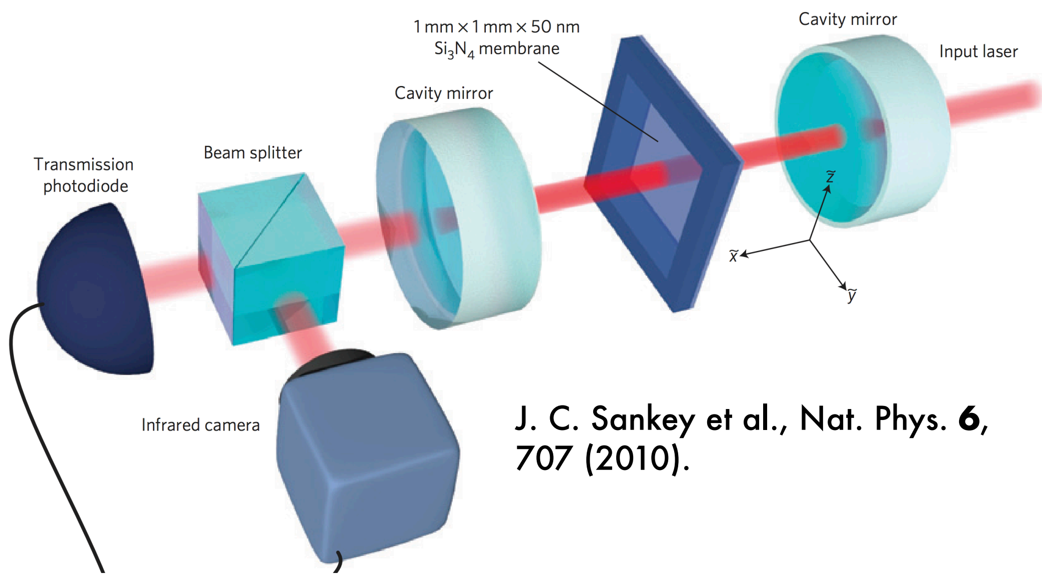
Gauge transformation

$$\varphi \to \varphi - \frac{\partial}{\partial t}\chi$$

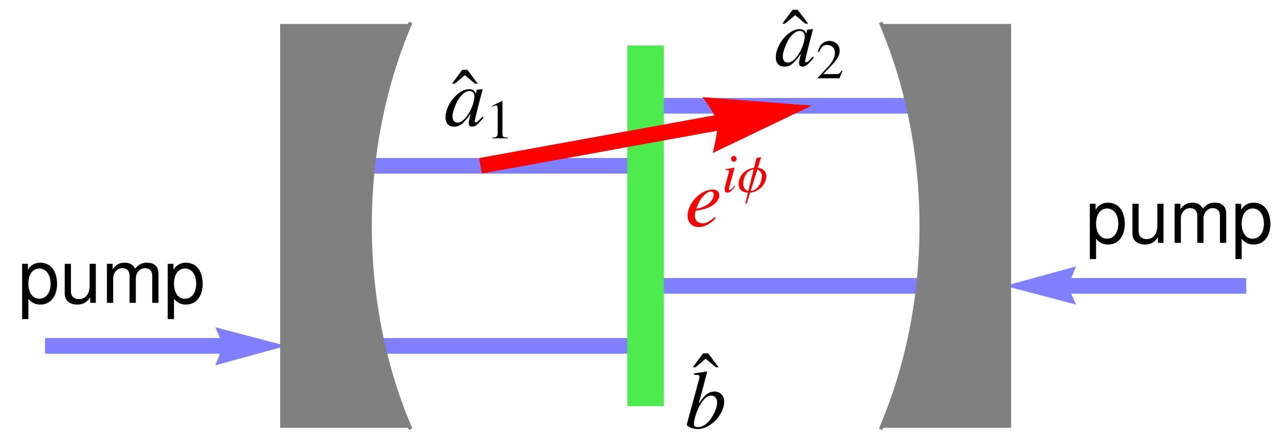
$$\vec{A} \to \vec{A} + \nabla\chi$$

- Quantum electrodynamics
- Quantum chromodynamics
- Lattice gauge theories

Synthetic gauge fields in OM arrays



J. C. Sankey et al., Nat. Phys. **6**, 707 (2010).



Hybridized modes with frequencies ν_1, ν_2

$$\hat{H}_{\text{int}} = J\left(\hat{a}_1^\dagger \hat{a}_2 \hat{b} + \text{h.c.}\right) \qquad \Omega \approx \nu_2 - \nu_1$$

Dynamical modulation of the mechanical mode $\langle \hat{b} \rangle = B\cos\left(\omega t + \phi\right)$

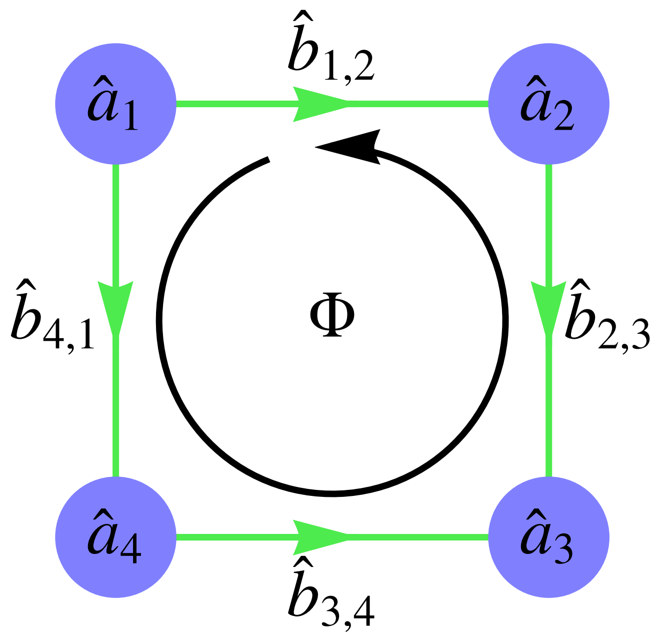
$$\hat{H}_{\text{eff}} = JB\left(\hat{a}_1^\dagger \hat{a}_2 e^{-i\phi} + \text{h.c.}\right)$$

Mechanical gauge field for photons with $U(1)$ symmetry

$$\hat{a}_2 \rightarrow \hat{a}_2 e^{-i\phi}$$

M. Schmidt et al., Optica **2**, 635 (2015).

Artificial magnetic fields for photons



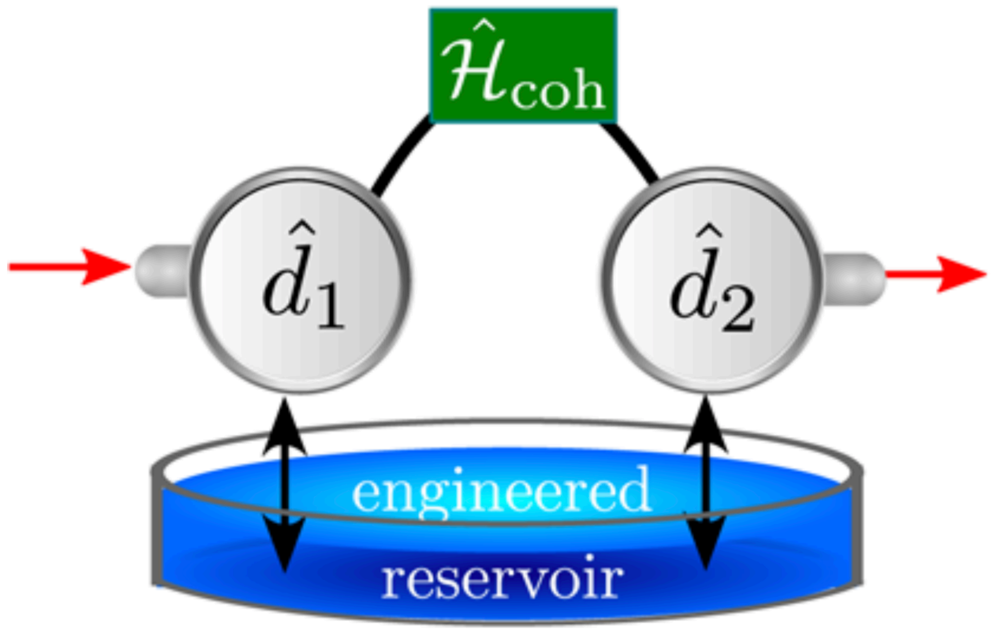
Artificial magnetic field

$$\phi_{i,j} \Longleftrightarrow \vec{A}$$

Synthetic magnetic flux

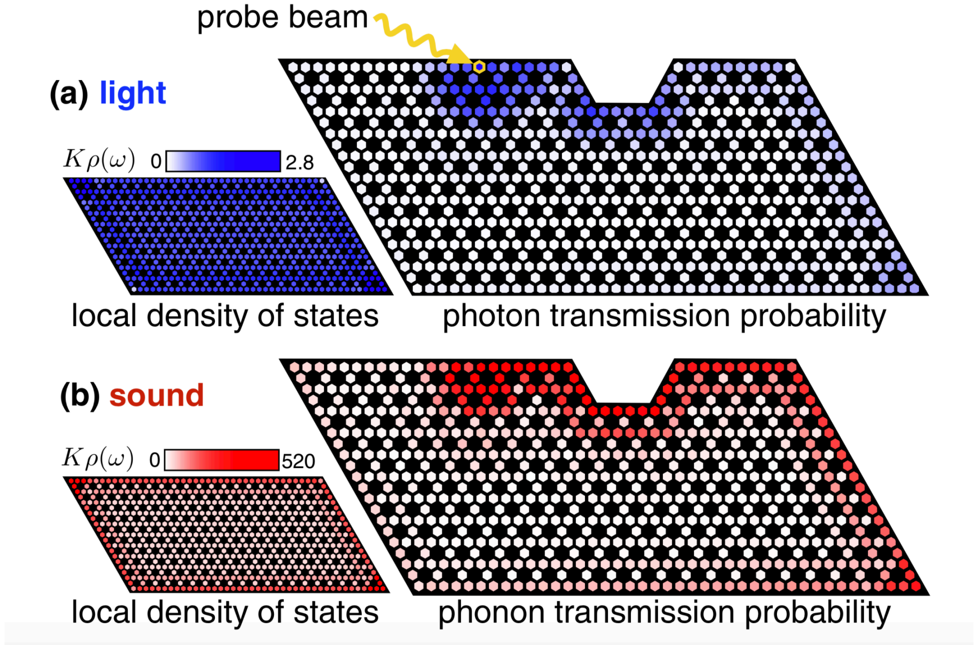
$$\Phi = -\phi_{1,2} - \phi_{2,3} - \phi_{3,4} - \phi_{4,1} \Longleftrightarrow \oint_{\partial S} \vec{A} \cdot \mathrm{d}\vec{l}$$

Nonreciprocal transport of light



A. Metelmann et al., Phys. Rev. X **5**, 021025 (2015).

Topological phases of sound and light, and robust edge states



V. Peano, et al., Phys. Rev. X **5**, 031011 (2015).

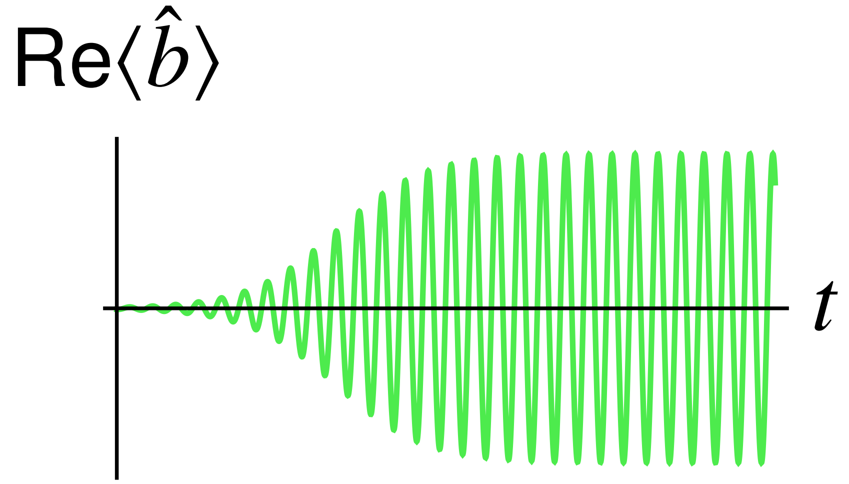
Outline

1. Optomechanical arrays
2. Synthetic gauge fields
3. Dynamical gauge fields $\Longrightarrow$ unidirectional transport
4. Dynamical gauge fields in the quantum regime

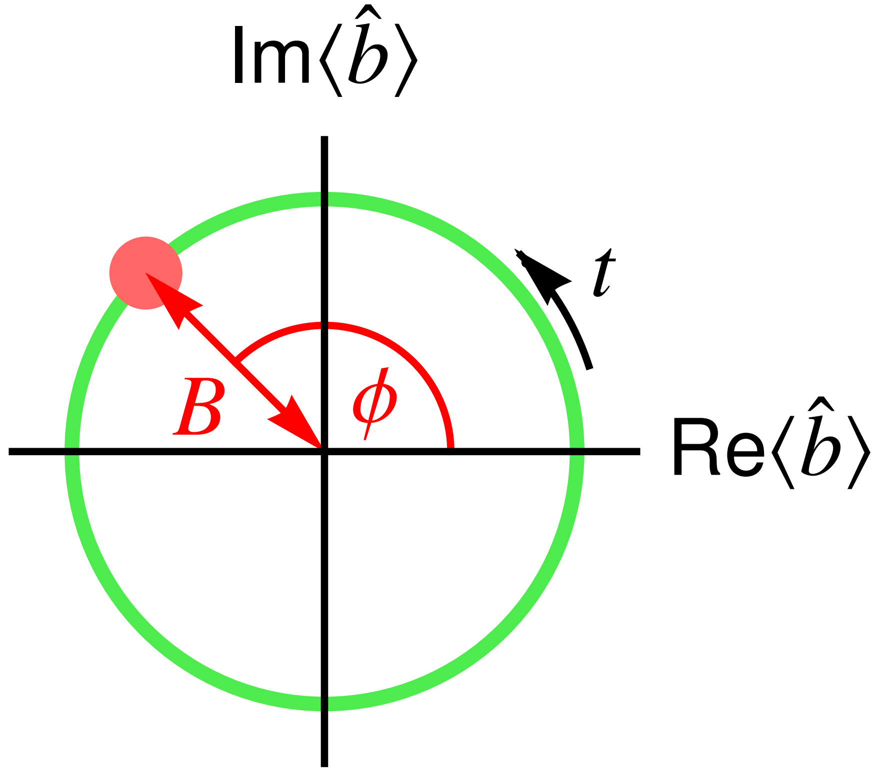
Dynamical gauge fields

Mechanical self-oscillations

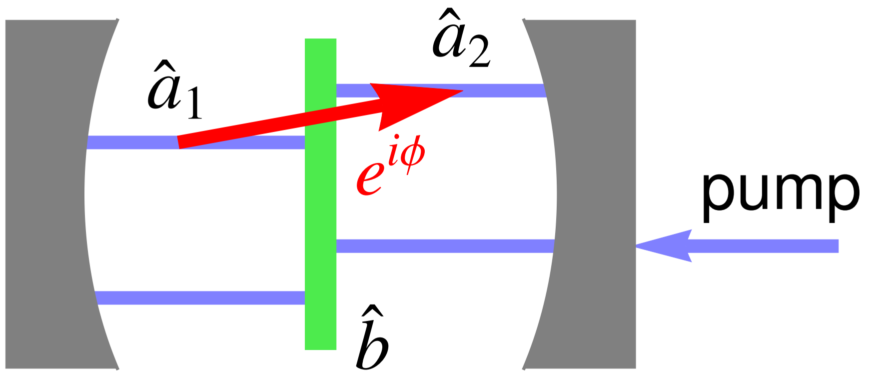
Driving on the blue sideband



F. Marquardt et al., Phys. Rev. Lett. **96**, 103901 (2006).



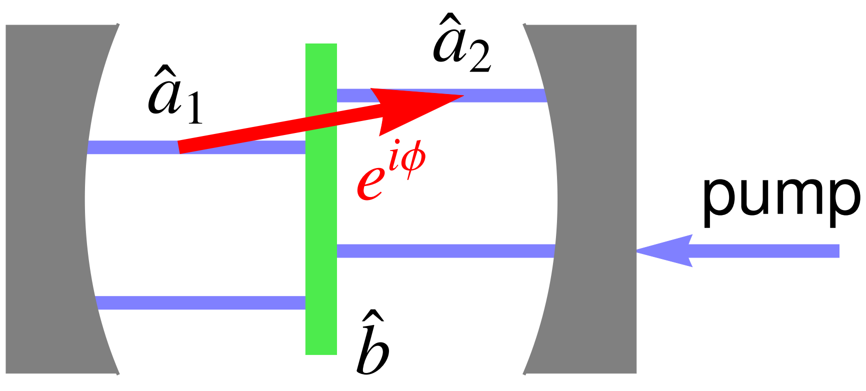
$$\langle\hat{b}\rangle = Be^{i\phi}$$



Backaction of optical excitations on the gauge field due to radiation pressure

S. Walter et al., New J. Phys. **18**, 113029 (2016).

Synthetic electric field



$$\hat{H}_{\text{eff}} = JB\left(\hat{a}_1^\dagger \hat{a}_2 e^{-i\phi} + \text{h.c.}\right)$$

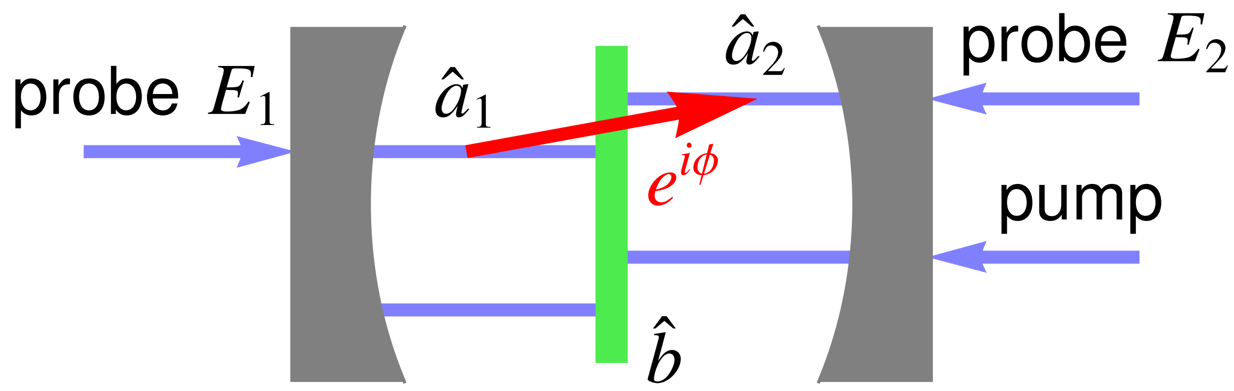
$$\dot{\phi} = -|a_1||a_2|\cos\left(\phi + \theta_1 - \theta_2\right)$$

Time-evolution of the mech. phase $\Longleftrightarrow$ Time-dependent vector potential

Synthetic electric field $\mathcal{E} = \dot{\phi}$ $\Longleftrightarrow$ $\vec{\mathcal{E}} = -\nabla\varphi - \frac{\partial}{\partial t}\vec{A}$

Example, a_1 driven:
ν_1 is fixed by laser.
$\nu_2 \rightarrow \nu_2 - \dot{\phi}$

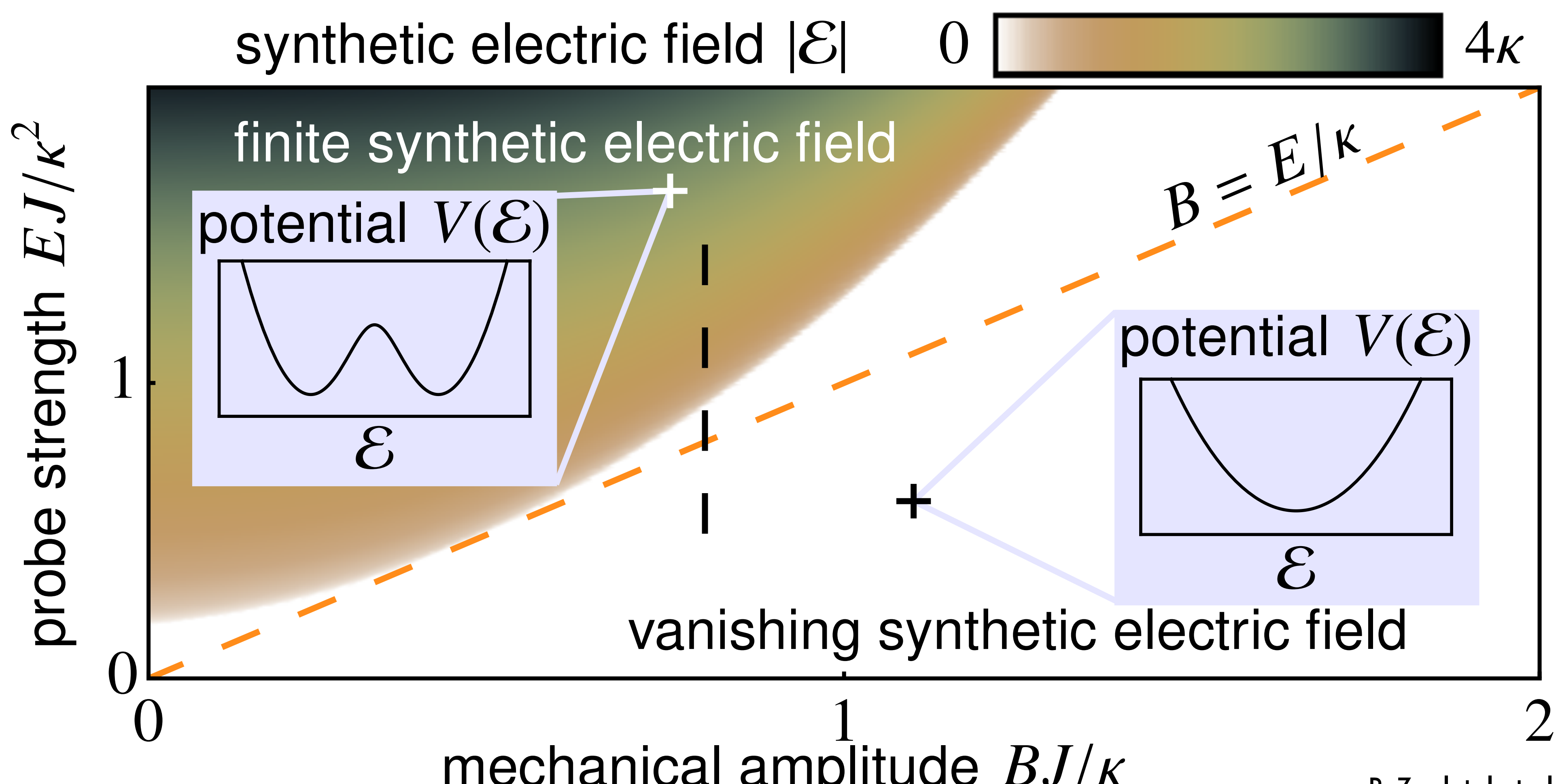
Dynamical phase diagram



Classical dynamics: $a_j = \langle \hat{a}_j \rangle$ **and** ϕ

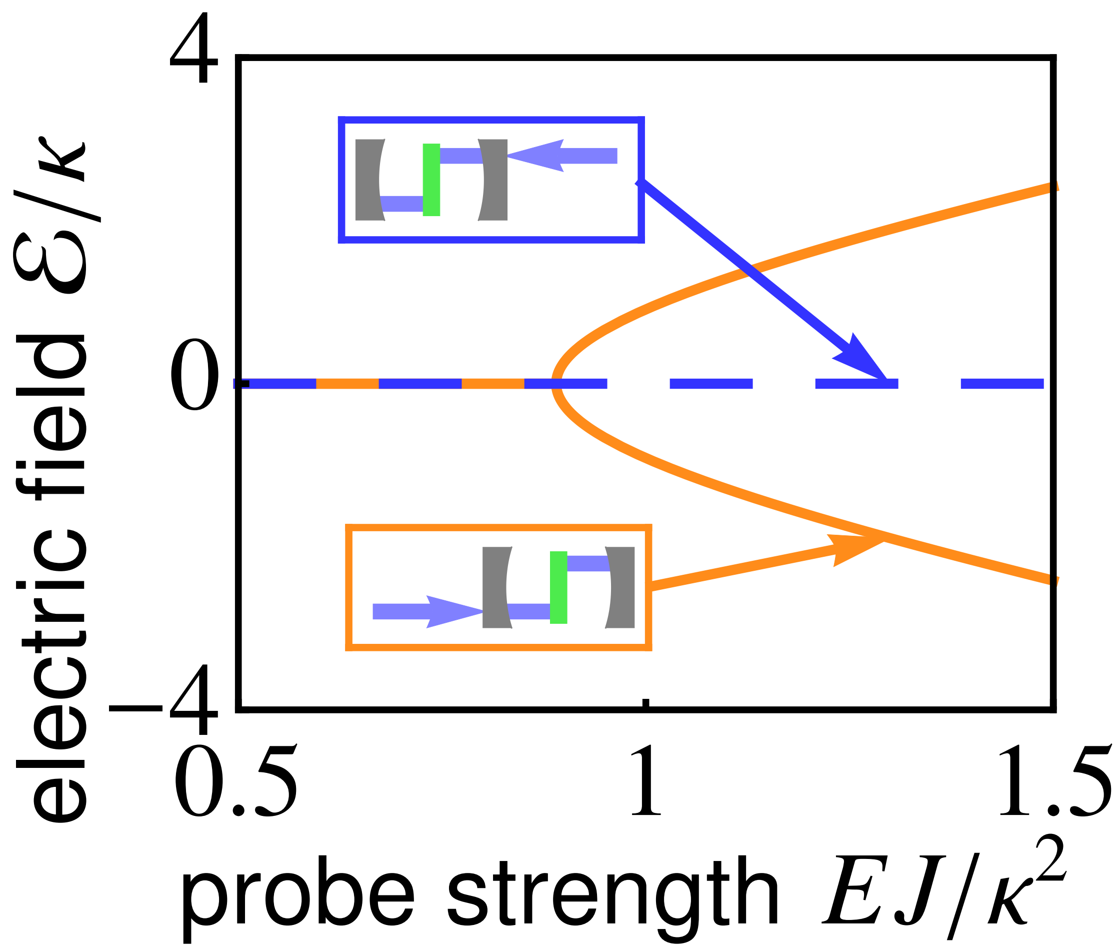
$$\dot{\phi} = -|a_1||a_2|\cos\left(\phi + \theta_1 - \theta_2\right)$$

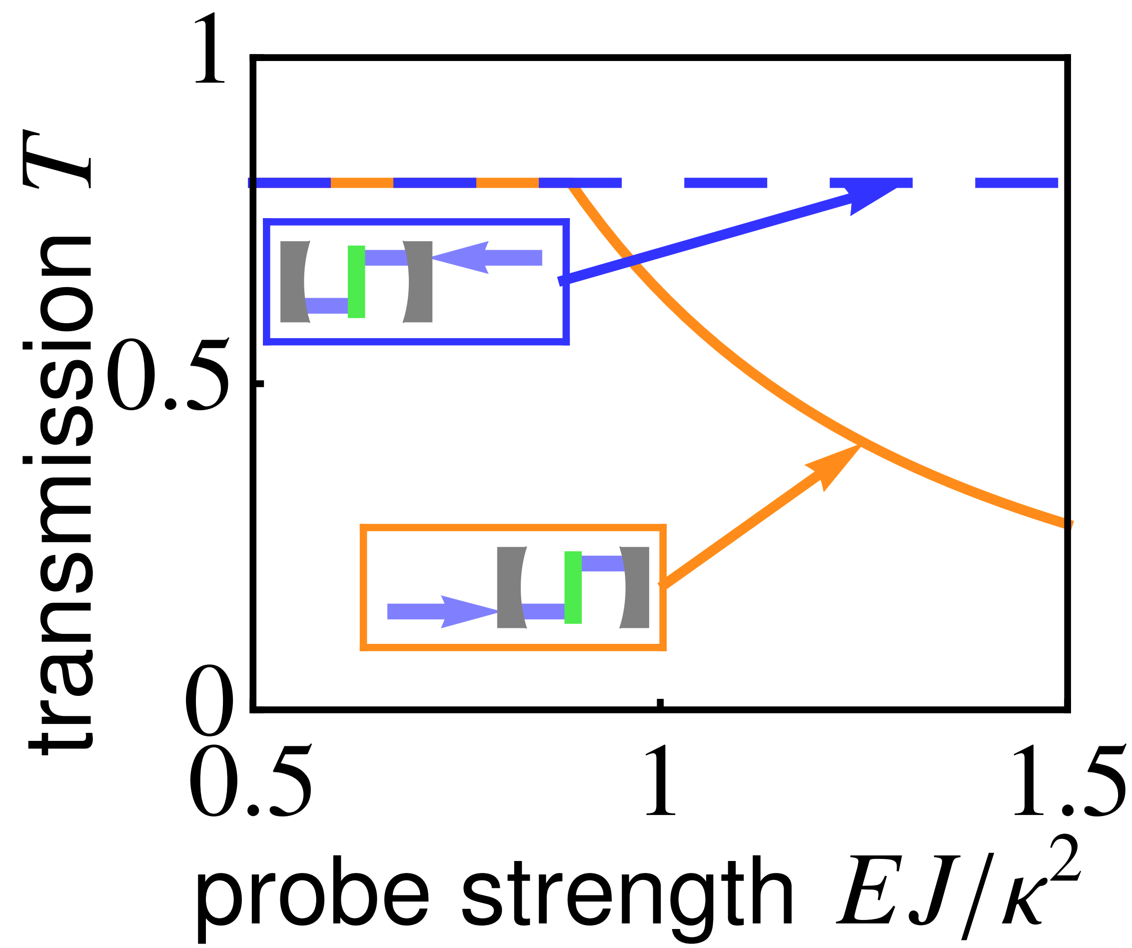
Photon decay rate κ



P. Zapletal et al., arXiv:1806.08191 (2018)

Unidirectional light transport





Synthetic electric field detunes the tunneling process
$\Longrightarrow$ transmission suppressed

This effect can be enhanced 1D arrays

P. Zapletal et al., arXiv:1806.08191 (2018)

Outline

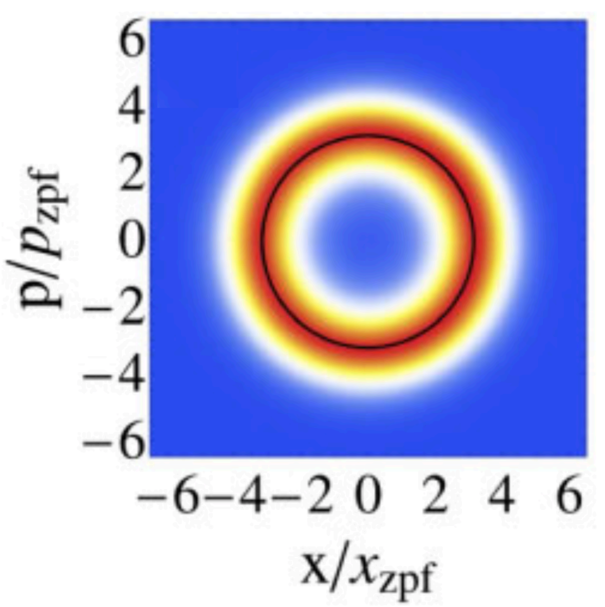
1. Optomechanical arrays
2. Synthetic gauge fields
3. Dynamical gauge fields $\Longrightarrow$ unidirectional transport
4. Dynamical gauge fields in the quantum regime

Synthetic el. fields in quantum regime

Effects of quantum fluctuations on unidirectional light transport

Model of mechanical self-oscillations:

Quantum van der Pol oscillator



S. Walter et al., Phys. Rev. Lett. **112**, 094102 (2014).

$$\dot{\rho} = -i\left[\hat{H},\rho\right] + \gamma_1 \mathcal{D}[\hat{b}^\dagger]\rho + \gamma_2 \mathcal{D}[\hat{b}^2]\rho$$

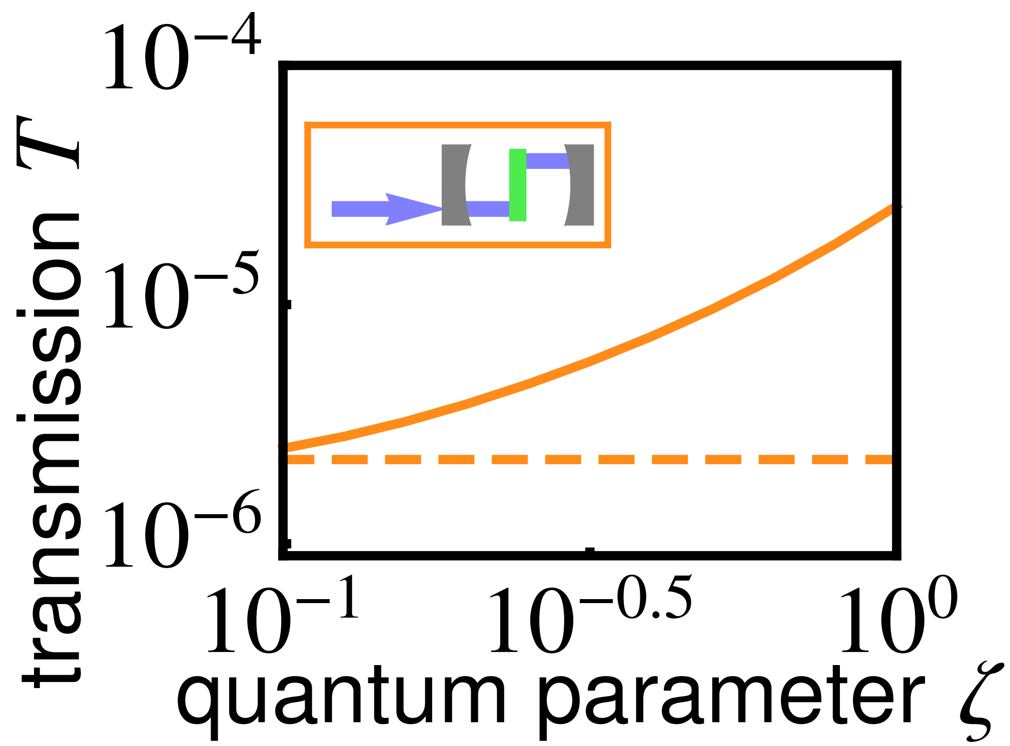
$$\mathcal{D}[\mathcal{O}]\rho = \mathcal{O}\rho\mathcal{O}^\dagger - \frac{1}{2}\left\{\mathcal{O}^\dagger\mathcal{O},\rho\right\}$$

Proposed for the membrane-in-the-middle setup

Classical-to-quantum crossover

Strength of quantum fluctuations controlled by the quantum parameter

$$\zeta = J/\kappa$$



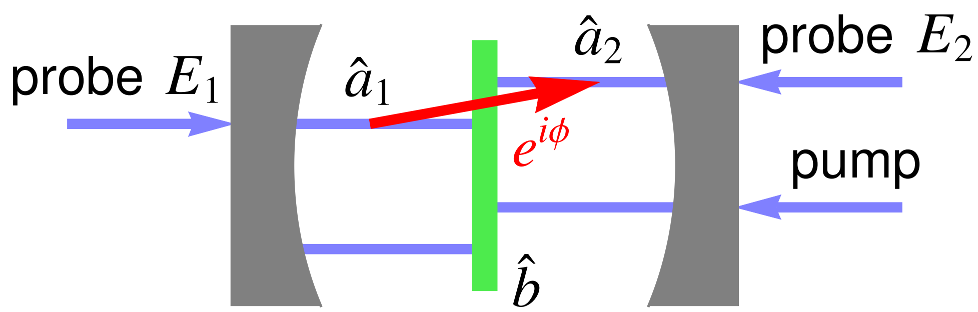
Quantum fluctuations broaden power spectra

$\Rightarrow$ increase transmission in the blockaded direction

$\Rightarrow$ isolation ratio decreased

However, unidirectional light transport is not completely destroyed.

Conclusions



$\Rightarrow$ Synthetic dynamical gauge fields

- Synthetic electric field $\Rightarrow$ unidirectional light transport

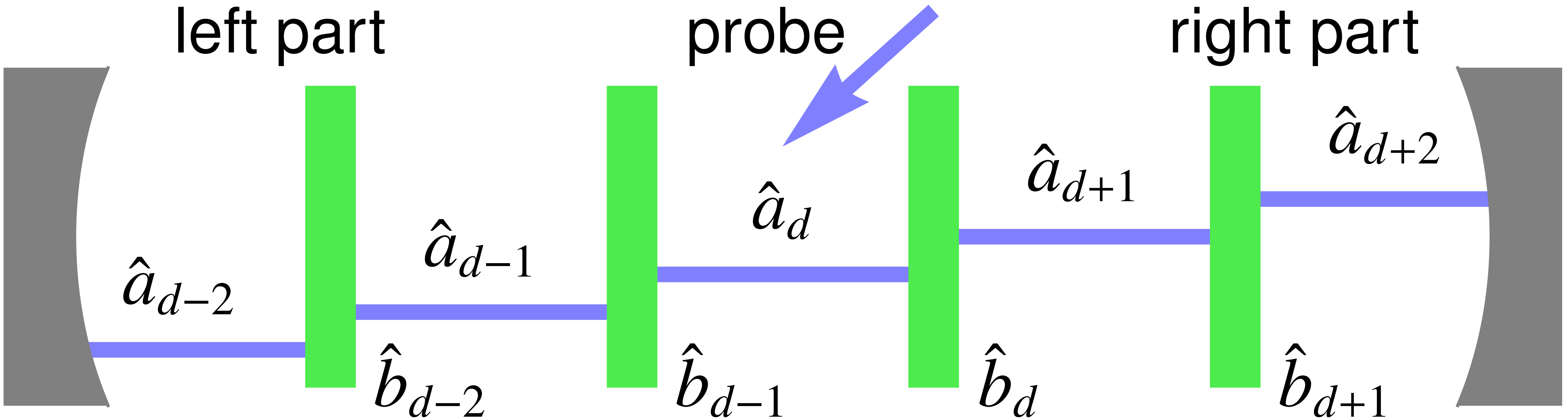
P. Zapletal et al., arXiv:1806.08191 (2018)

- Readily realizable with state-of-the-art optomechanics
- Unidirectional light transport reachable also in 2D square arrays
- In the quant. regime, isolation ratio decreased by quant. fluctuations

Outlook:

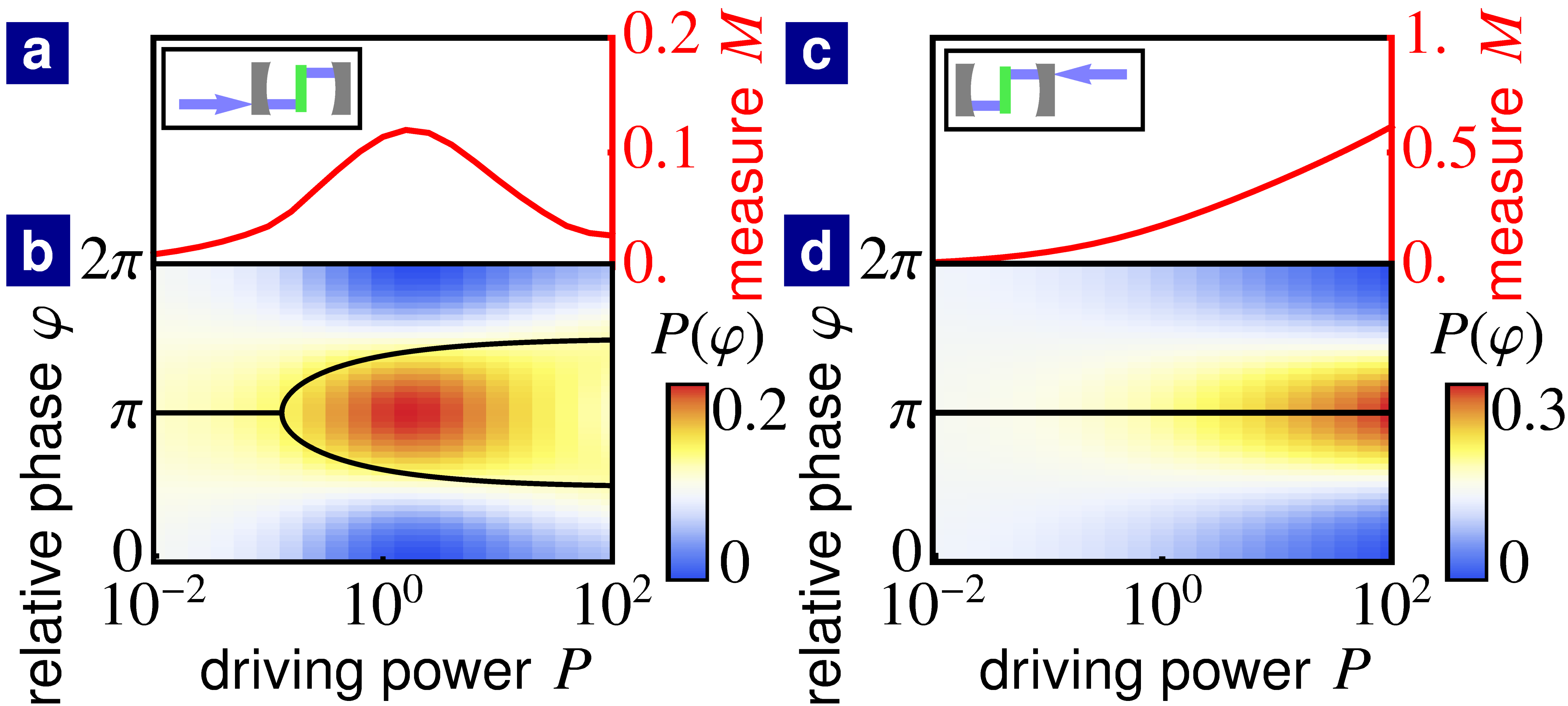
- Thermal fluctuations (Langevin equations)
- Incoherent driving and heat fluxes
- Synthetic electric fields and synchronization

One-Dimensional Arrays



Isolation ratio is exponentially increased $R_n = \left| \frac{a_{d+n}}{a_{d-n}} \right| = R_1^n$

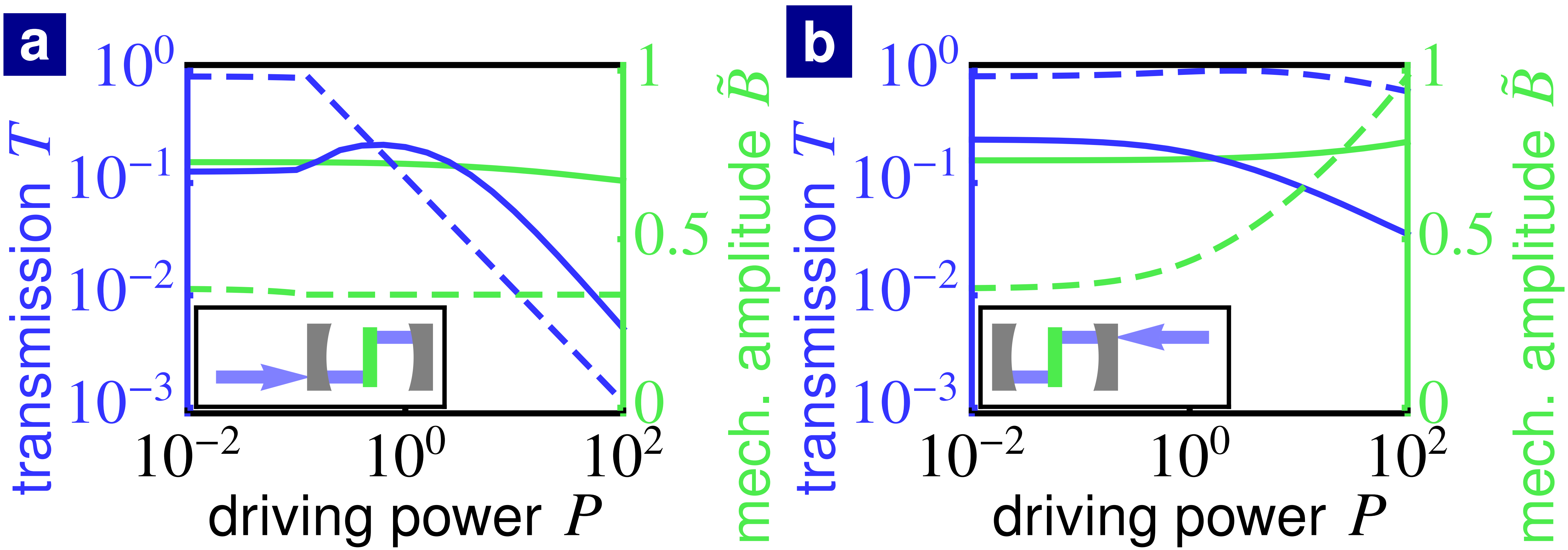
Generation of synthetic el. field in the quantum regime



Relative phase φ between the mech. mode and the non-driven opt. mode

Phase coherence measure $M = 2\pi \max\left(P\left(\varphi\right)\right) - 1$

Transmission in the quantum regime



Classical-to-quantum crossover