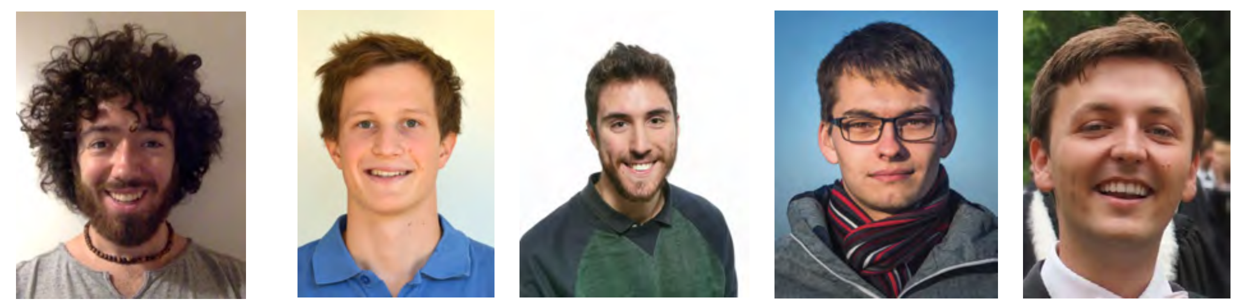
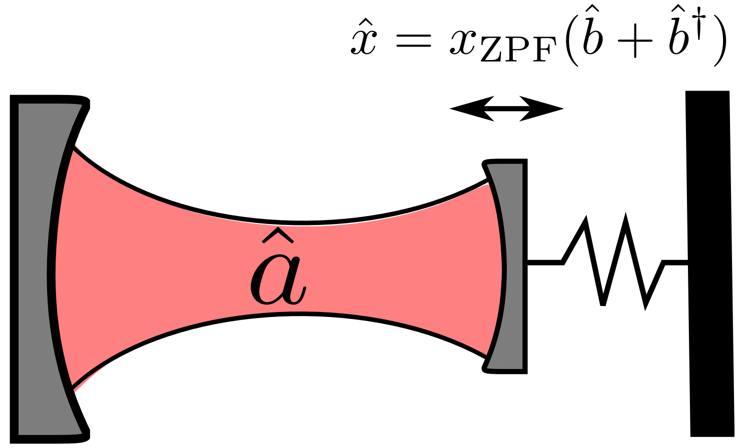
Cavity optomechanics: platform for nonreciprocity and synchronization

Andreas Nunnenkamp
Cavendish Laboratory

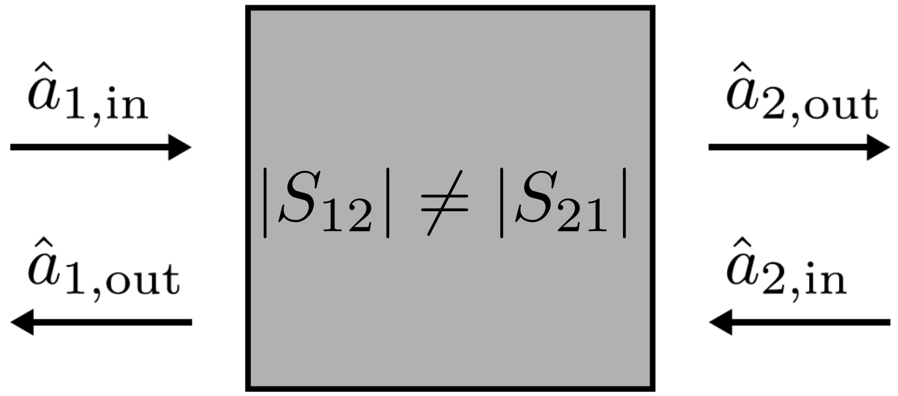


UNIVERSITY OF CAMBRIDGE
EPFL
HITACHI Inspire the Next
UNI BASEL
THE ROYAL SOCIETY
Hybrid Optomechanical Technologies
THE WINTON PROGRAMME FOR THE Physics of Sustainability

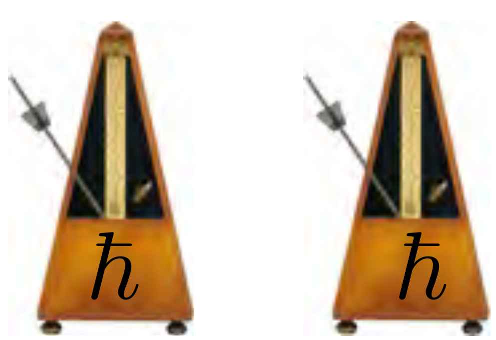
Outline



Cavity optomechanics



Nonreciprocal devices



Quantum synchronization

Cavity optomechanics

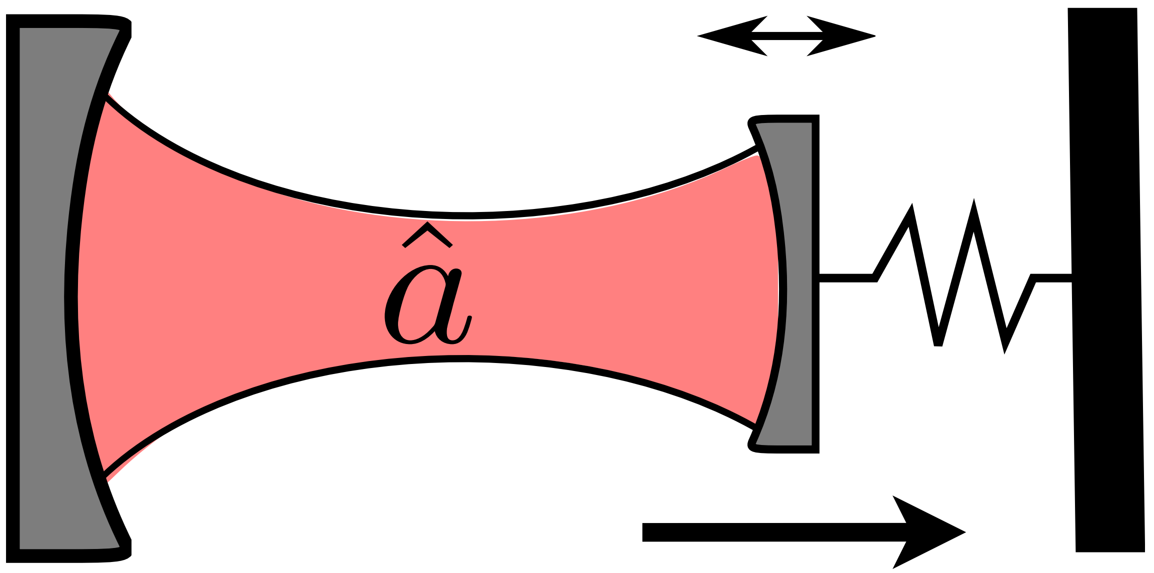
$$\hat{H} = \hbar\omega_C(\hat{x})\hat{a}^\dagger\hat{a} + \hbar\omega_M\hat{b}^\dagger\hat{b}$$

photons phonons

For small displacements

$$\omega_C(\hat{x}) = \omega_R + \frac{\partial\omega_C}{\partial x}\hat{x} + \ldots$$

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



Two parametrically coupled oscillators

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

radiation-pressure force

$$\hat{H}_{\mathrm{int}} = -\hat{F}\hat{x} \qquad \hat{F} = \frac{\hbar\omega_R}{L}\hat{a}^\dagger\hat{a}$$

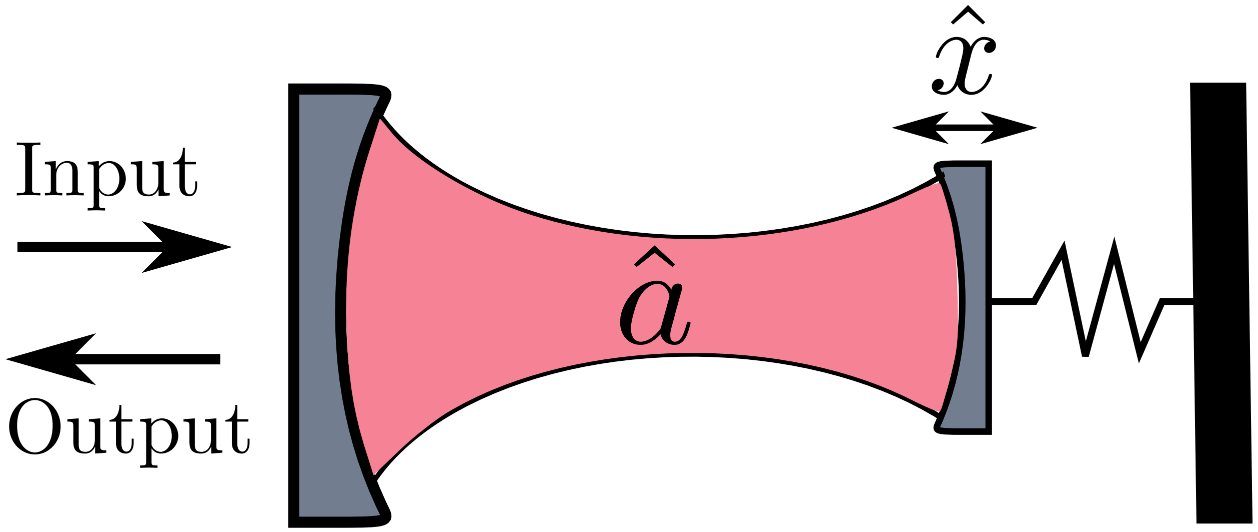
AN, Børkje, and Girvin, PRL 2011

First analysis of single-photon coupling

Børkje, **AN**, and Girvin, PRA 2010

Signature of radiation pressure shot noise

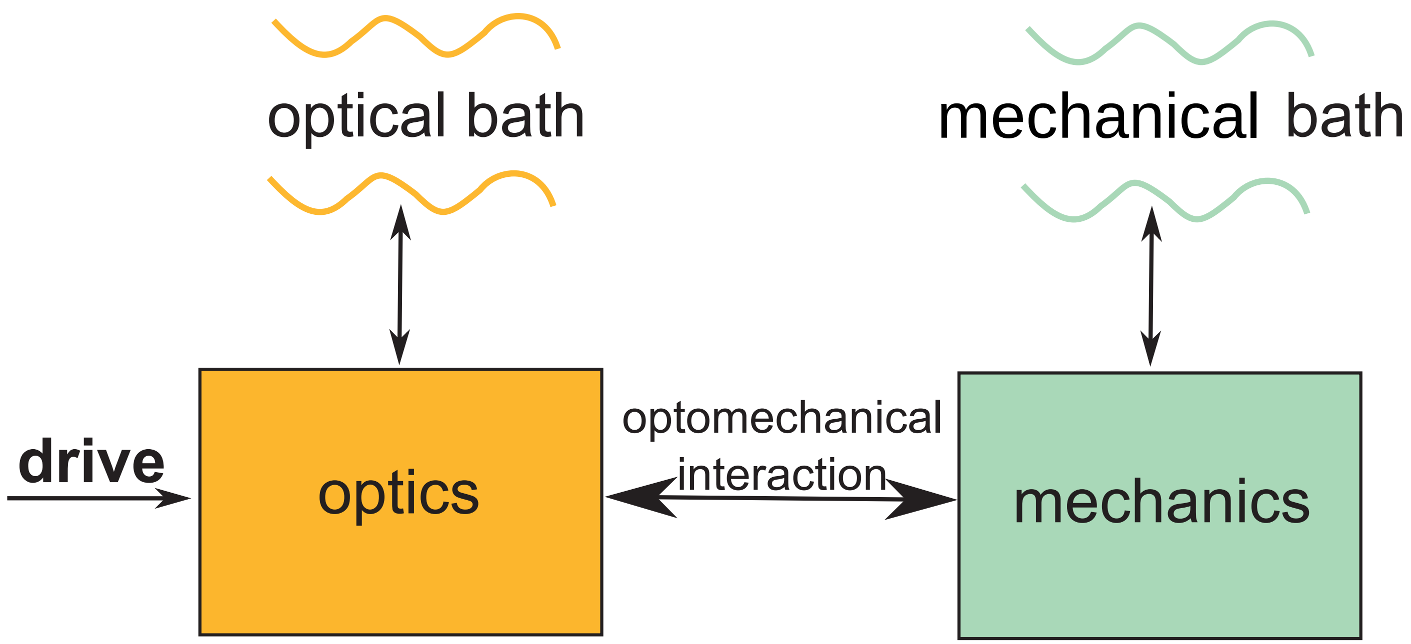
Cavity optomechanics



- open quantum system
- coherence and dissipation
- far from equilibrium

+

$$\hat{H}_{\text{int}} = -\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$$



rich physics: steady states, limit cycles, classical chaos

Cavity optomechanics

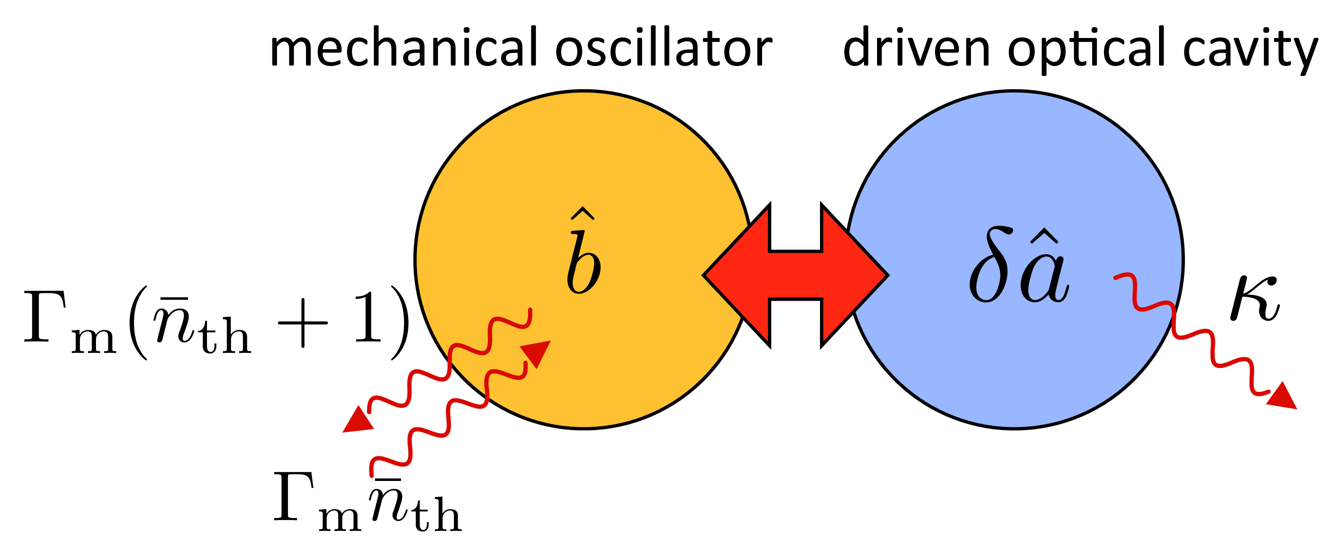
$$\hbar g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$$

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

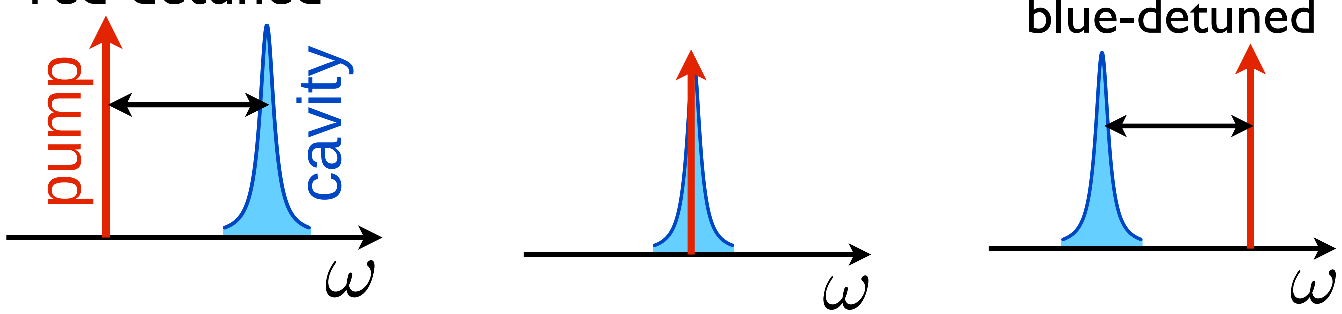
$$\hbar g_0 (\alpha \delta\hat{a}^\dagger + \alpha^* \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

$$g = g_0 \alpha$$

enhanced, reconfigurable coupling with tunable phase



Quantum optomechanics toolbox



red-detuned		blue-detuned
$\Delta = -\omega_m$	$\Delta = 0$	$\Delta = +\omega_m$
beam-splitter (cooling)	QND	squeezer (entanglement)
$\delta\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\delta\hat{a}$	$\hat{x}_a\hat{x}_b$	$\delta\hat{a}^\dagger\hat{b}^\dagger + \hat{b}\delta\hat{a}$

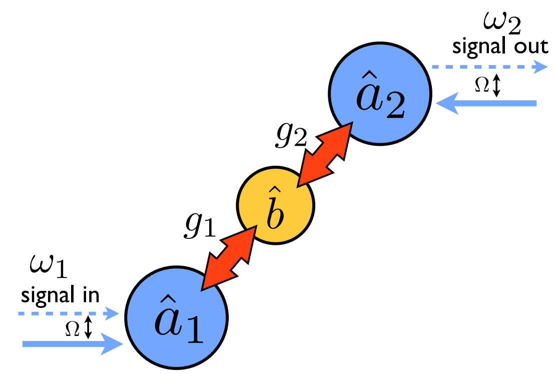
Input-output scattering matrix

$$\hat{a}_{\mathrm{out}} = S(\omega)\hat{a}_{\mathrm{in}}$$

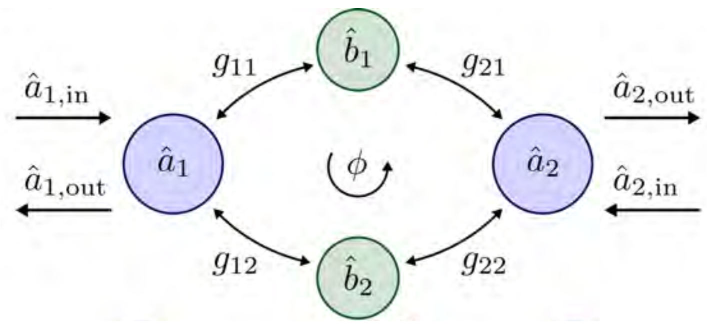
Aspelmeyer, Kippenberg, and Marquardt, Rev. Mod. Phys. **86**, 1391 (2014)

Hybrid optomechanical technologies ‘HOT’

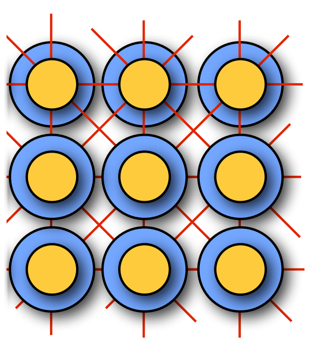
Quantum-limited transducer
(microwave to optical link)



Nonreciprocal devices
(isolator, circulator, amplifier)



Mechanical “metamaterials”
Topological light and sound



Hybrid Optomechanical Technologies

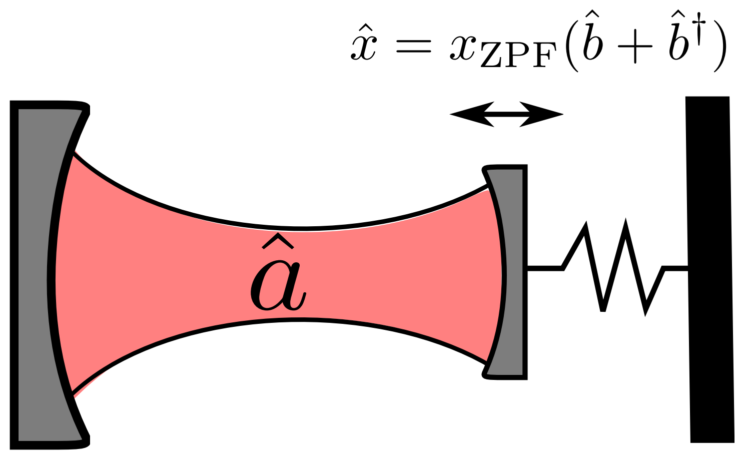
€10Mio, 4 years,
17 partners

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

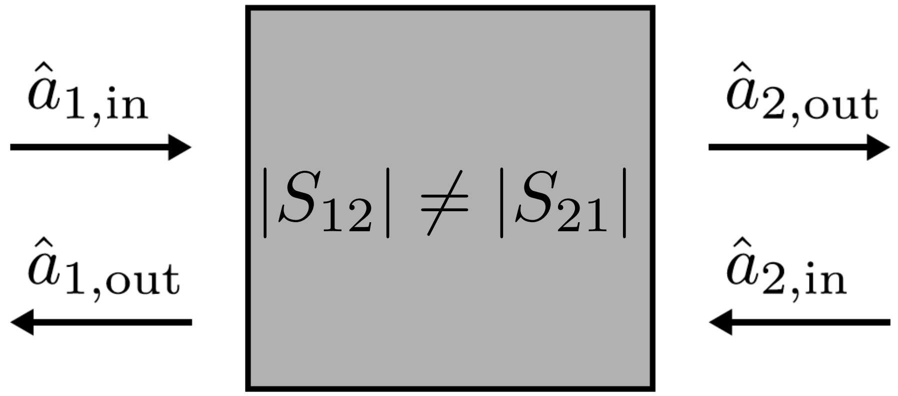
UNIVERSITY OF CAMBRIDGE

HITACHI
Inspire the Next

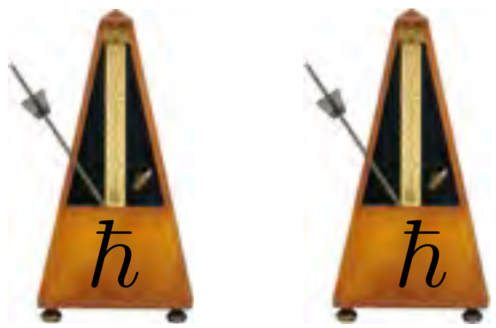
Outline



Cavity optomechanics



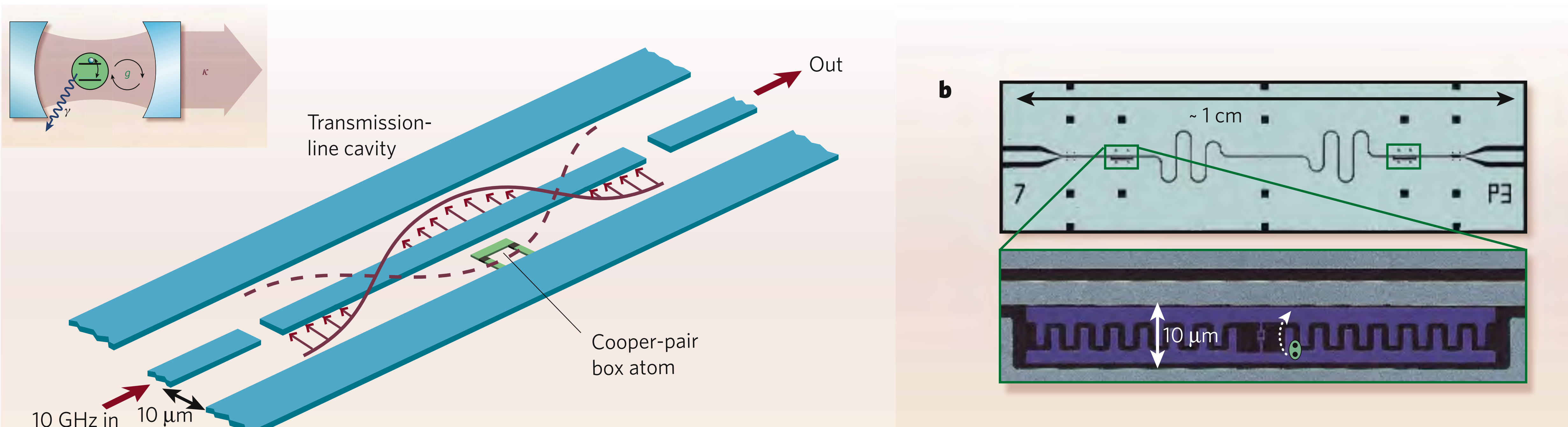
Nonreciprocal devices



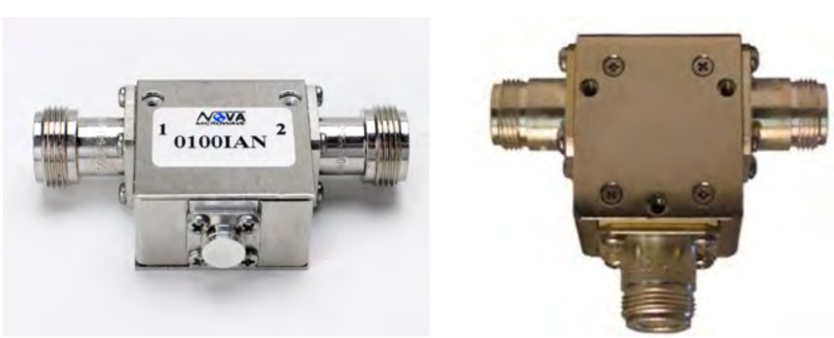
Quantum synchronization

Nonreciprocal devices by reservoir engineering

(quantum) source → non-reciprocal device e.g. isolator, circulator → amplifier, read-out



Schoelkopf and Girvin, Nature **451**, 664 (2008)

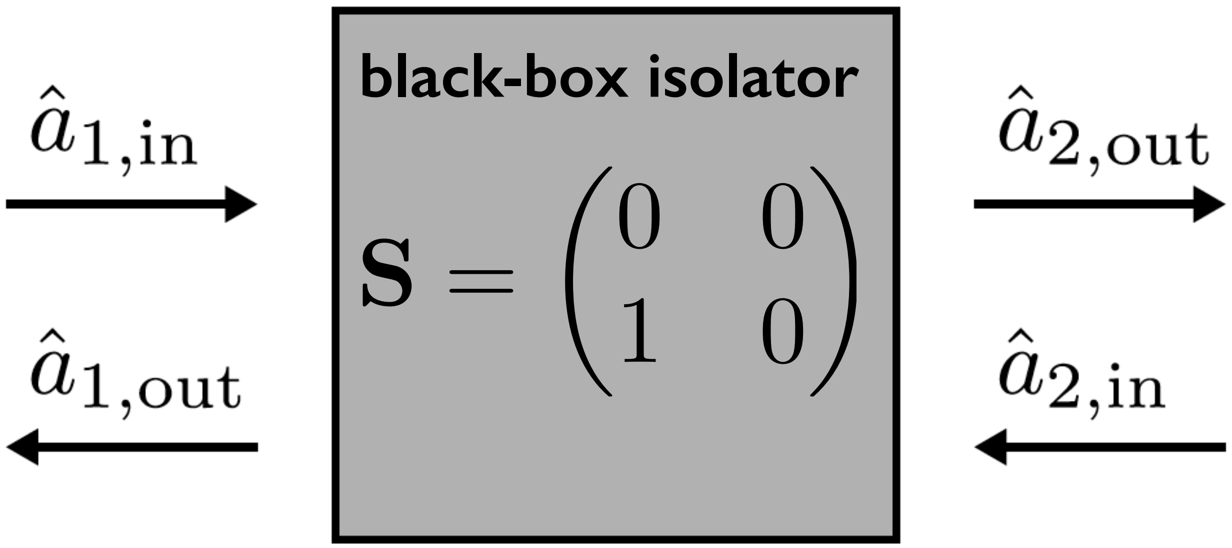


Magneto-optical effect (YIG) breaks Lorentz reciprocity.

But: bulky, lossy, large magnetic fields
→ searching for on-chip, reconfigurable, magnetic-field-free, nonreciprocal device

Jalas *et al.*, Nature Photonics **7**, 579 (2013)
Verhagen and Alu, Nature Physics **13**, 922 (2017)

Nonreciprocal devices by reservoir engineering

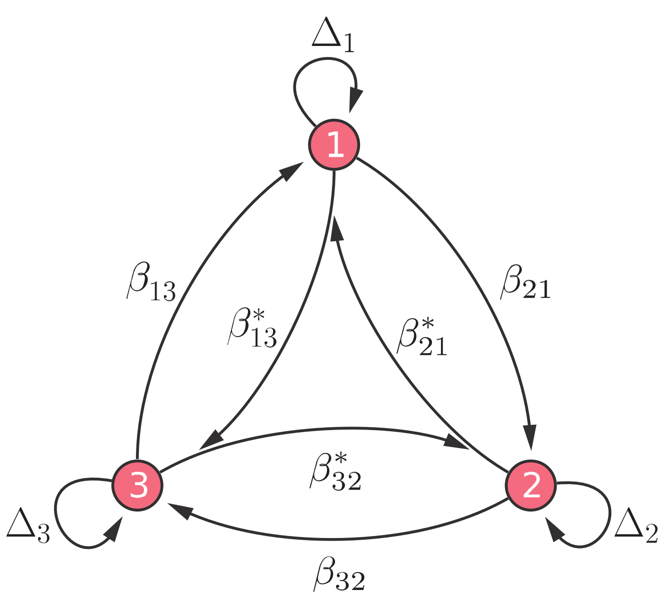


$$\begin{pmatrix} \hat{a}_{1,\mathrm{out}} \\ \hat{a}_{2,\mathrm{out}} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} \hat{a}_{1,\mathrm{in}} \\ \hat{a}_{2,\mathrm{in}} \end{pmatrix}$$

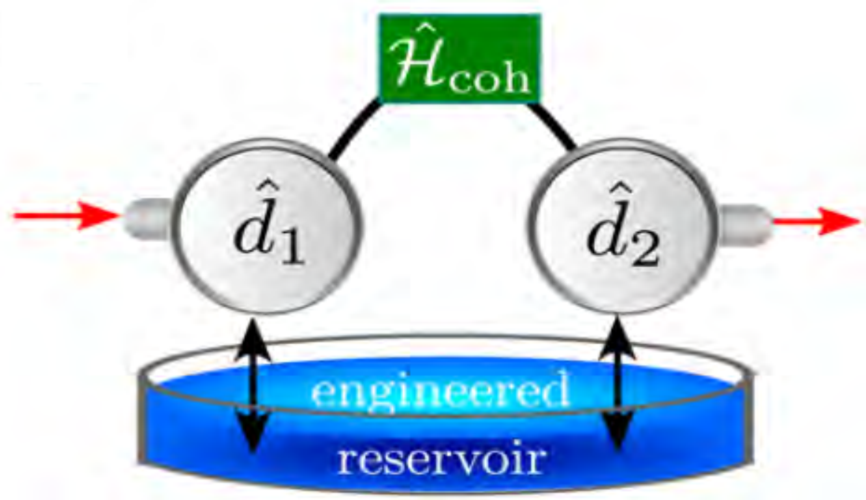
nonreciprocal if

$$|S_{12}| \neq |S_{21}|$$

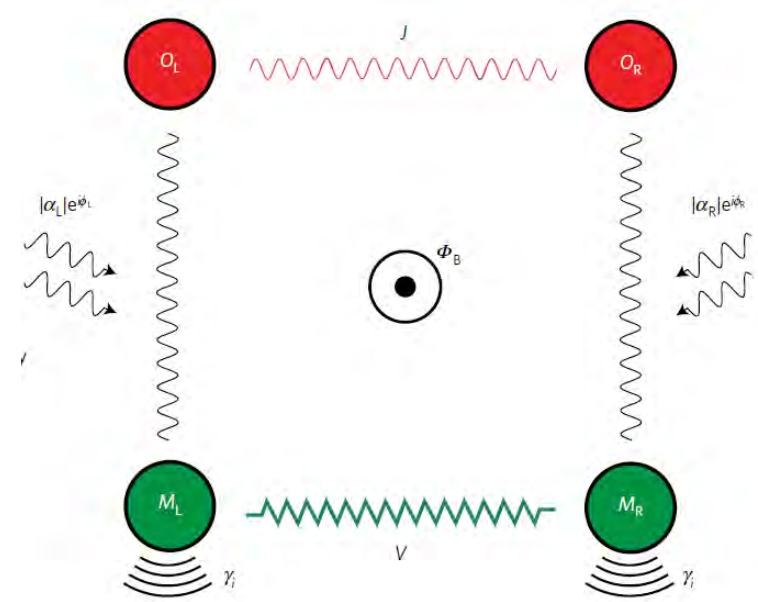
Some of the recent work on non-reciprocity using reservoir engineering



Ranzani and Aumentado,
NJP **17**, 023024 (2015)

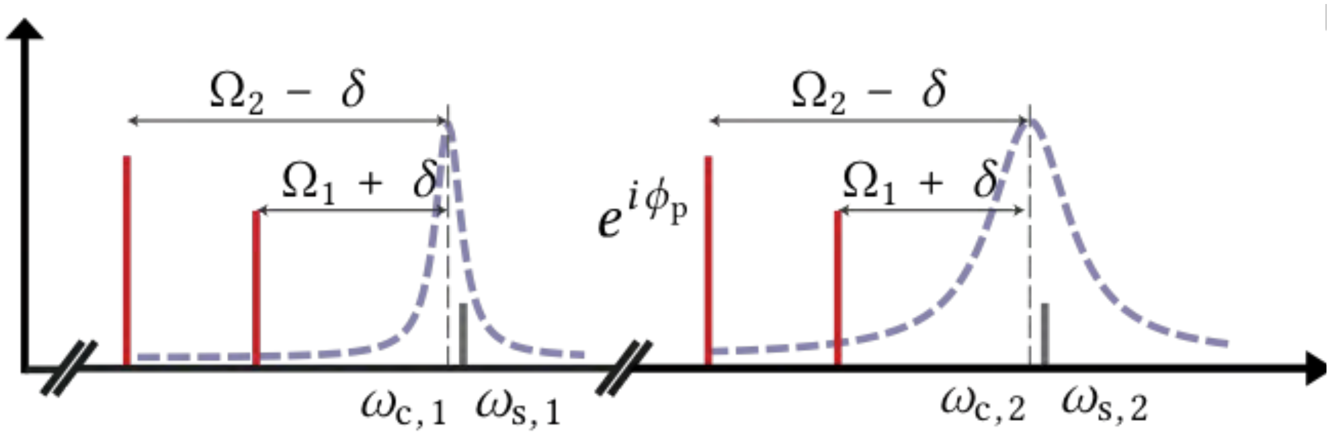


Metelmann and Clerk,
PRX **5**, 021025 (2015)

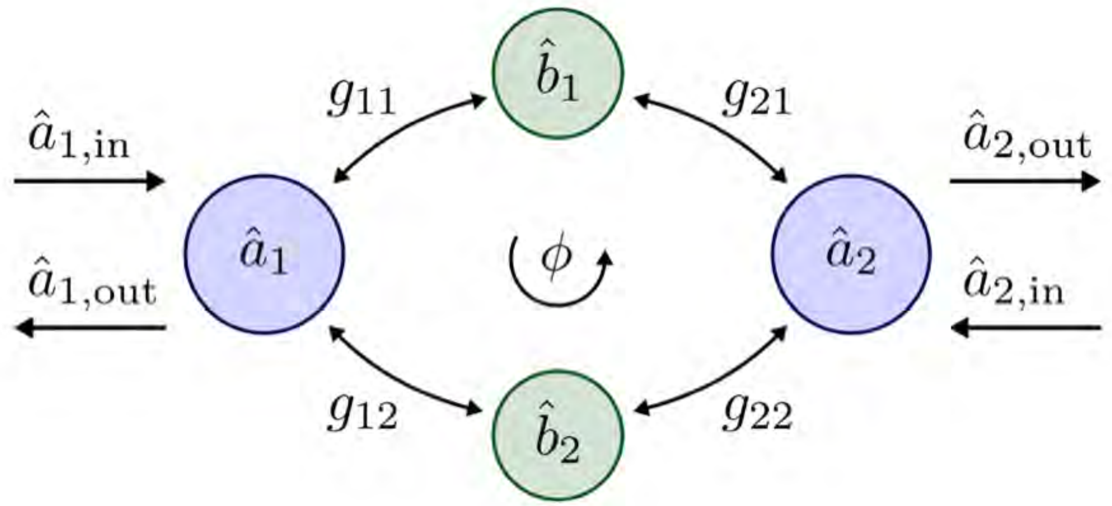


Fang, …, Painter
Nat. Phys. **13**, 465 (2017)

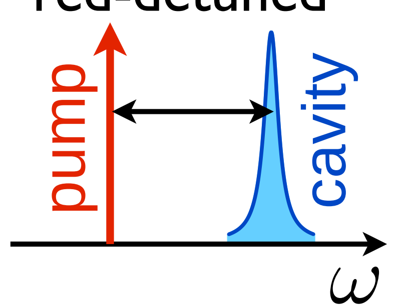
Nonreciprocal devices by reservoir engineering



two cavities, two mechanics, four coherent drives



optomechanical plaquette with gauge-invariant phase



$$\Delta = -\omega_m$$

beam-splitter (cooling)

$$\hat{a}\hat{b}^\dagger + \hat{a}^\dagger\hat{b}$$

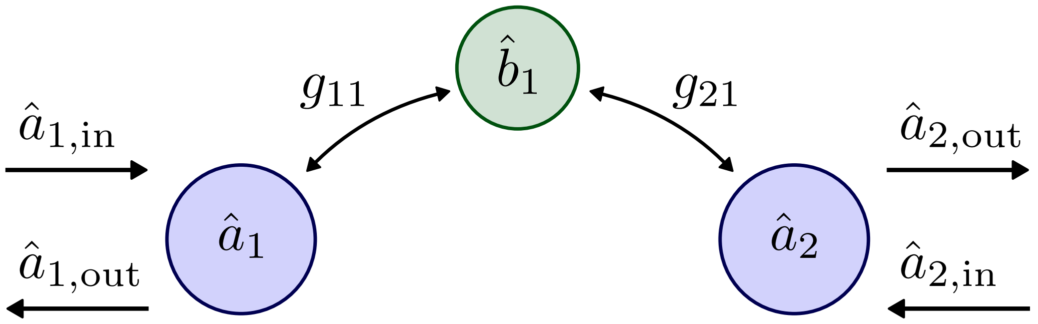
$$H = -\delta\, \hat{b}_1^\dagger \hat{b}_1 + \delta\, \hat{b}_2^\dagger \hat{b}_2 + g_{11}(\hat{a}_1\hat{b}_1^\dagger + \hat{a}_1^\dagger\hat{b}_1) + g_{21}(\hat{a}_2\hat{b}_1^\dagger + \hat{a}_2^\dagger\hat{b}_1)$$
$$+ g_{12}(\hat{a}_1\hat{b}_2^\dagger + \hat{a}_1^\dagger\hat{b}_2) + g_{22}(e^{i\phi}\hat{a}_2\hat{b}_2^\dagger + e^{-i\phi}\hat{a}_2^\dagger\hat{b}_2)$$

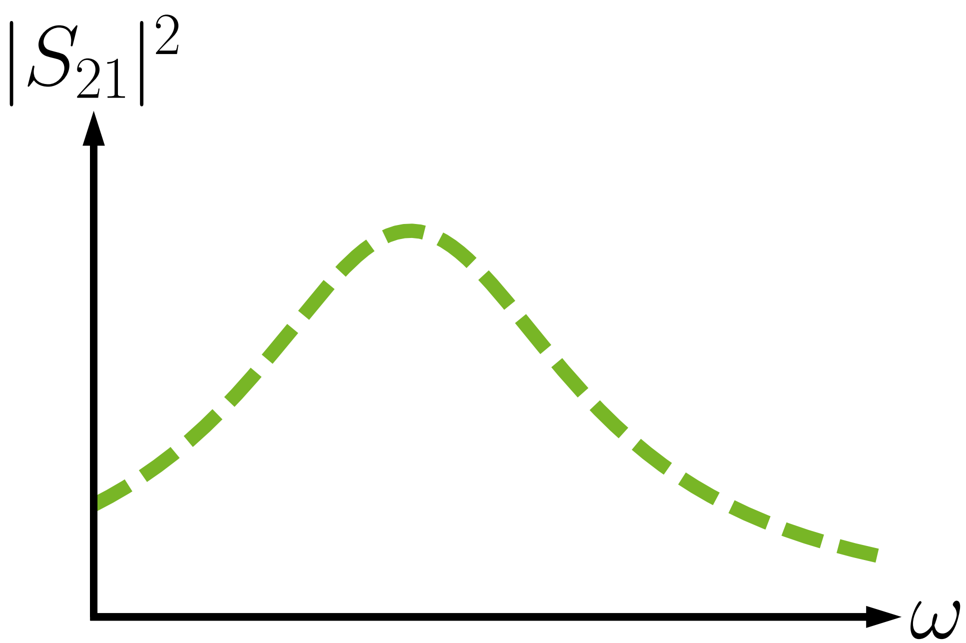
Artificial magnetic field for photons and phonons in a "synthetic dimension" by drives (broken time reversal)

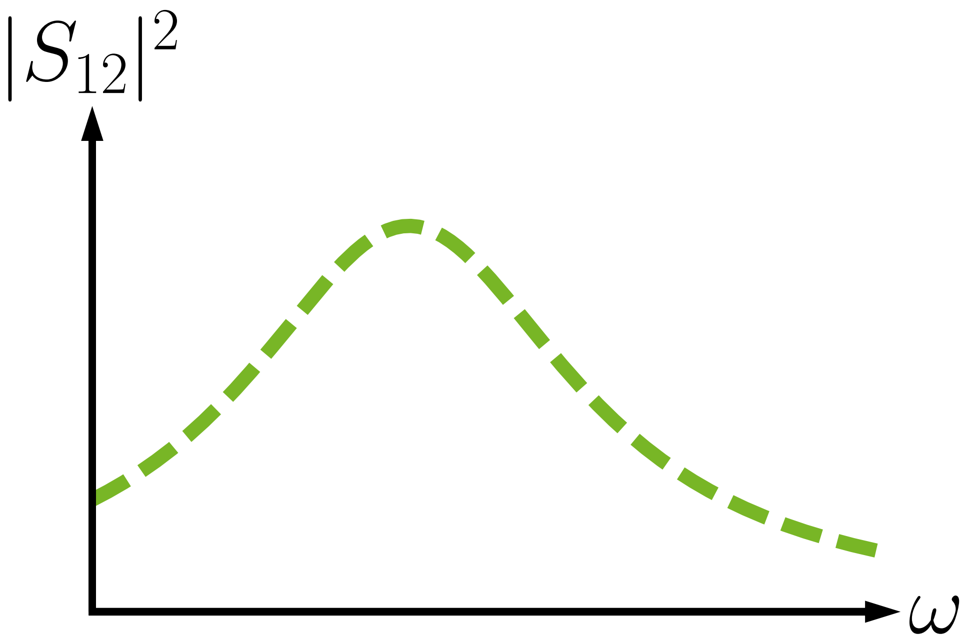
Bernier et al., Nat. Commun. **8**, 604 (2017)
also: Peterson et al., Phys. Rev. X **7**, 031001 (2017)

Nonreciprocal devices by reservoir engineering

single path: reciprocal frequency conversion



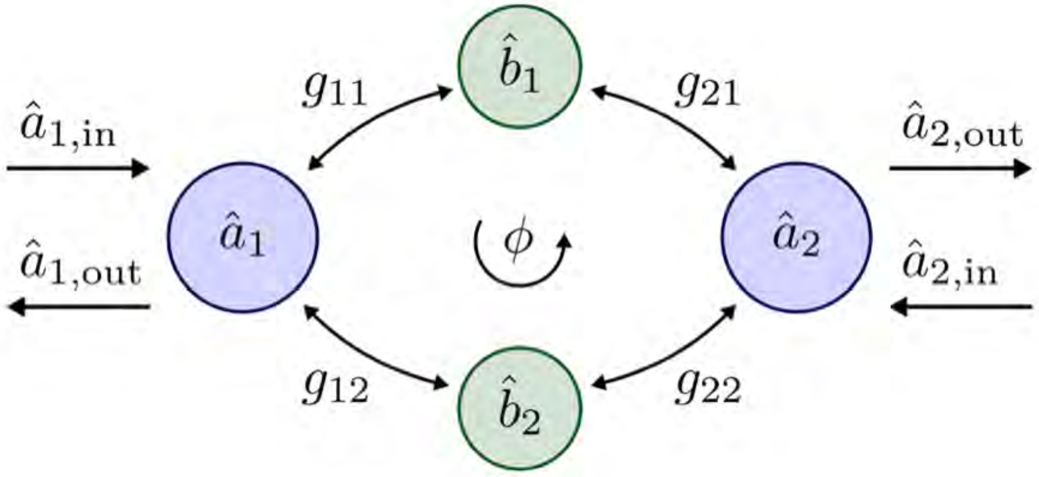




Andrews *et al.*, Nature Physics **10**, 321 (2014)
Lecocq *et al.*, PRL **116**, 043601 (2016)

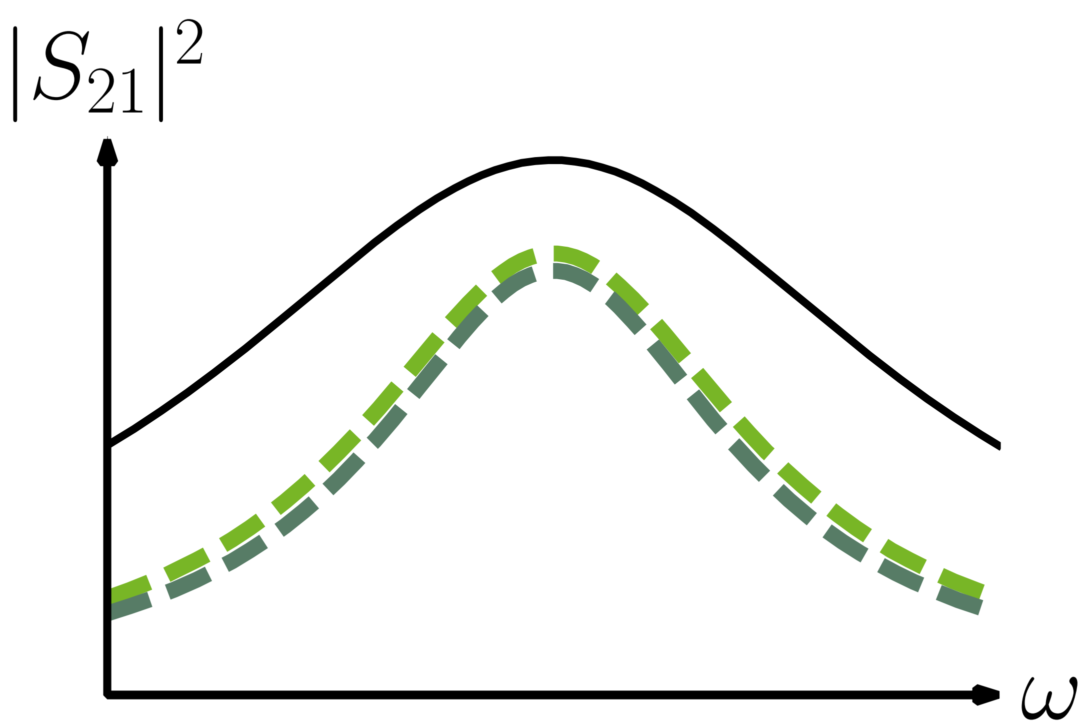
Nonreciprocal devices by reservoir engineering

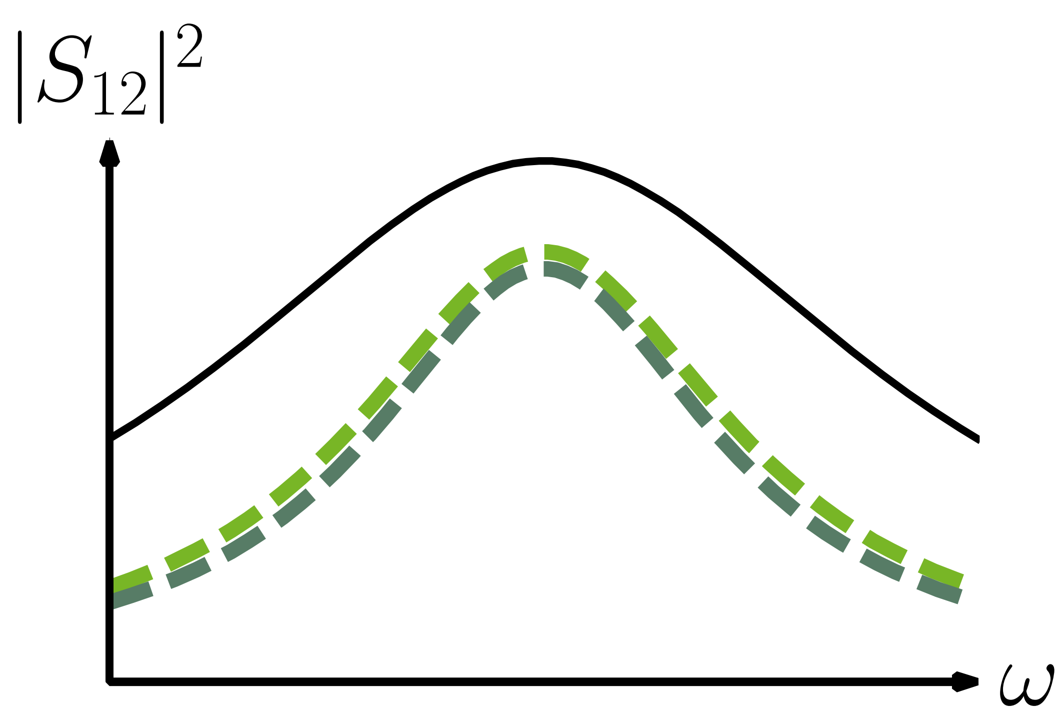
two symmetric paths : still reciprocal frequency conversion



Interference of two coupling amplitudes

$$\frac{S_{12}(\omega)}{S_{21}(\omega)} = \frac{g_{11}\chi_1(\omega)g_{21} + g_{12}\chi_2(\omega)g_{22}e^{+i\phi}}{g_{11}\chi_1(\omega)g_{21} + g_{12}\chi_2(\omega)g_{22}e^{-i\phi}}$$

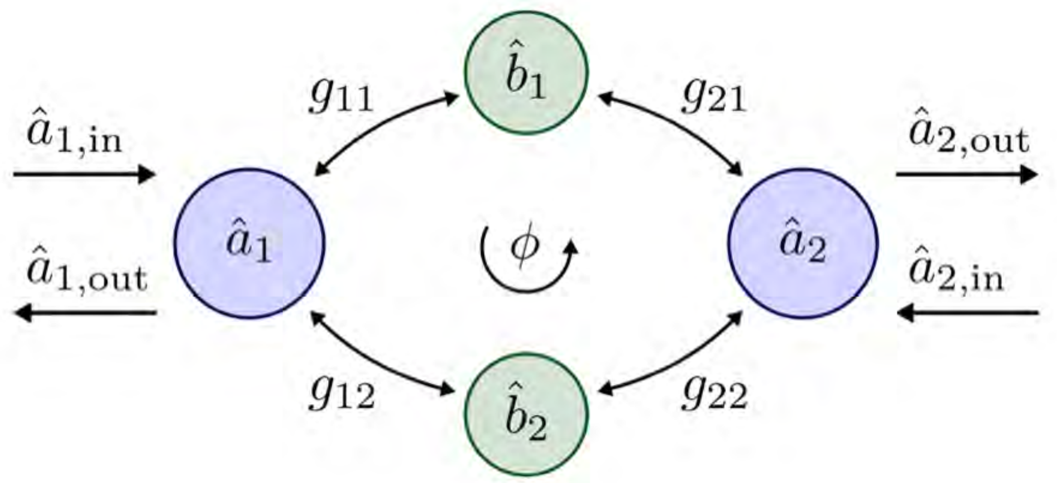




Bernier… Malz, **AN**…, Nat. Commun. **8**, 604 (2017)

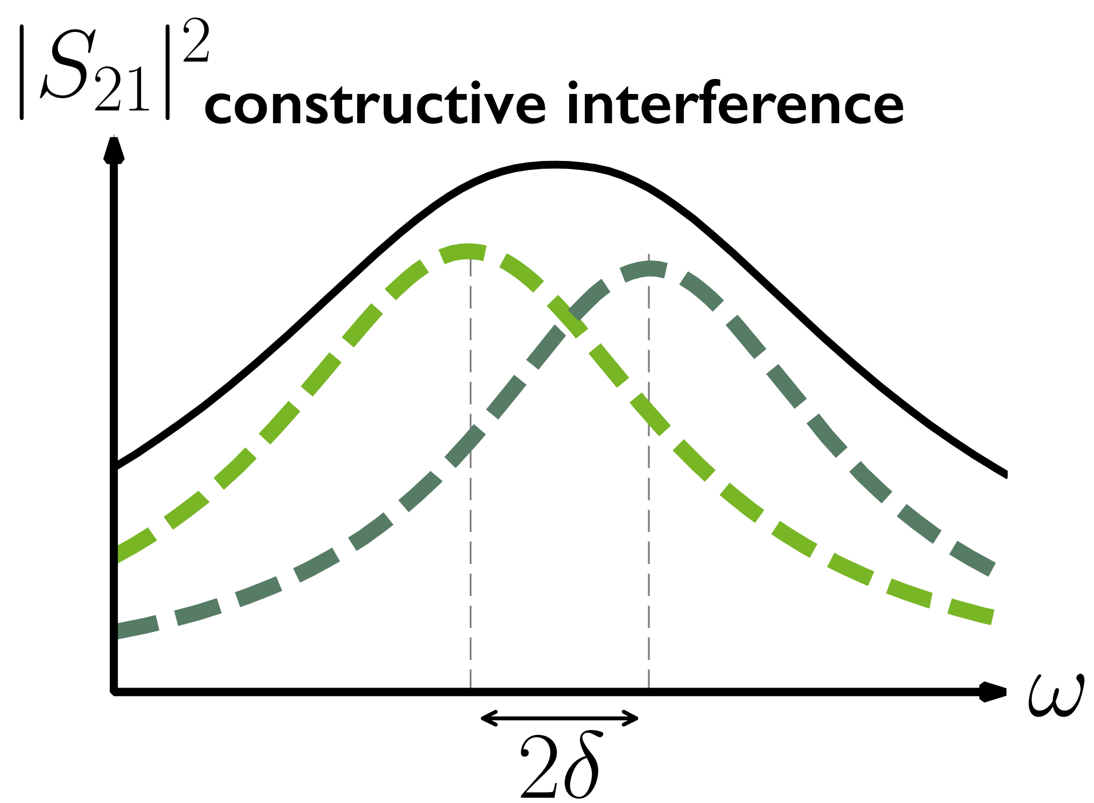
Nonreciprocal devices by reservoir engineering

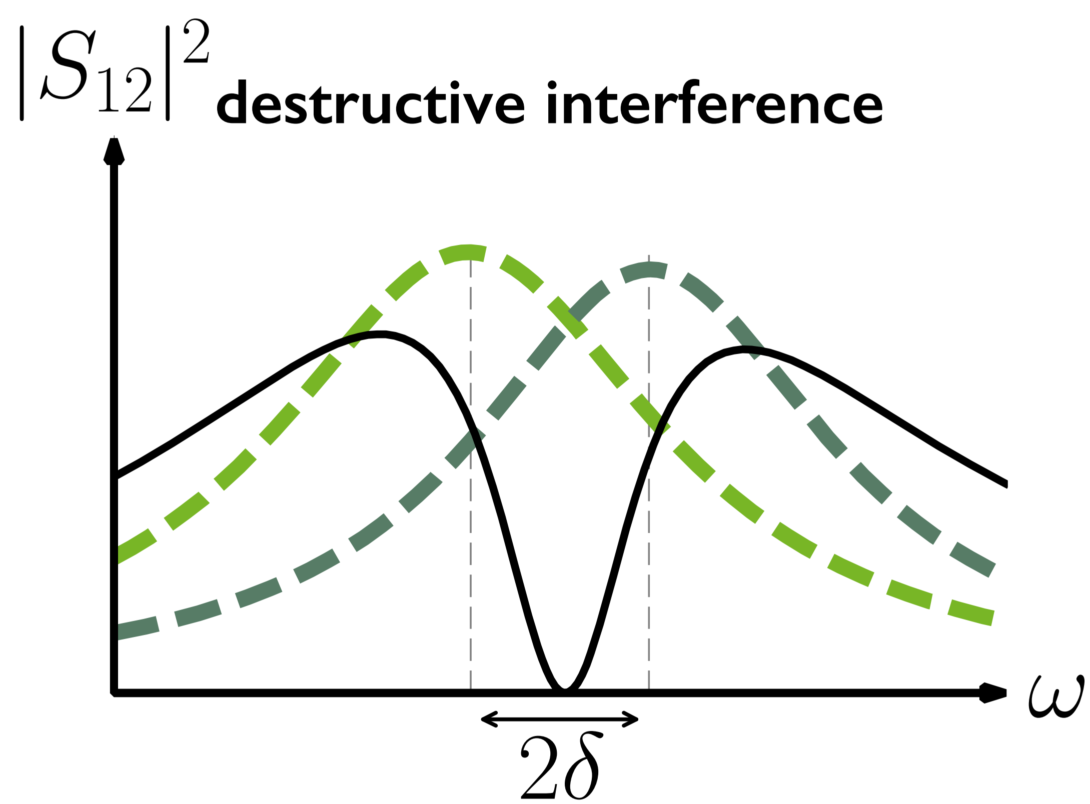
two asymmetric paths: non-reciprocal frequency conversion



Interference of two coupling amplitudes (broken time reversal, dissipation, asymmetry)

$$\frac{S_{12}(\omega)}{S_{21}(\omega)} = \frac{g_{11}\chi_1(\omega)g_{21} + g_{12}\chi_2(\omega)g_{22}e^{+i\phi}}{g_{11}\chi_1(\omega)g_{21} + g_{12}\chi_2(\omega)g_{22}e^{-i\phi}}$$

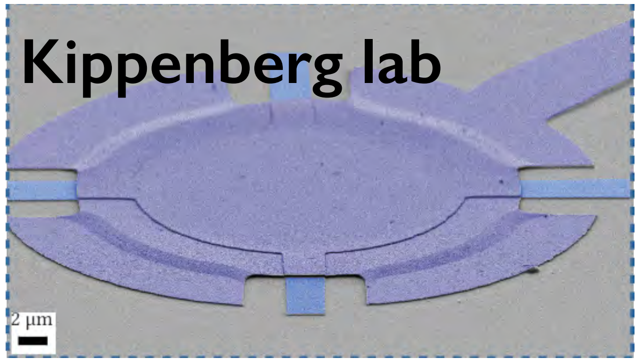


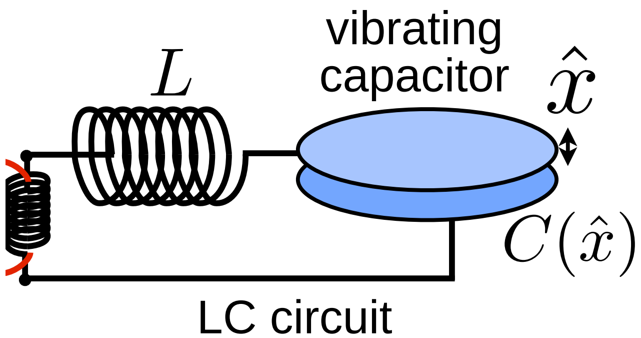


Bernier… Malz, **AN**…, Nat. Commun. **8**, 604 (2017)

Nonreciprocal devices by reservoir engineering

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE



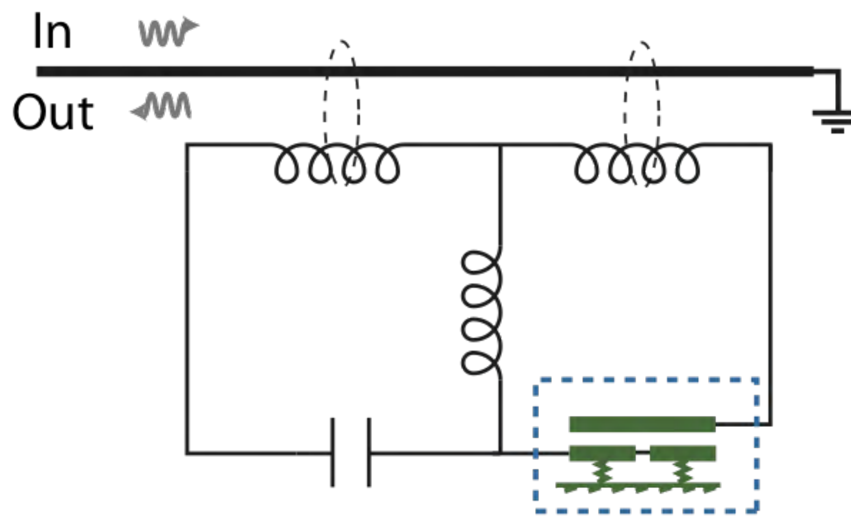


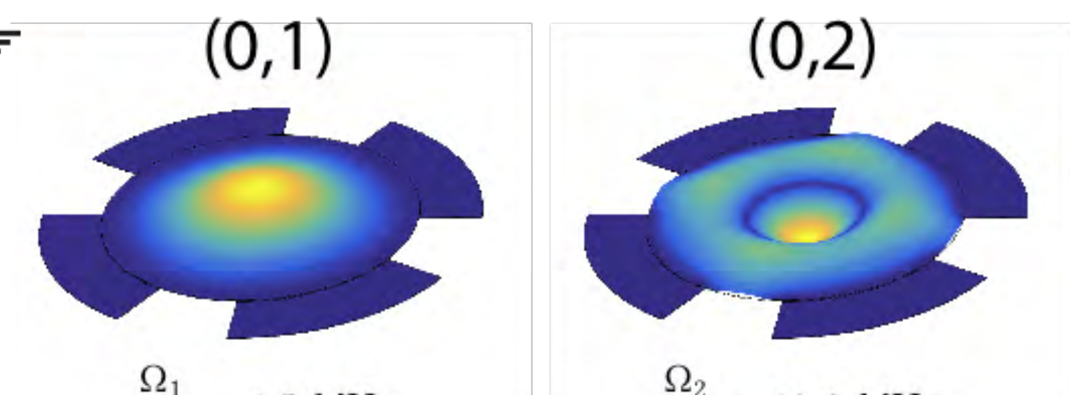
$$\hat{H} = \hbar\omega_C(\hat{x})\hat{a}^\dagger\hat{a}$$

nature physics
ARTICLES
PUBLISHED ONLINE: 15 MAY 2017 | DOI: 10.1038/NPHYS4121

A dissipative quantum reservoir for microwave light using a mechanical oscillator

L. D. Tóth[1†], N. R. Bernier[1†], A. Nunnenkamp[2], A. K. Feofanov[1*] and T. J. Kippenberg[1*]





$\frac{\Omega_1}{2\pi} = 6.5$ MHz

$\frac{\Omega_2}{2\pi} = 10.9$ MHz

$(\omega_{c,1},\omega_{c,2}) = 2\pi\cdot(0.2,3.4)$ MHz

$(\kappa_1,\kappa_2) = 2\pi\cdot(0.2,3.4)$ MHz

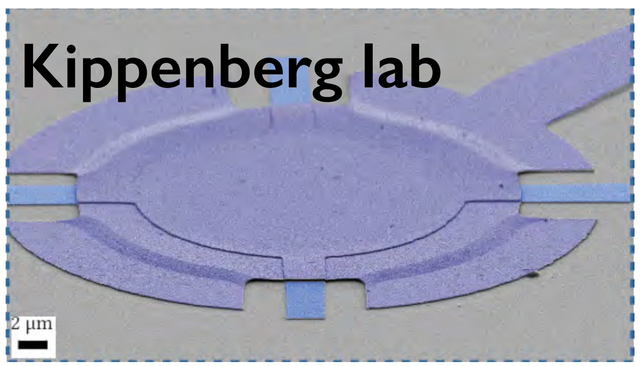
$(\Gamma_1,\Gamma_2) = 2\pi\cdot(30,10)$ Hz

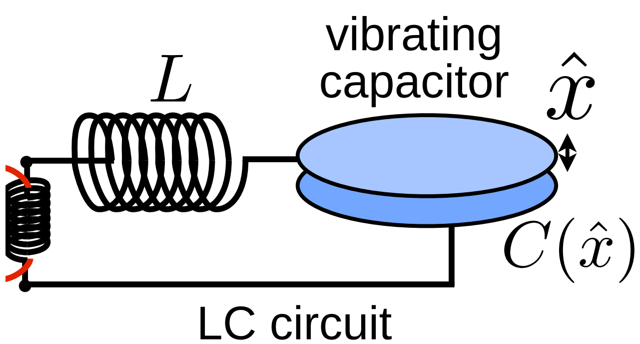
$(g_{0,1},g_{0,2}) = 2\pi\cdot(91,12)$ Hz

Bernier… Malz, **AN**…, Nat. Commun. **8**, 604 (2017)

Nonreciprocal devices by reservoir engineering

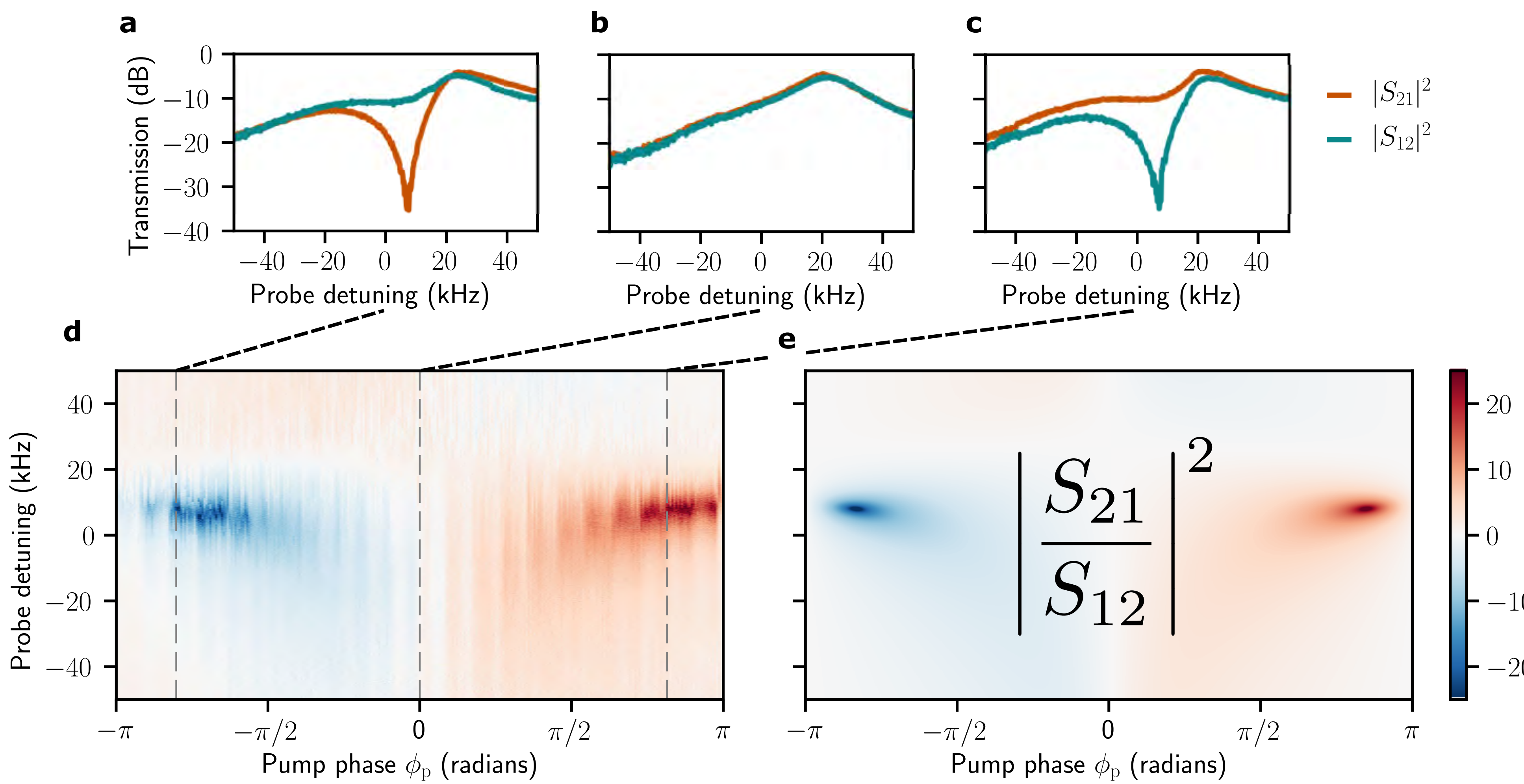
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE





$$\hat{H} = \hbar\omega_C(\hat{x})\hat{a}^\dagger\hat{a}$$

low insertion loss,
low added noise

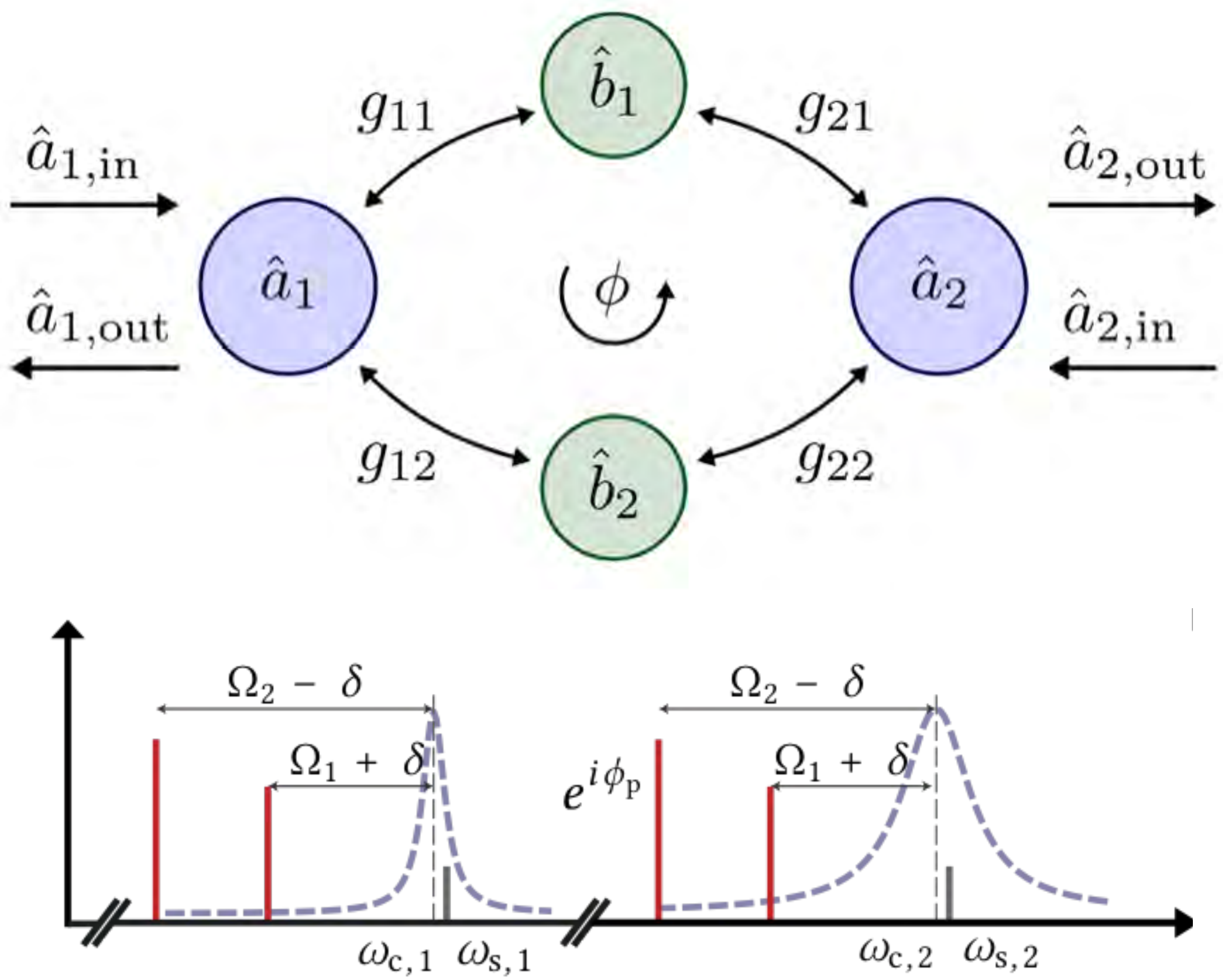


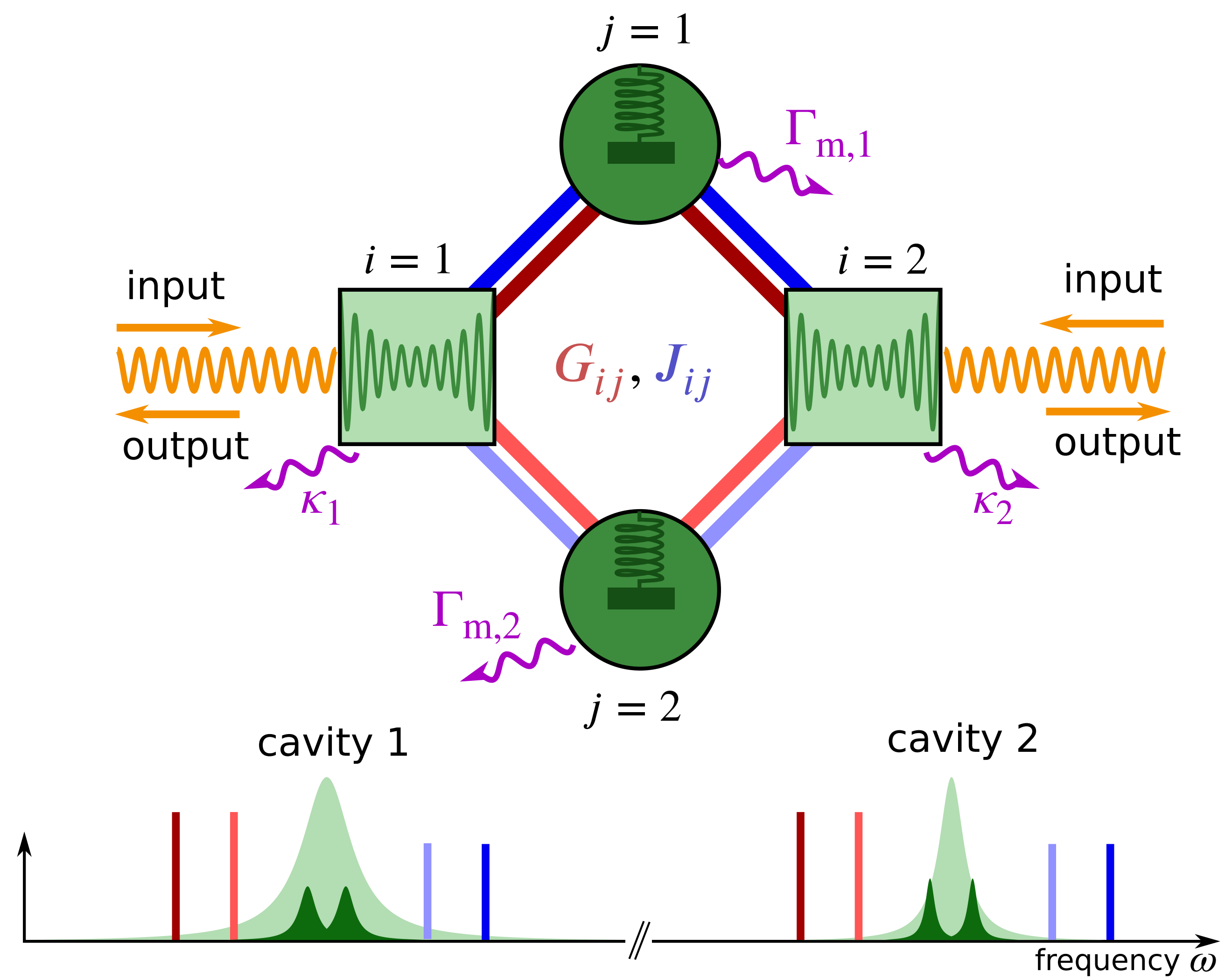
Nonreciprocal (20dB), reconfigurable, on-chip electro-mechanical circuit!

Quantum thermodynamics
Barzanjeh, …, Xuereb,
PRL **120**, 060601 (2018)

Bernier… Malz, **AN**…, Nat. Commun. **8**, 604 (2017)

Nonreciprocal devices by reservoir engineering



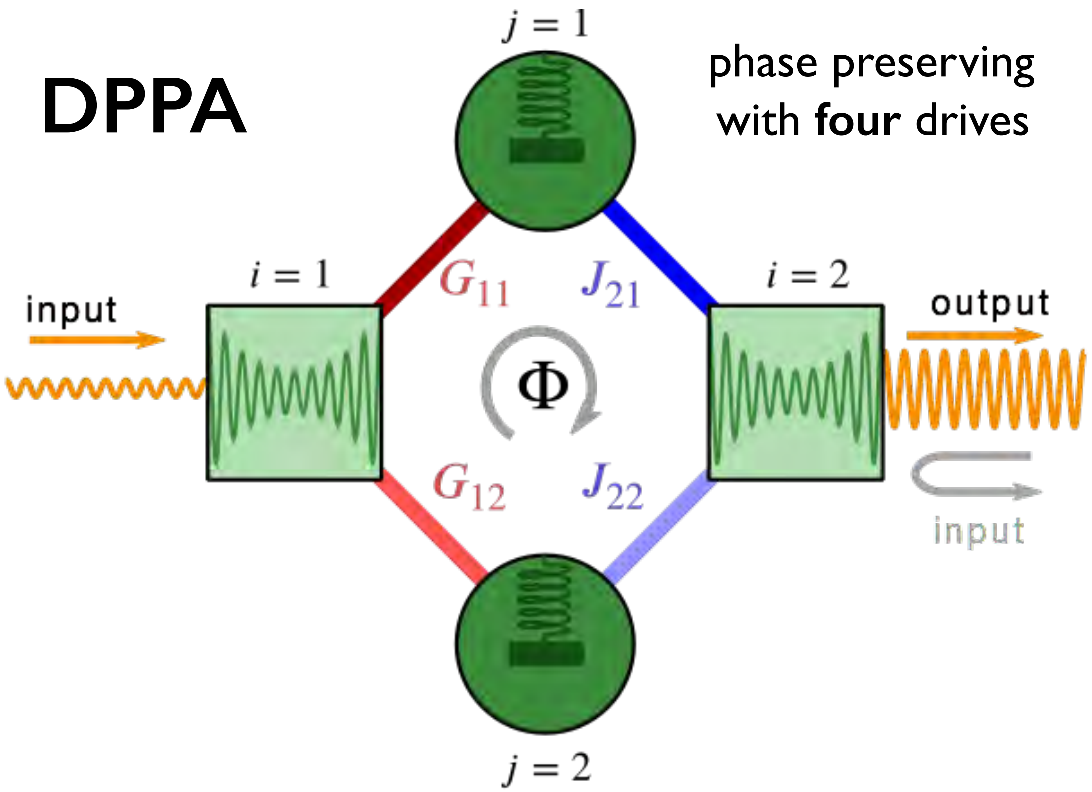


Bernier et al., Nat. Commun. **8**, 604 (2017)
Peterson et al., Phys. Rev. X **7**, 031001 (2017)
Barzanjeh et al., Nat. Commun. **8**, 953 (2017)

Malz *et al.*, PRL **120**, 023601 (2018)

Nonreciprocal devices by reservoir engineering

DPPA



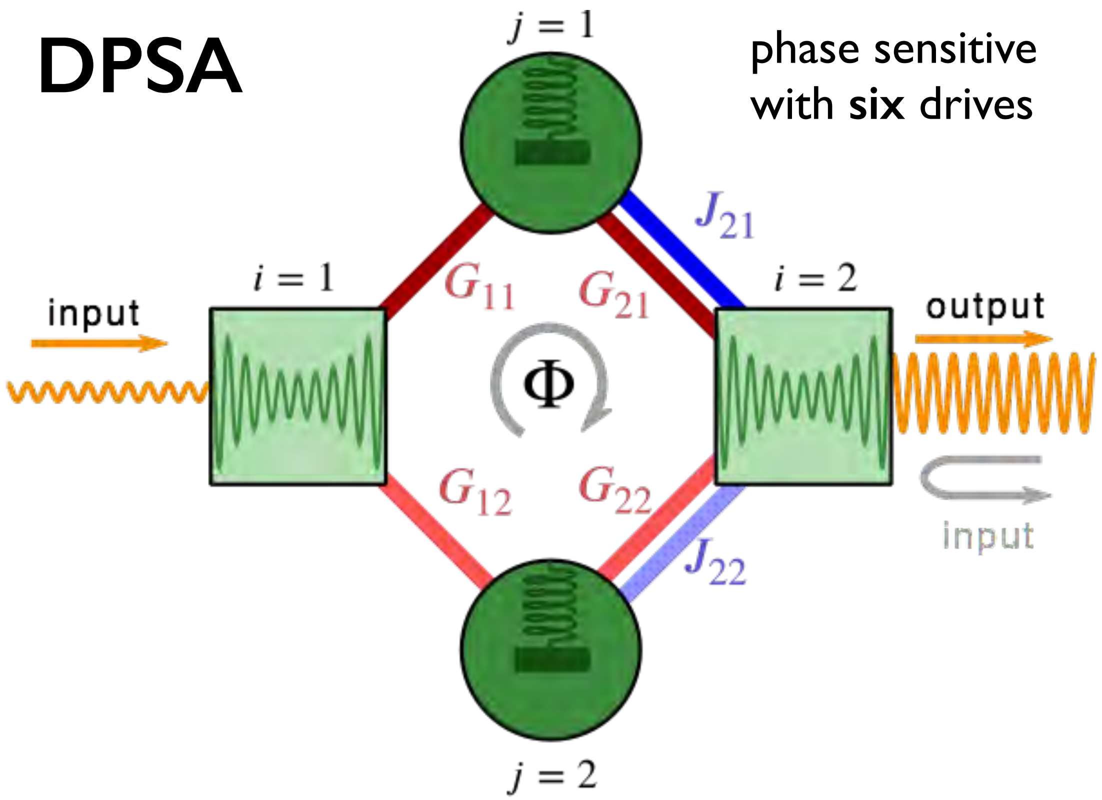
- isolation and "impedance matching"
- unlimited gain $\mathcal{G} = \frac{4C_1C_2}{(C_1 - C_2)^2}$
- quantum limited $\mathcal{N}_{\mathrm{DPPA}} \to \frac{1}{2}$

Scattering matrix (rich behavior off-resonance)

$$\begin{pmatrix} a_{1,\mathrm{out}}(0) \\ a^\dagger_{2,\mathrm{out}}(0) \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{i\sqrt{\mathcal{G}}}{\sqrt{4C_1}} & \frac{i\sqrt{\mathcal{G}}}{\sqrt{4C_1}} & -\sqrt{\mathcal{G}} & \frac{C_1+C_2}{C_2-C_1} \end{pmatrix} \begin{pmatrix} b_{1,\mathrm{in}}(0) \\ b_{2,\mathrm{in}}(0) \\ a_{1,\mathrm{in}}(0) \\ a^\dagger_{2,\mathrm{in}}(0) \end{pmatrix}$$

Malz *et al.*, PRL **120**, 023601 (2018)

Nonreciprocal devices by reservoir engineering



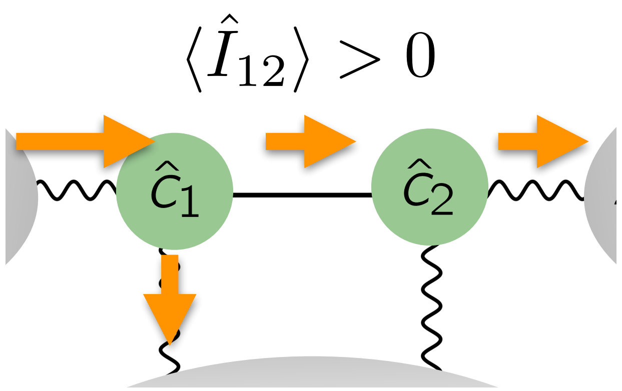
- QND measurement couples one optical quadrature to the mechanical oscillators
- unlimited gain $\mathcal{G} = \frac{8\mathcal{C}_2(2\mathcal{C}_1 - 1)}{\mathcal{C}_1^2}$
- unlimited gain-bandwidth product
- quantum limited $\mathcal{N}_{\text{DPSA}} \to 0$

$$\begin{pmatrix} U_{1,\text{out}} \\ V_{1,\text{out}} \\ U_{2,\text{out}} \\ V_{2,\text{out}} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & \sqrt{\mathcal{G}} & 0 & -1 \end{pmatrix} \begin{pmatrix} U_{1,\text{in}} \\ V_{1,\text{in}} \\ U_{2,\text{in}} \\ V_{2,\text{in}} \end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ \sqrt{2\mathcal{F}} & 0 & \sqrt{2\mathcal{F}} & 0 \end{pmatrix} \begin{pmatrix} X_{1,\text{in}} \\ P_{1,\text{in}} \\ X_{2,\text{in}} \\ P_{2,\text{in}} \end{pmatrix}$$

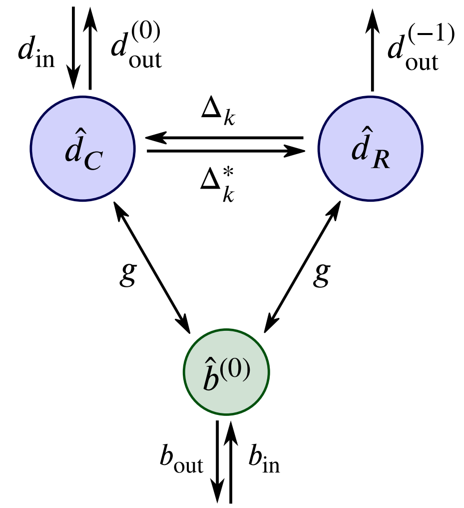
with noise scattering intensity $\mathcal{F} \equiv 4\mathcal{C}_2/\mathcal{C}_1^2,$

Malz *et al.*, PRL **120**, 023601 (2018)

Nonreciprocal devices by reservoir engineering

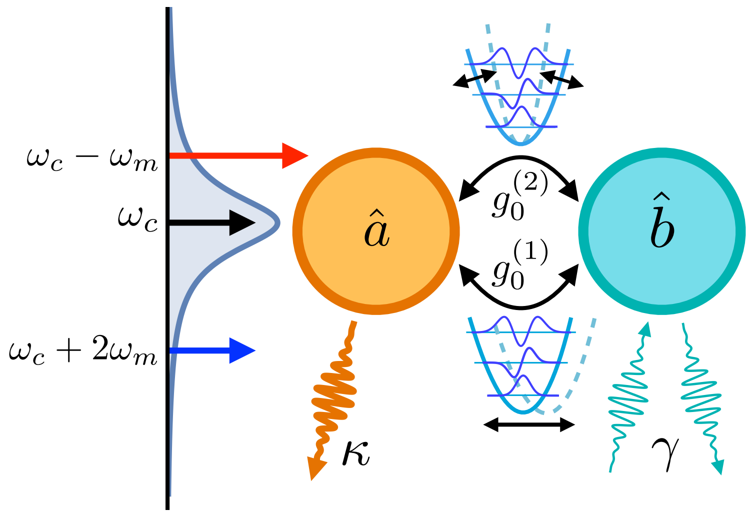


Current rectification in serial spinless double quantum dot
Malz and **AN**,
PRB **97**, 165308 (2018)



Motional Sideband Asymmetry and Kerr-type nonlinearities
…,Malz, **AN**,…,
in preparation

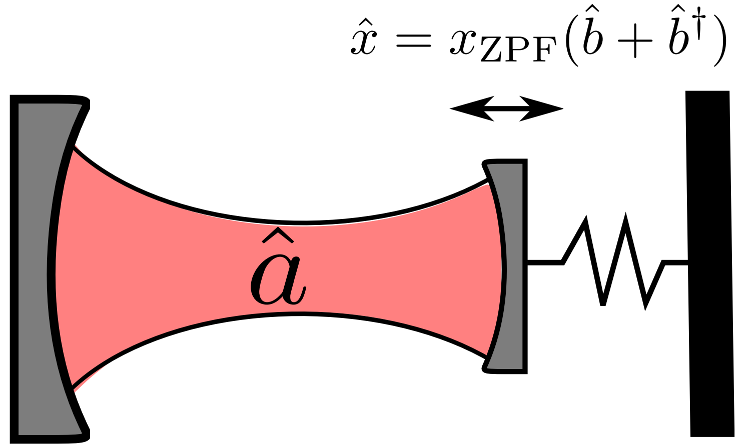
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



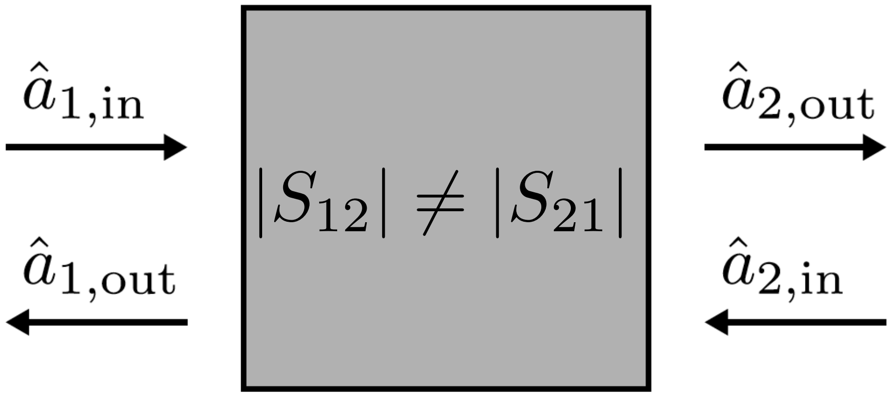
Unconditional preparation of nonclassical massive states
Brunelli,…,**AN**,…,
arXiv:1804.00014

QUEEN'S UNIVERSITY BELFAST

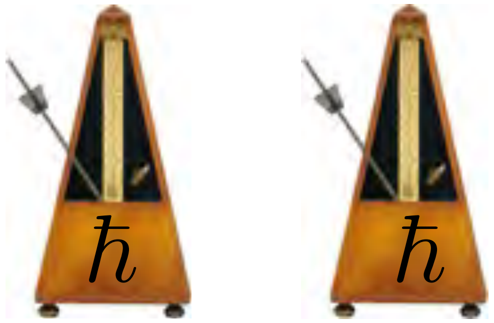
Outline



Cavity optomechanics



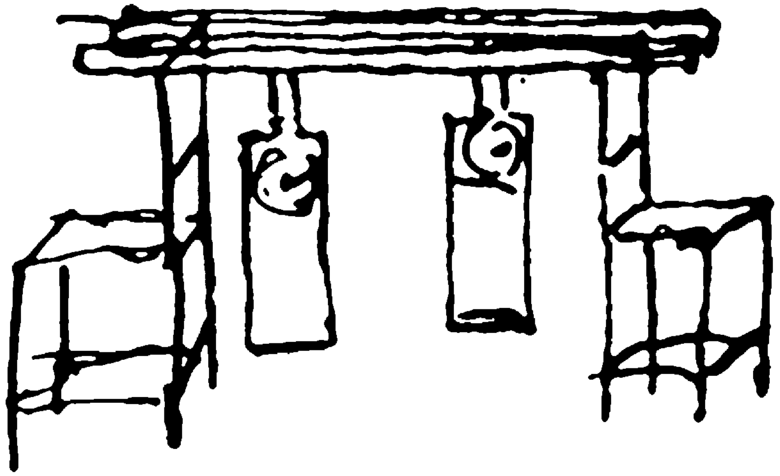
Nonreciprocal devices



Quantum synchronization

Quantum synchronization

Christiaan Huygens
(1629 – 1695)



Letter to Royal Society of London
"adjustment of rhythms of oscillating objects due to weak interaction"

- fireflies, heart, neurons, algae…
- Josephson junctions, lasers, spin torque oscillators…
- power networks, GPS, …

Synchronization is ubiquitous!

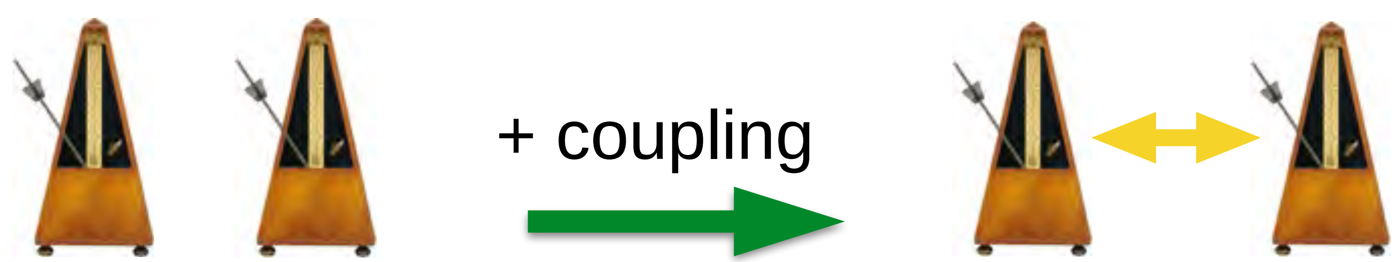
Quantum synchronization

self-oscillator
(limit-cycle) oscillator

ω_0

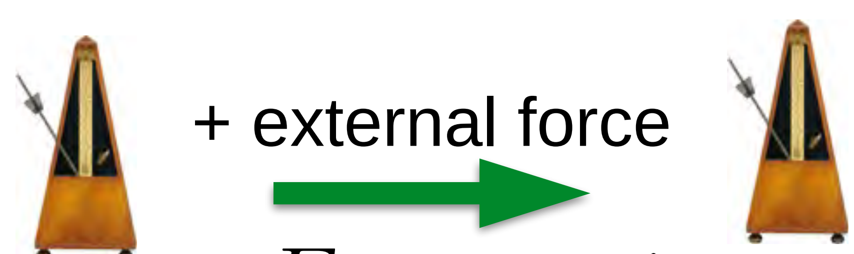
- driven into oscillation by an energy source
- characterized by a natural frequency
- NB. It is <u>not</u> a harmonic degree of freedom.

synchronization

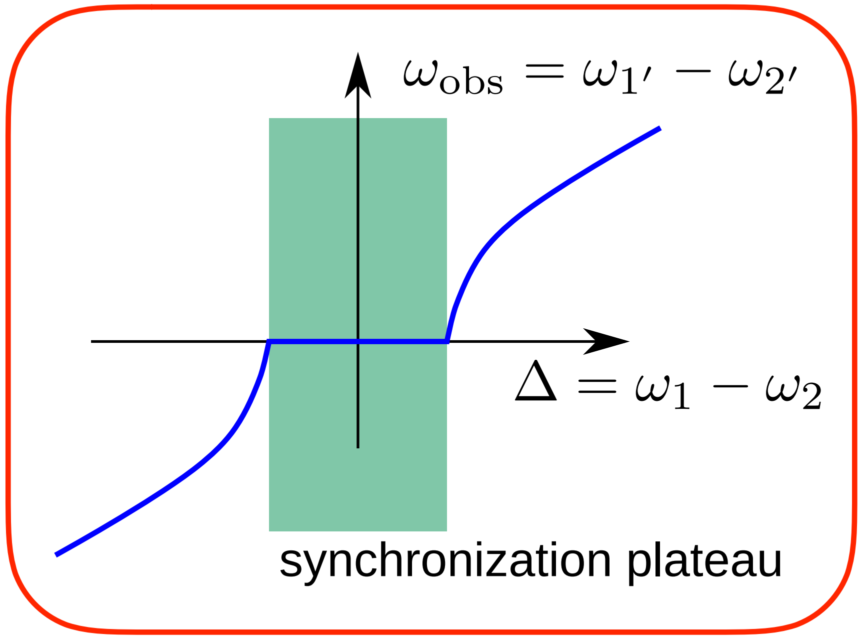


ω_1 ω_2 + coupling $\rightarrow$ $\omega_{1'}$ $\omega_{2'}$

injection locking
(synchronization to external force)

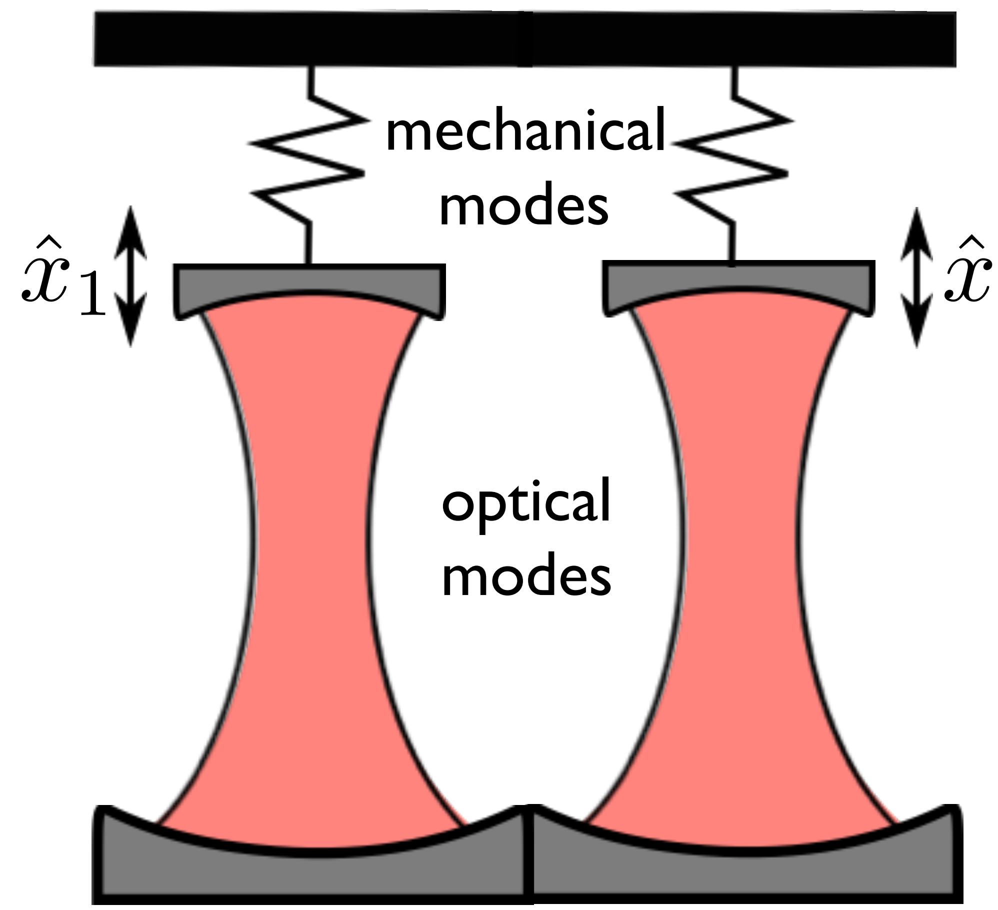


ω_0 + external force $\rightarrow$ $F_0 \cos \omega_d t$ ω_0'

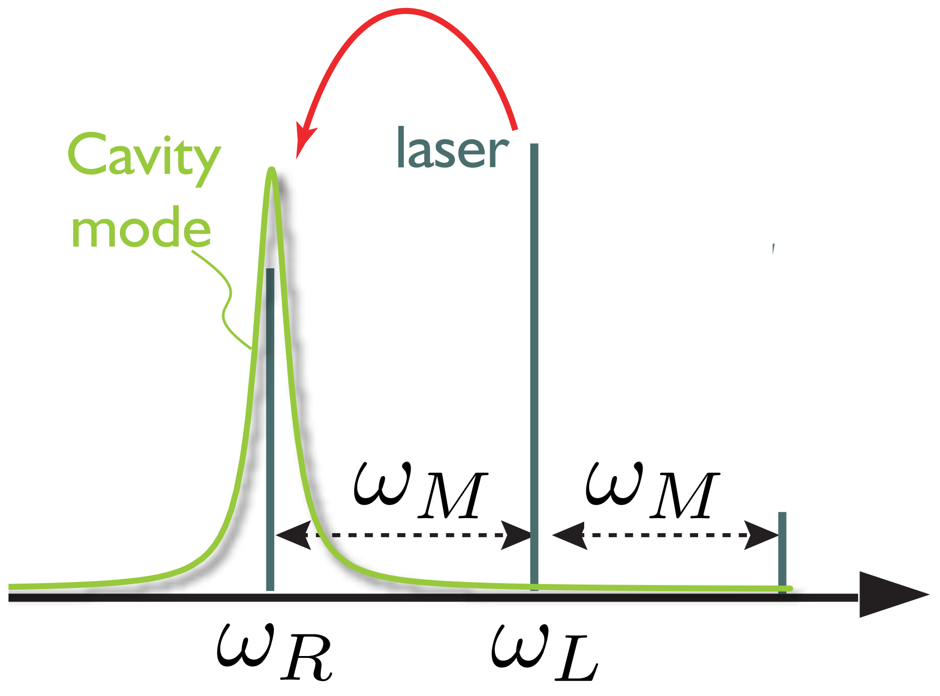


Pikovsky, Rosenblum, and Kurths, *Synchronization: A Universal Concept in Nonlinear Science*, CUP (2001)

Quantum synchronization

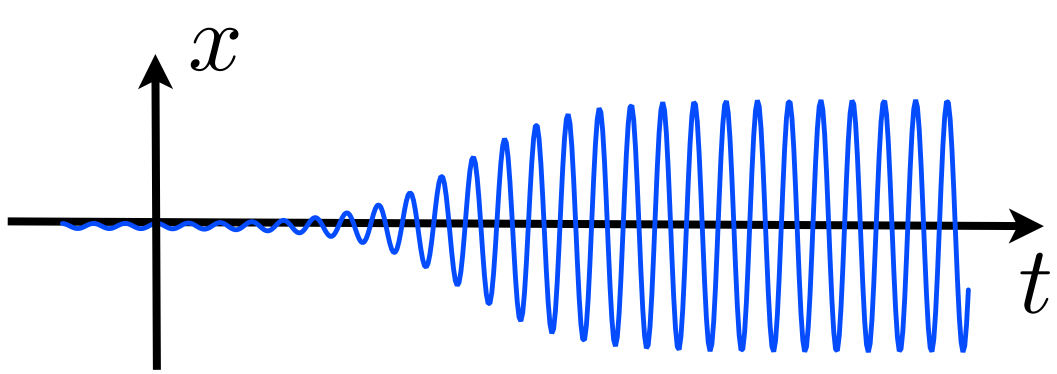


What is the fate of synchronization in the quantum regime?



Self-sustained oscillations

$$\Gamma_m + \Gamma_{\text{opt}} < 0$$



Heinrich,…, Marquardt, PRL **107**, 043603 (2011)
Ludwig and Marquardt, PRL **111**, 073603 (2013)
Mari, …, Fazio, PRL **111**, 103605 (2013) & more

Quantum synchronization

simplest model: *driven van der Pol oscillator*

$$\ddot{x} + (-\gamma_1 + \gamma_2 x^2)\dot{x} + \omega_0^2 x = \Omega \cos(\omega_d t)$$

γ_1 negative damping ("battery")

γ_2 nonlinear damping

Ω strength of the external driving field

Δ detuning $\Delta = \omega_d - \omega_0$

Balthasar van der Pol

Sir Edward Appleton

Quantum synchronization

Phase space amplitude in the rotating frame

$$\mathrm{Re}[\beta(t)] \sim x(t)$$
$$\mathrm{Im}[\beta(t)] \sim p(t)$$

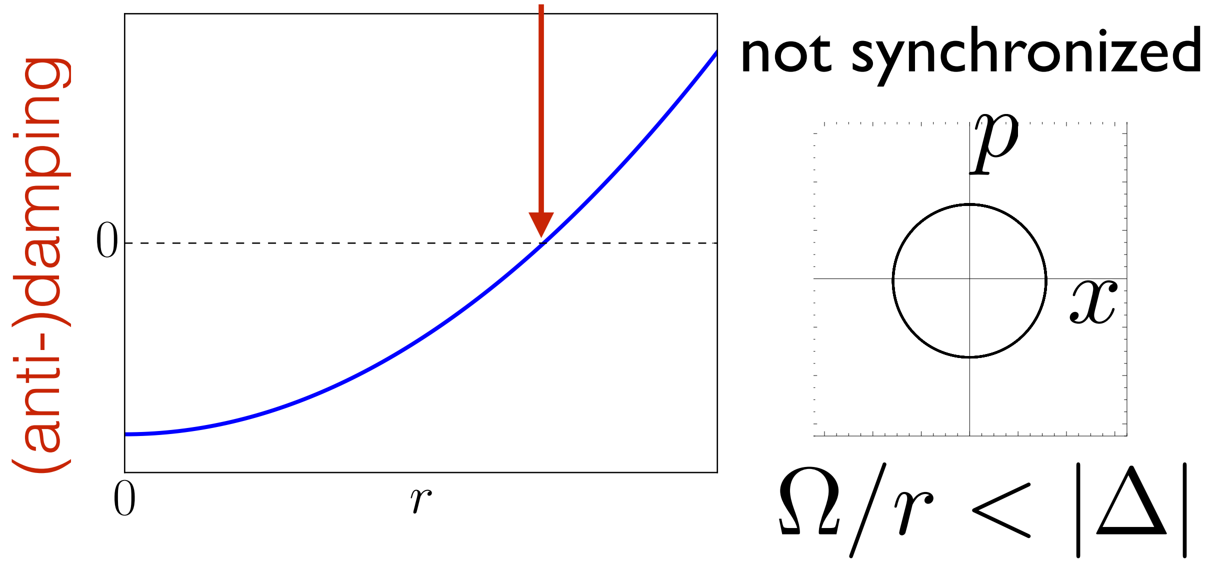
negative damping — drive

$$\dot\beta = i\Delta\beta + \frac{\gamma_1}{2}\beta - \gamma_2|\beta|^2\beta - \Omega$$

detuning — non-linear damping

$$\Delta = \omega_d - \omega_0$$

limit cycle $r = \sqrt{\frac{\gamma_1}{2\gamma_2}}$

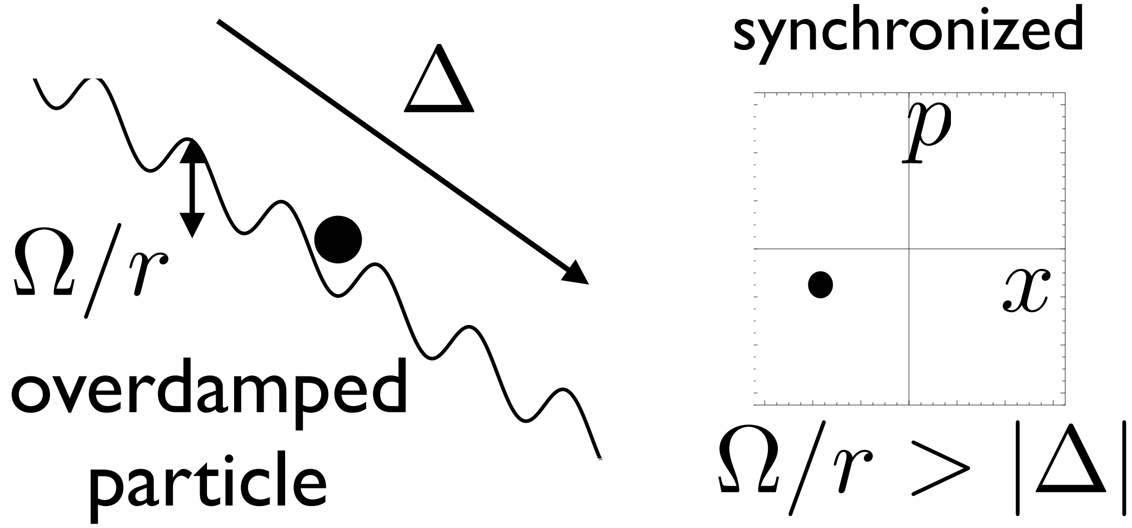


Using polar coordinates $\beta = re^{i\phi}$

$$\dot r = \left(\frac{\gamma_1}{2} - \gamma_2 r^2\right) r - \Omega\cos\phi$$

$$\dot\phi = \Delta + \frac{\Omega}{r}\sin\phi$$

Adler (1946)



Quantum synchronization

classical van der Pol oscillator

negative damping — drive

$$\frac{d}{dt}\beta = i\Delta\beta + \frac{\gamma_1}{2}\beta - \gamma_2|\beta|^2\beta - \Omega$$

detuning — non-linear damping

quantum van der Pol oscillator

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

drive — non-linear damping

$$\frac{d\rho}{dt} = -i\left[-\Delta\hat{b}^\dagger\hat{b} + i\Omega(\hat{b} - \hat{b}^\dagger), \rho\right] + \gamma_1\mathcal{D}[\hat{b}^\dagger]\rho + \gamma_2\mathcal{D}[\hat{b}^2]\rho$$

detuning — negative damping

Walter, Nunnenkamp, and Bruder, PRL **112**, 094102 (2013)
also: Lee and Sadeghpour, PRL **111**, 234101 (2013)

Quantum synchronization

quantum van der Pol oscillator

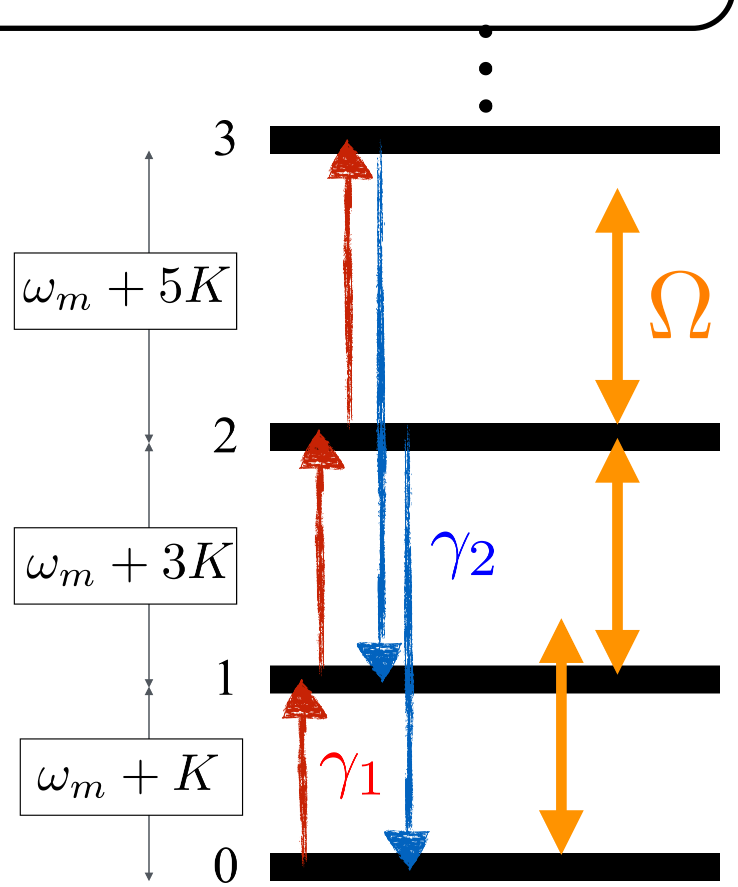
$$\mathcal{D}[O]\rho = O\rho O^\dagger - \frac{1}{2}\{O^\dagger O, \rho\}$$

drive — non-linear damping

$$\frac{d\rho}{dt} = -i\left[-\Delta\hat{b}^\dagger\hat{b} + i\Omega(\hat{b} - \hat{b}^\dagger), \rho\right] + \gamma_1\mathcal{D}[\hat{b}^\dagger]\rho + \gamma_2\mathcal{D}[\hat{b}^2]\rho$$

detuning — negative damping

Add $\hat{H}_{\text{Kerr}} = K(\hat{b}^\dagger\hat{b})^2$



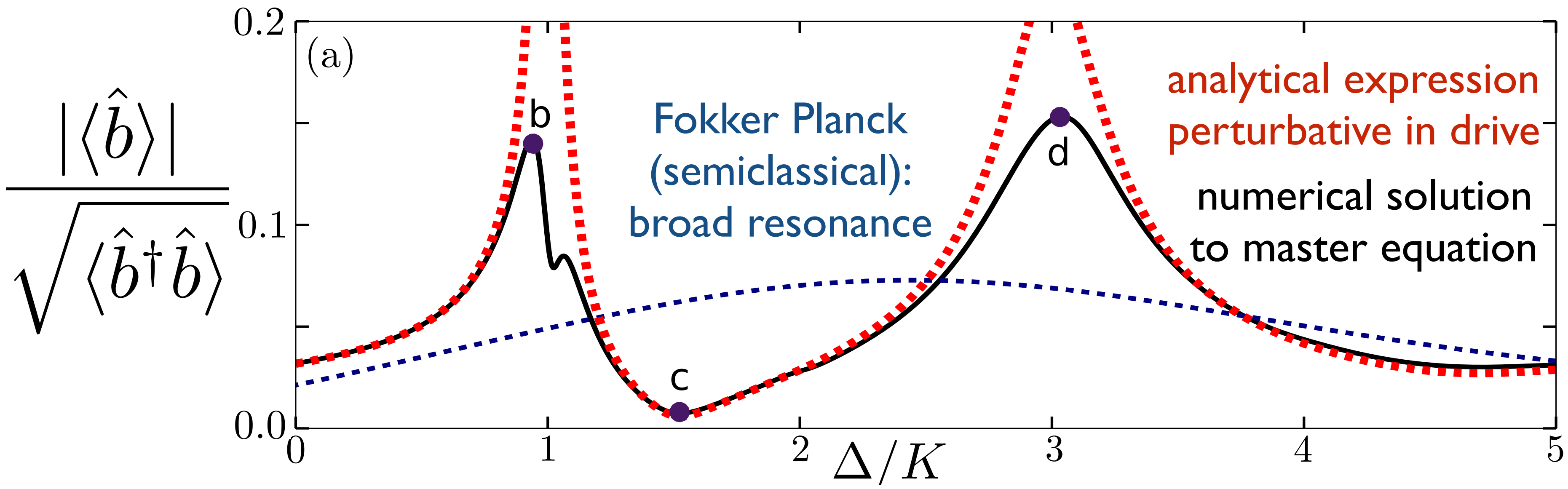
Genuine quantum features:

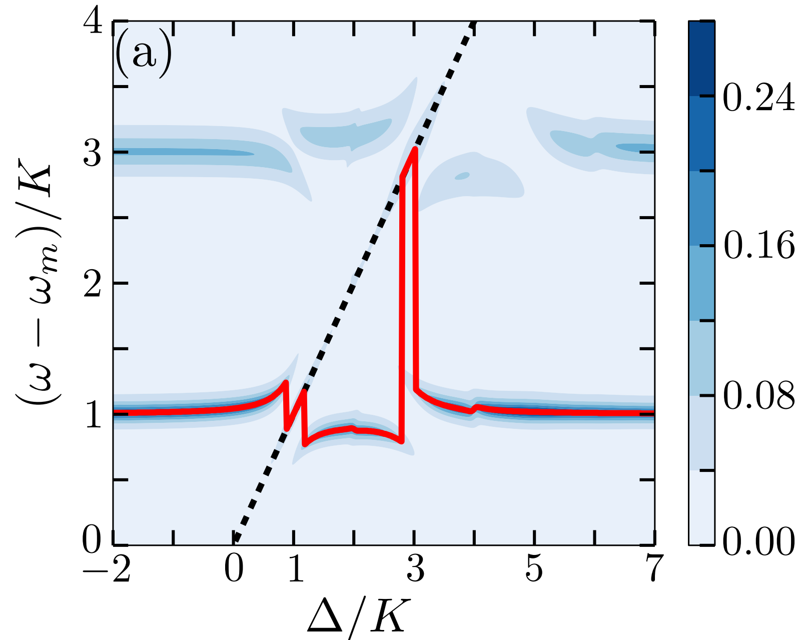
- footprint of quantized Fock levels
- negative steady-state Wigner density

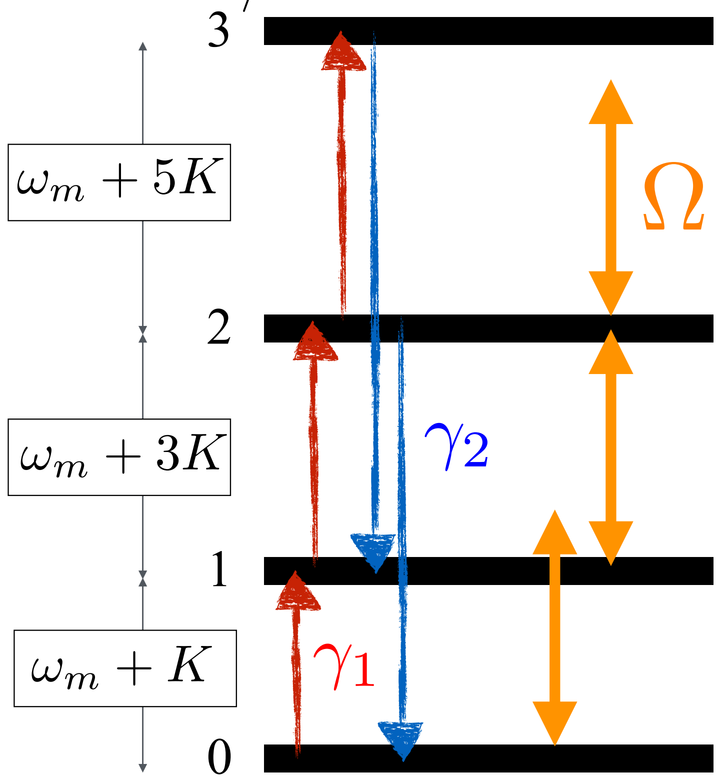
Lörch, Amitai, **AN**, and Bruder, Phys. Rev. Lett. **117**, 073601 (2016)

Quantum synchronization

Aim: To study the tendency to phase locking





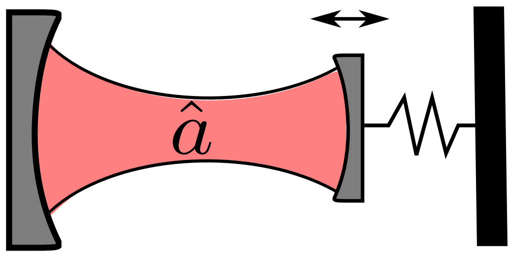


Multiple phase locking resonances are footprint of quantized energy levels.

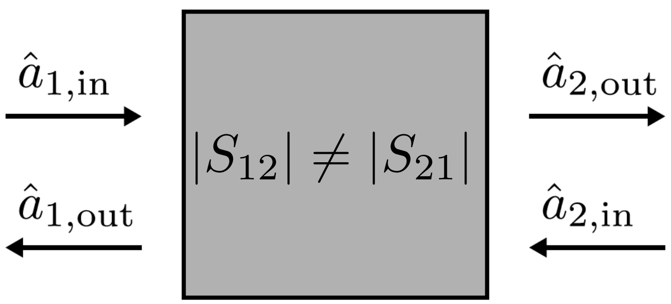
$(\gamma_2/\gamma_1 = 7,\ E/\gamma_1 = 4.5,\ K/\gamma_1 = 100)$

Lörch, Amitai, **AN**, and Bruder, Phys. Rev. Lett. **117**, 073601 (2016)

Cavity optomechanics

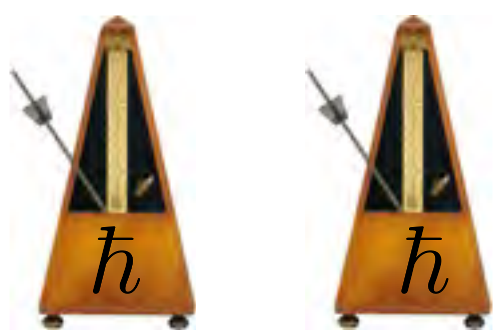


New platform for quantum science and technology



Non-reciprocal devices with reservoir engineering

- Optomechancial isolator and circulator proposal
- Proposal for optomechanical directional amplifier
- Proposal for current rectification in double QD



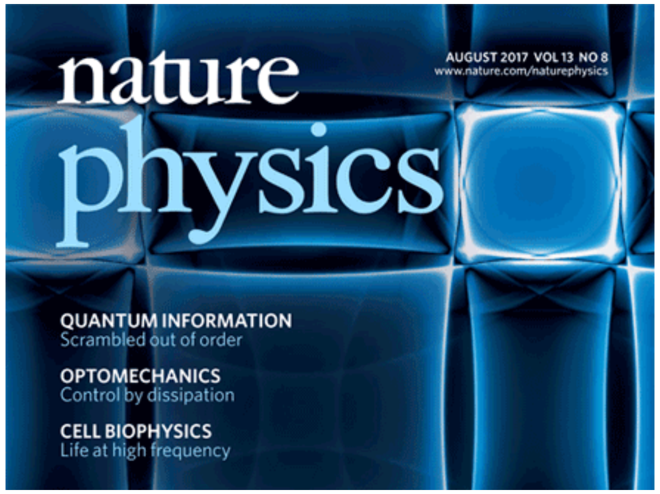
Platform for synchronization in quantum regime

- Quantum noise generically destroys locking
- Genuine quantum features in sync identified
- "Quantum synchronization blockade"

THE ROYAL SOCIETY

Hybrid Optomechanical Technologies

THE WINTON PROGRAMME FOR THE Physics of Sustainability



Nat. Phys. **13**, 787 (2017)
Nat. Comm. **8**, 604 (2017)
PRL **120**, 023601 (2018)
PRB **97**, 165308 (2018)

PRL **112**, 094102 (2014)
PRL **117**, 073601 (2016)
PRL **118**, 243602 (2017)