ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

# Engineered dissipative reservoir for microwave light using circuit optomechanics

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

1. EPFL – Institute of Physics
2. University of Cambridge – Cavendish laboratory

Workshop on Quantum Science and Quantum Technologies, Trieste, Italy

September 14, 2017

European Research Council

QSIT Quantum Science and Technology — National Centre of Competence in Research

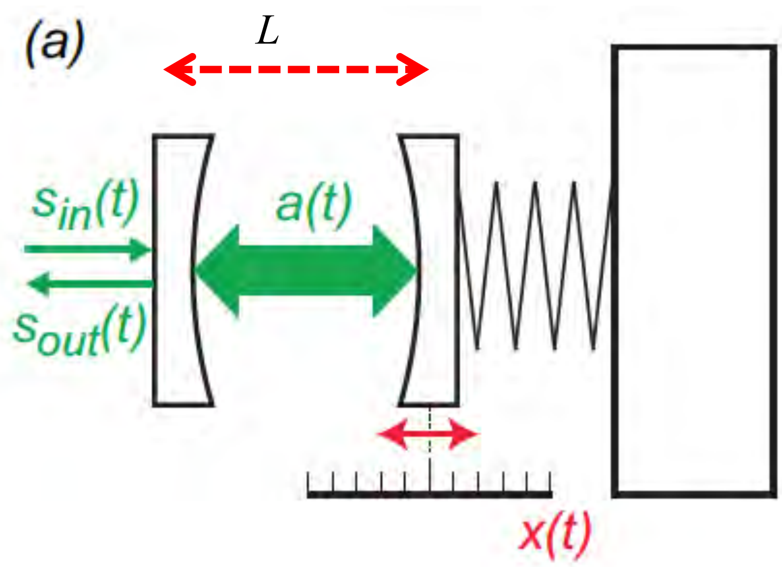
OMT OPTOMECHANICAL TECHNOLOGIES

FNSNF Swiss National Science Foundation

Hybrid Optomechanical Technologies

# Canonical model for a cavity optomechanical system

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE




$$\hat{H}_{\text{int}} = -\hbar G \hat{a}^{\dagger}\hat{a}\hat{x}$$

Optical frequency shift $$\dot{\hat{a}} = i\left[\hat{H},\hat{a}\right]/\hbar = i\left(\omega_{\text{c}} - G\hat{x}\right)\hat{a}$$

Radiation pressure force $$\hat{F}_{\text{rp}} = -\frac{d\hat{H}_{\text{int}}}{d\hat{x}} = \hbar G \hat{a}^{\dagger}\hat{a}$$

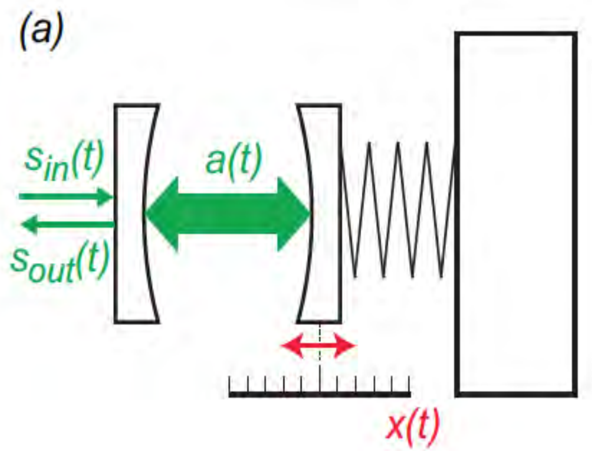
measurement leads to a radiation pressure '*backaction*'

**Vacuum optomechanical coupling rate** $$g_0 = G\sqrt{\frac{\hbar}{2m\Omega_{\text{m}}}}$$

# Radiation pressure Dynamical backaction



Optical field responds on the mechanical motion with delay $\tau \approx \kappa^{-1}$




$$\frac{d^2x}{dt^2} + \Gamma_m \frac{dx}{dt} + \Omega_m^2 x = \frac{F_{rp}\left(x\left(t-\tau\right)\right)}{m_{eff}}$$

Taylor expansion yields:

$$F_{rp}\left(x\left(t-\tau\right)\right) \approx \frac{dF}{dx}x - \tau\frac{dF}{dx}\frac{dx}{dt}$$

$$\Gamma_{opt} \approx \tau \frac{dF}{dx} \cdot \frac{1}{m_{eff}}$$

$\Delta > 0$ Amplification Blue detuning
Dynamical backaction induced Parametric instability
(JETP 1970, Braginsky)

$\Delta < 0$ Cooling Red detuning
(JETP 1970, Braginsky)

Braginsky, V. B. & Manukin A. B. *Measurement of Weak Forces in Physics Experiments*. (1977)
Braginsky, V. B. & Khalili, F. Y. *Quantum Measurement*. (1992)
Braginsky, V. B., Strigin, S. E. & Vyatchanin, S. P. Analysis of parametric oscillatory instability in power recycled LIGO interferometer. *Physics Letters A* **305**, 111-124 (2002)

# Frequency domain picture

$\Delta = -\Omega_m \quad H_{int} \approx -\hbar g_0 \sqrt{n_c}\left(\delta \hat{a}^\dagger \hat{b} + \delta \hat{a} \hat{b}^\dagger\right)$

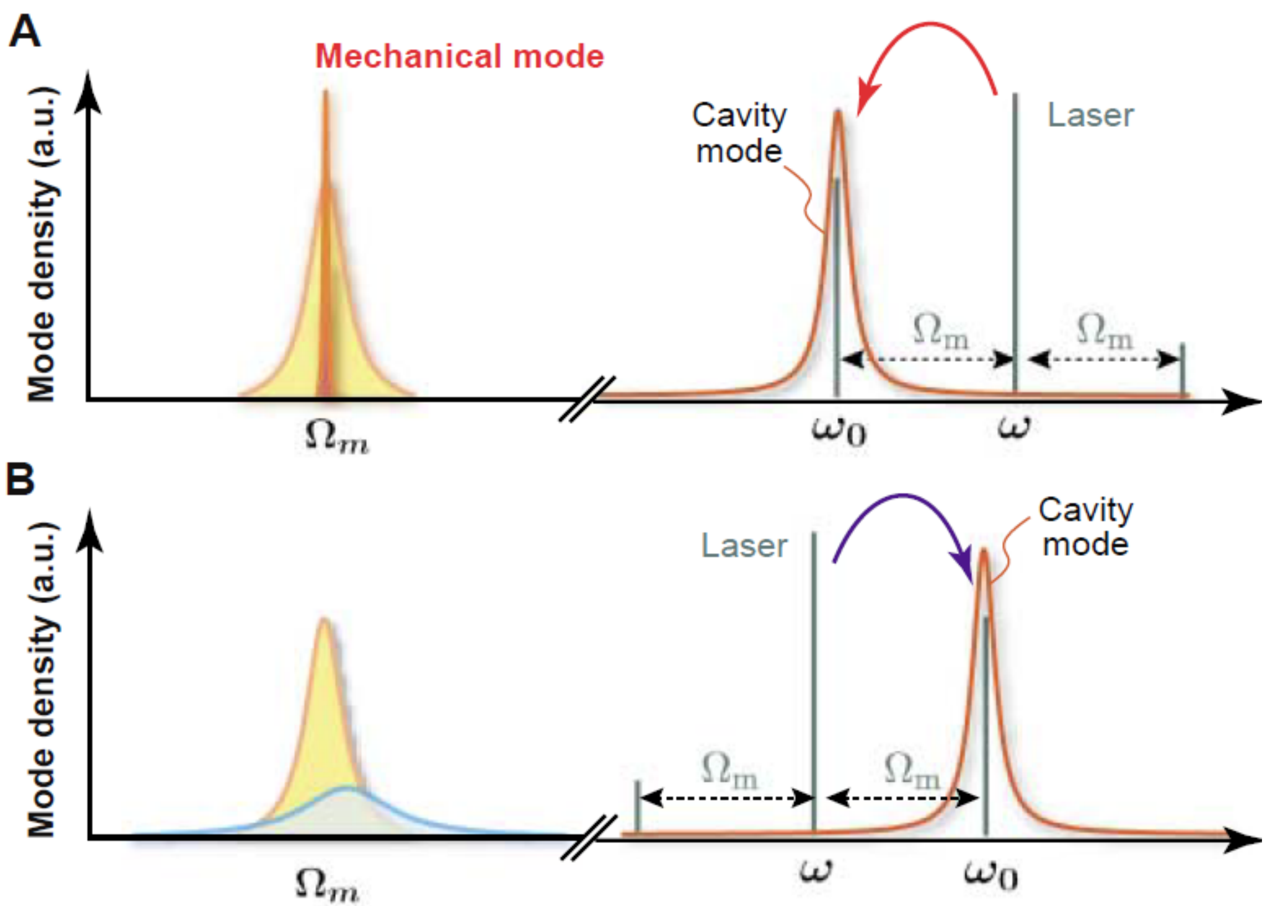
Coherent exchange of quanta, cooling

$\Delta = +\Omega_m \quad H_{int} \approx -\hbar g_0 \sqrt{n_c}\left(\delta \hat{a}^\dagger \hat{b}^\dagger + \delta \hat{a} \hat{b}\right)$

Two-mode squeezing, amplification

Amplification

Resolved sideband Cooling

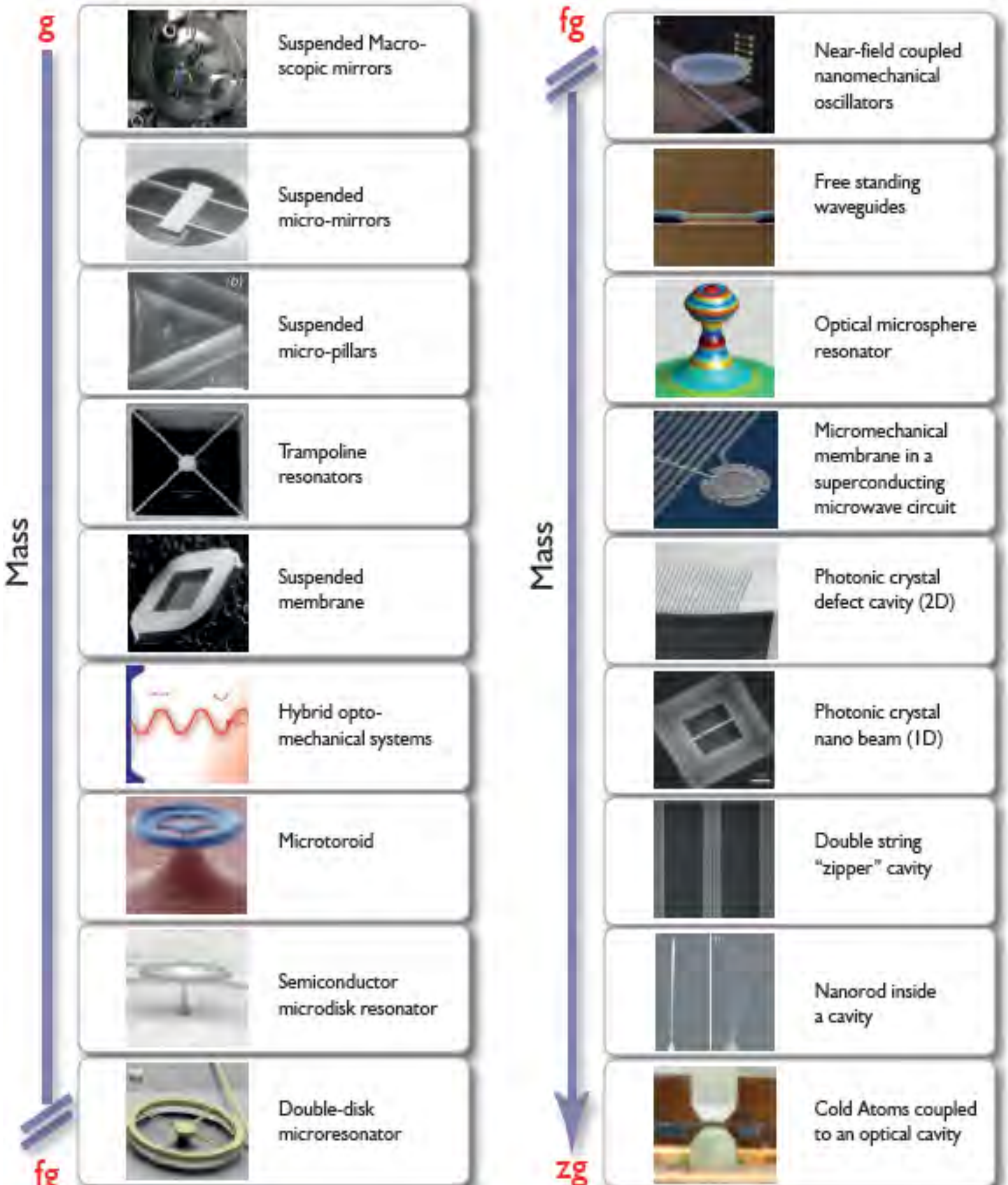


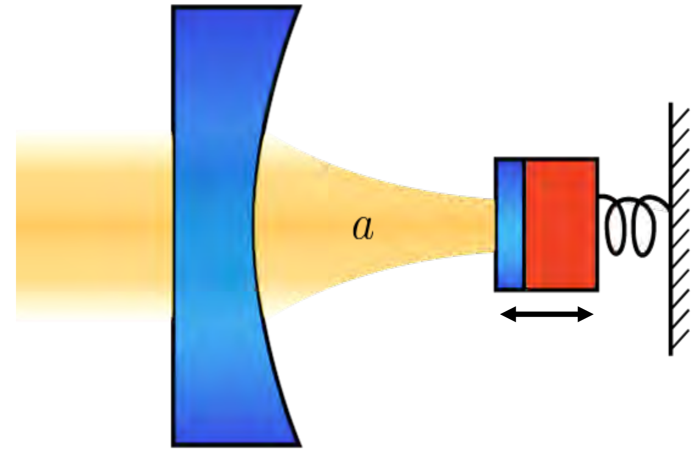


I. Wilson-Rae, N. Nooshi, W. Zwerger, T. J. Kippenberg. *Phys. Rev. Lett*. **99,** 093901 (2007)
F. Marquardt, J. P. Chen, A. A. Clerk, S. M. Girvin. *Phys. Rev. Lett*. **99**, 093902 (2007)

# Cavity optomechanics today

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE




M. Aspelmeyer, T. J. Kippenberg, F. Marquardt. *Rev. Mod. Phys.* **86**, 1391 (2014)

# Cavity optomechanics today

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$$\delta\dot{\hat{a}} = +i\Delta\delta\hat{a} - \frac{\kappa}{2}\delta\hat{a} + ig_0\sqrt{n_\mathrm{c}}(\hat{b}+\hat{b}^\dagger) + \sqrt{\kappa_\mathrm{ex}}\,\delta\hat{a}_\mathrm{in,ex} + \sqrt{\kappa_0}\,\delta\hat{a}_\mathrm{in,0}$$

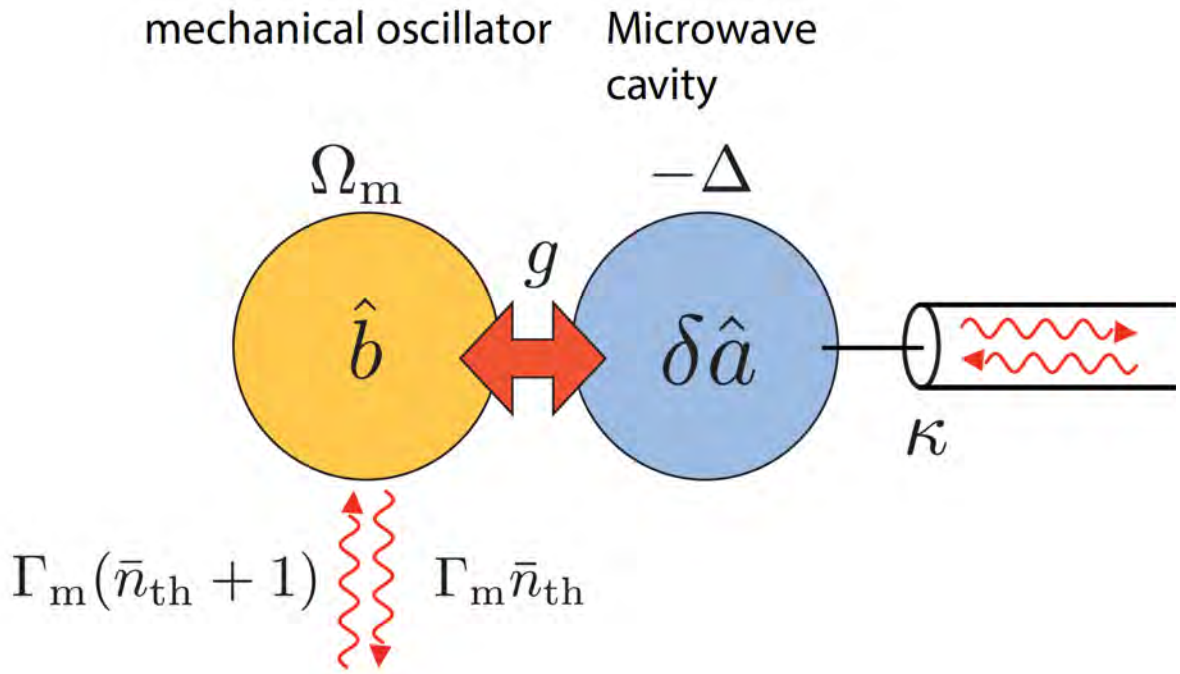
$$\dot{\hat{b}} = -i\Omega_\mathrm{m}\hat{b} - \frac{\Gamma_\mathrm{m}}{2}\hat{b} + ig_0\sqrt{n_\mathrm{c}}(\delta\hat{a}+\delta\hat{a}^\dagger) + \sqrt{\Gamma_\mathrm{m}}\,\hat{b}_\mathrm{in}$$

M. Aspelmeyer, T. J. Kippenberg, F. Marquardt. *Rev. Mod. Phys.* **86**, 1391 (2014)

# Cavity optomechanics and reservoir engineering

$\kappa \gg \Gamma_m$

$k_B T \ll \hbar\omega$

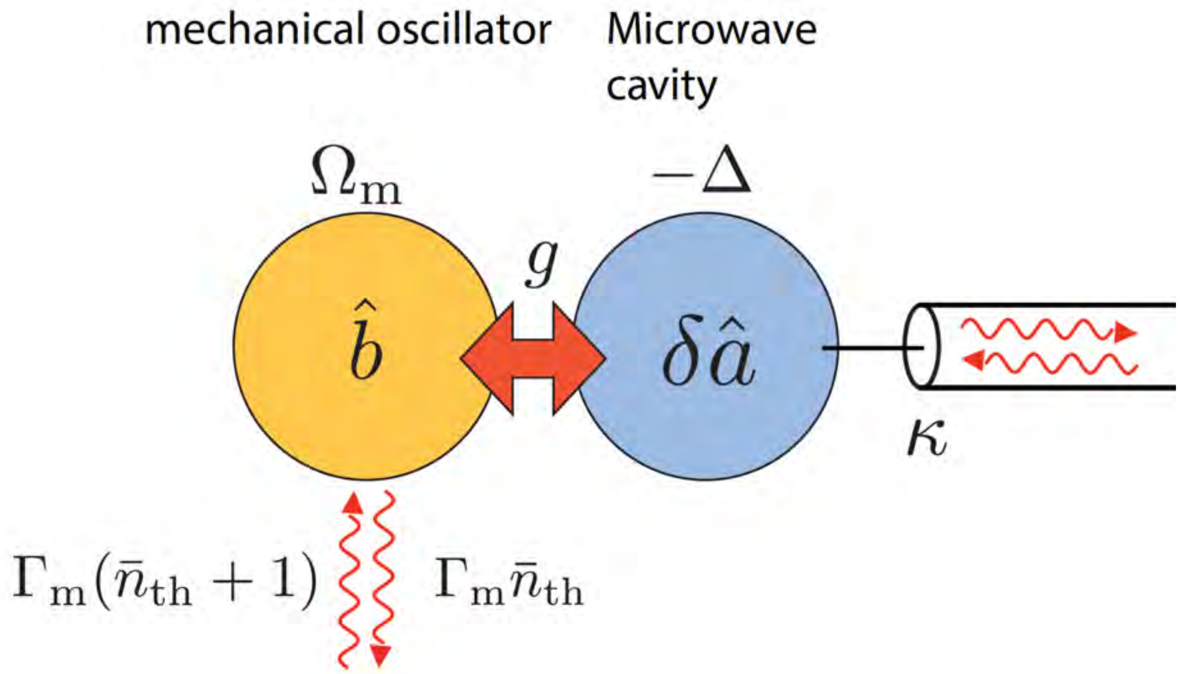


# Cavity optomechanics and reservoir engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$\kappa \gg \Gamma_m$

$k_B T \ll \hbar\omega$




Electromagnetic mode constitutes a cold dissipative bath for the mechanical sub-system. We can *prepare* the state (e.g. ground state or squeezed state) of the *mechanical* oscillator by *controlling coupling* between the mechanical resonator and the electromagnetic mode.


J. F. Poyatos, J. I. Cirac, P. Zoller. *Phys. Rev. Lett.* **77**, 4728 (1996)
A. Kronwald, F. Marquardt, A. A. Clerk. *Phys. Rev. A* **88**, 063833 (2013)

# Cavity optomechanics and reservoir engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$\kappa \gg \Gamma_m$ $\qquad$ $k_B T \ll \hbar\omega$

- Resolved sideband cooling & amplification of mechanical motion
- Opto- and electromechanically induced transparency (OMIT/EMIT)
- Back-action evading measurements
- Mechanical squeezing via optomechanical reservoir engineering

Electromagnetic mode constitutes a cold dissipative bath for the mechanical sub-system. We can *prepare* the state (e.g. ground state or squeezed state) of the *mechanical* oscillator by *controlling coupling* between the mechanical resonator and the electromagnetic mode.

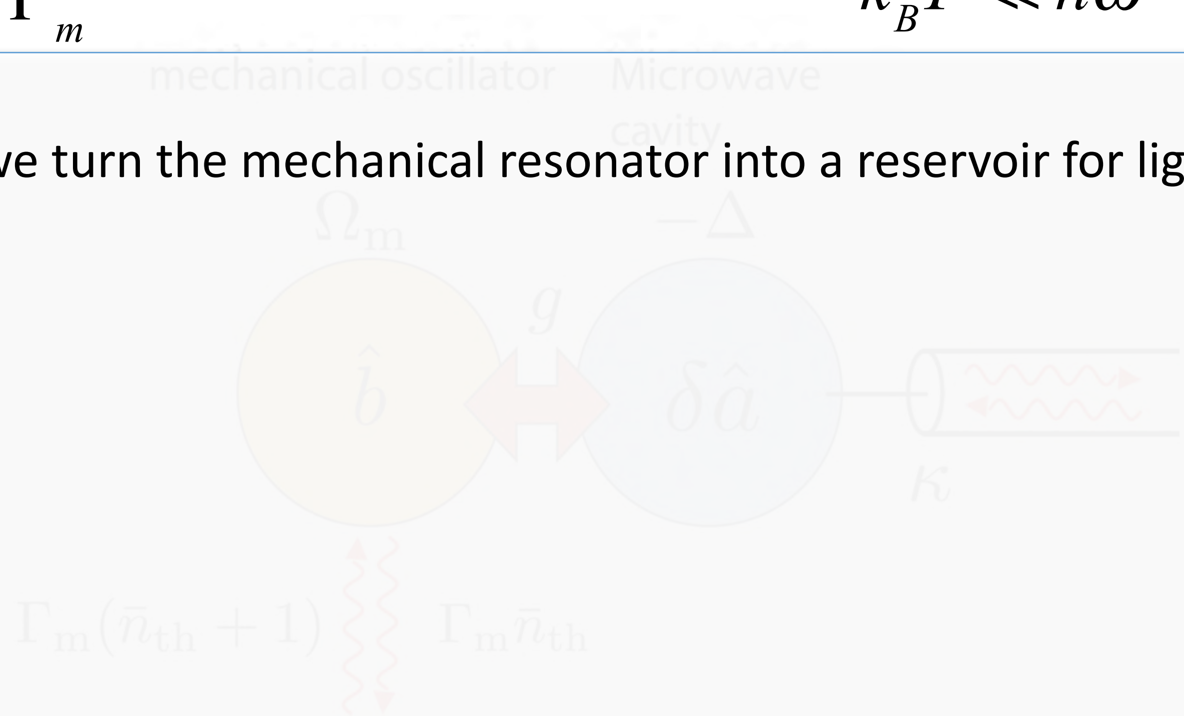
J. F. Poyatos, J. I. Cirac, P. Zoller. *Phys. Rev. Lett.* **77**, 4728 (1996)
A. Kronwald, F. Marquardt, A. A. Clerk. *Phys. Rev. A* **88**, 063833 (2013)

# Cavity optomechanics and reservoir engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$\kappa \gg \Gamma_m$ $k_B T \ll \hbar\omega$

Can we turn the mechanical resonator into a reservoir for light?




Electromagnetic mode constitutes a cold dissipative bath for the mechanical sub-system. We can *prepare* the state (e.g. ground state or squeezed state) of the *mechanical* oscillator by *controlling coupling* between the mechanical resonator and the electromagnetic mode.


J. F. Poyatos, J. I. Cirac, P. Zoller. *Phys. Rev. Lett.* **77**, 4728 (1996)
A. Kronwald, F. Marquardt, A. A. Clerk. *Phys. Rev. A* **88**, 063833 (2013)

# Cavity optomechanics and reservoir engineering



$\kappa \gg \Gamma_m$ $\qquad$ $k_B T \ll \hbar\omega$

Can we turn the mechanical resonator into a reservoir for light?

Yes!

We need

$$\kappa \ll \Gamma_m$$

Electromagnetic mode constitutes a cold dissipative bath for the mechanical sub-system. We can *prepare* the state (e.g. ground state or squeezed state) of the *mechanical* oscillator by *controlling coupling* between the mechanical resonator and the electromagnetic mode.

J. F. Poyatos, J. I. Cirac, P. Zoller. *Phys. Rev. Lett*. **77**, 4728 (1996)
A. Kronwald, F. Marquardt, A. A. Clerk. *Phys. Rev. A* **88**, 063833 (2013)

# The reversed dissipation regime

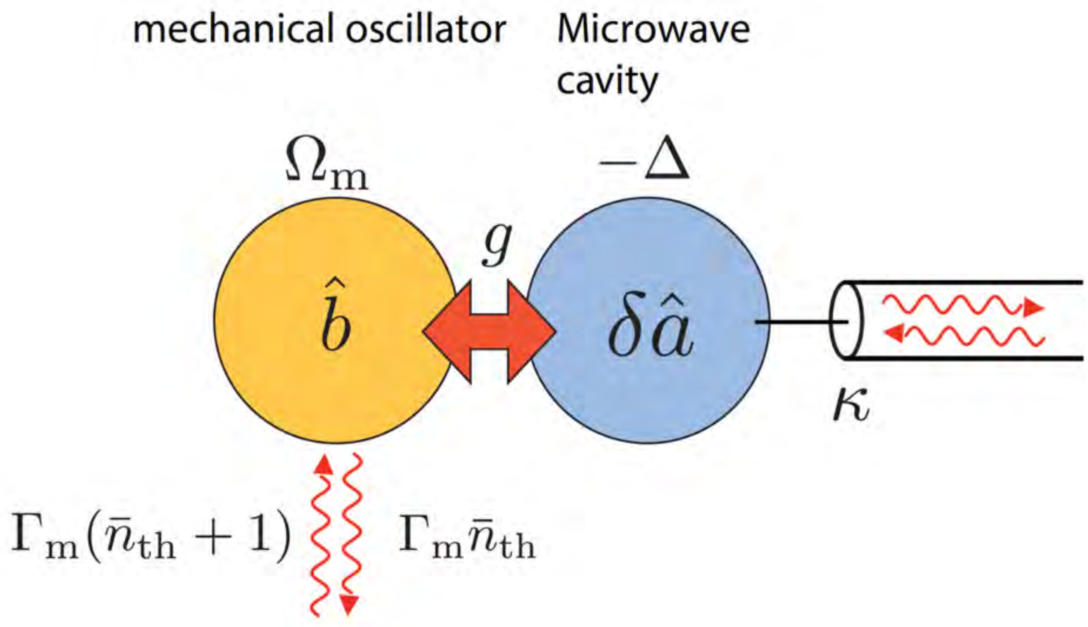
## Optomechanical interactions

$\Delta = -\Omega_m$

$$H_{int} \approx -\hbar g_0 \sqrt{n_c} \left( \delta\hat{a}^{\dagger}\hat{b} + \delta\hat{a}\hat{b}^{\dagger} \right)$$

Coherent exchange of quanta, cooling

Electromagnetic mode damps mechanical oscillator on red sideband




Conventional dissipation hierarchy: $\kappa \gg \Gamma_m$

A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett.* **113,** 023604 (2014)

# The reversed dissipation regime

## Optomechanical interactions

$\Delta = -\Omega_{\mathrm{m}}$

$$H_{\mathrm{int}} \approx -\hbar g_0 \sqrt{n_{\mathrm{c}}}\left(\delta\hat{a}^{\dagger}\hat{b} + \delta\hat{a}\hat{b}^{\dagger}\right)$$

Coherent exchange of quanta, cooling

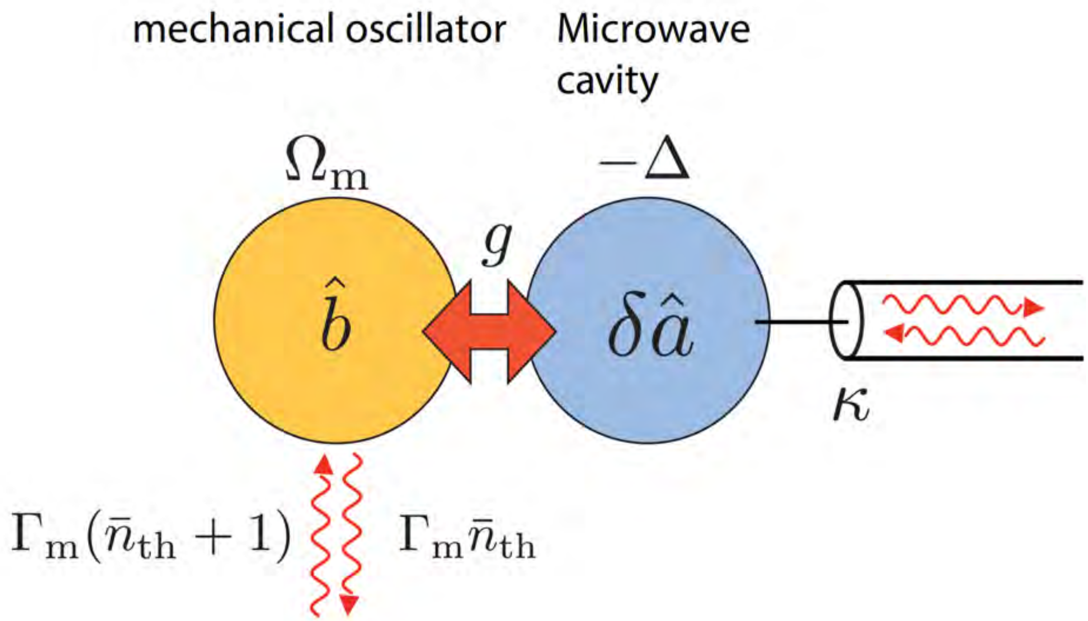
Electromagnetic mode damps mechanical oscillator on red sideband

$\Delta = +\Omega_{\mathrm{m}}$

$$H_{\mathrm{int}} \approx -\hbar g_0 \sqrt{n_{\mathrm{c}}}\left(\delta\hat{a}^{\dagger}\hat{b}^{\dagger} + \delta\hat{a}\hat{b}\right)$$

Amplification and two mode squeezing

Electromagnetic mode amplifies mechanical oscillator on blue sideband




Conventional dissipation hierarchy: $\kappa \gg \Gamma_{\mathrm{m}}$

A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett.* **113,** 023604 (2014)

# The reversed dissipation regime

## Optomechanical interactions

$\Delta = -\Omega_m$

$$H_{int} \approx -\hbar g_0 \sqrt{n_c}\left(\delta\hat{a}^\dagger\hat{b} + \delta\hat{a}\hat{b}^\dagger\right)$$

Coherent exchange of quanta, cooling

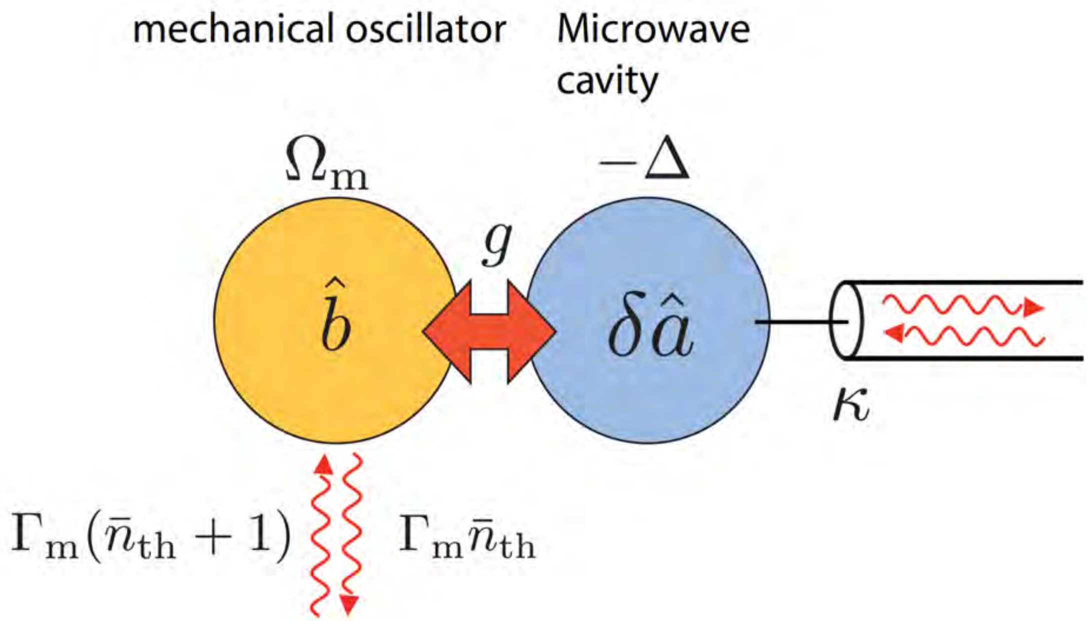
Electromagnetic mode damps mechanical oscillator on red sideband

$\Delta = +\Omega_m$

$$H_{int} \approx -\hbar g_0 \sqrt{n_c}\left(\delta\hat{a}^\dagger\hat{b}^\dagger + \delta\hat{a}\hat{b}\right)$$

Amplification and two mode squeezing

Electromagnetic mode amplifies mechanical oscillator on blue sideband




Conventional dissipation hierarchy: $\kappa \gg \Gamma_m$

$\Gamma_{eff} \rightarrow \kappa_{eff}$

**Reversed dissipation** hierarchy : $\kappa \ll \Gamma_m$

Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.

A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett*. **113,** 023604 (2014)

# The reversed dissipation regime

**Reversed dissipation** hierarchy : $\kappa << \Gamma_m$

$$\Gamma_{\text{eff}} \rightarrow \kappa_{\text{eff}}$$

Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.

A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett*. **113,** 023604 (2014)

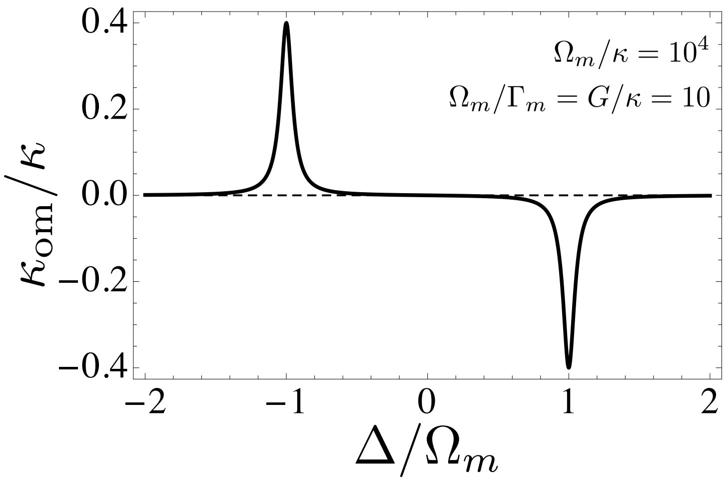
# The reversed dissipation regime

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

**Reversed dissipation** hierarchy : $\kappa \ll \Gamma_{\mathrm{m}}$

$$\Gamma_{\mathrm{eff}} \rightarrow \kappa_{\mathrm{eff}}$$

Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.




**Change in the electromagnetic decay rate (mechanical damping)**

$$\kappa_{\mathrm{om}} = \frac{\Gamma_{\mathrm{eff}} g_0^{\,2} n_{\mathrm{c}}}{(\Gamma_{\mathrm{eff}}/2)^2 + (\Delta + \Omega_{\mathrm{m}})^2} - \frac{\Gamma_{\mathrm{eff}} g_0^{\,2} n_{\mathrm{c}}}{(\Gamma_{\mathrm{eff}}/2)^2 + (\Delta - \Omega_{\mathrm{m}})^2}$$

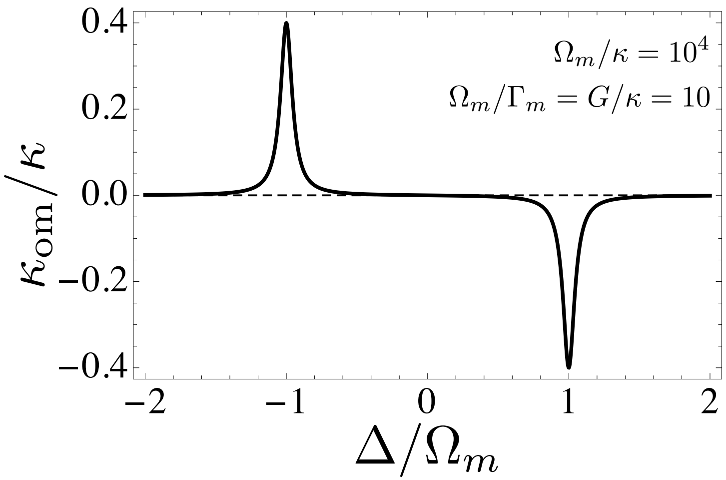
A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett*. **113,** 023604 (2014)

# The reversed dissipation regime

**Reversed dissipation** hierarchy : $\kappa << \Gamma_m$

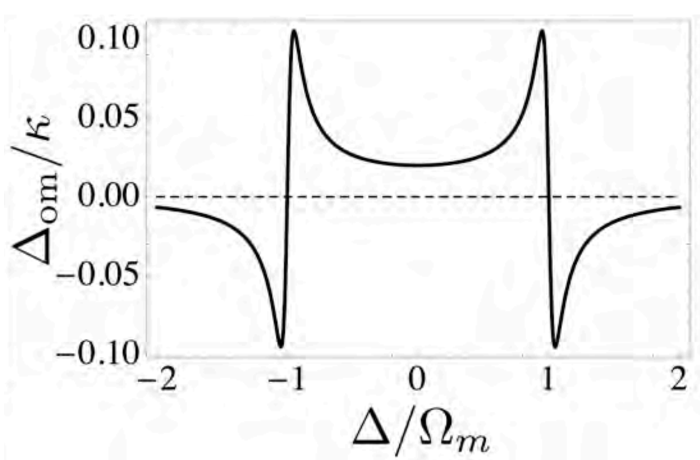
$\Gamma_{eff} \rightarrow \kappa_{eff}$

Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.




**Change in the electromagnetic decay rate (mechanical damping)**

$$\kappa_{om} = \frac{\Gamma_{eff} g_0^{\ 2} n_c}{(\Gamma_{eff}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{eff} g_0^{\ 2} n_c}{(\Gamma_{eff}/2)^2 + (\Delta - \Omega_m)^2}$$




**Change in the electromagnetic resonance freq.**

$$\Delta\omega_{om} = \frac{\Gamma_{eff} g_0^{\ 2} n_c (\Delta - \Omega_m)}{(\Gamma_{eff}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{eff} g_0^{\ 2} n_c (\Delta + \Omega_m)}{(\Gamma_{eff}/2)^2 + (\Delta - \Omega_m)^2}$$

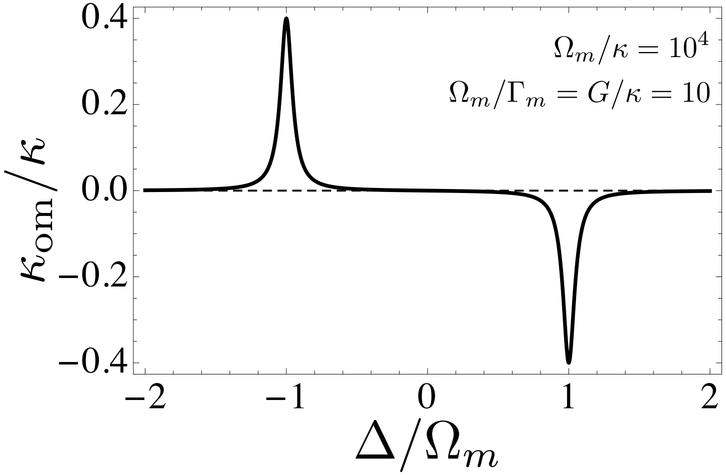
A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett*. **113,** 023604 (2014)

# The reversed dissipation regime

**Reversed dissipation** hierarchy : $\kappa << \Gamma_m$

$\Gamma_{eff} \rightarrow \kappa_{eff}$

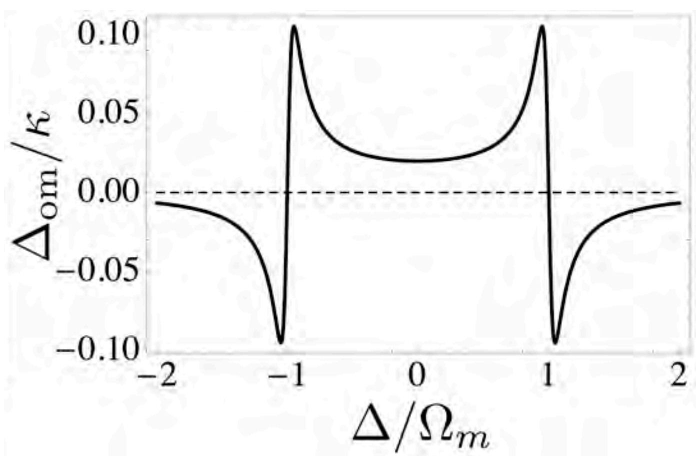
Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.




**Change in the electromagnetic decay rate (mechanical damping)**

$$\kappa_{om} = \frac{\Gamma_{eff} g_0^{\ 2} n_c}{(\Gamma_{eff}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{eff} g_0^{\ 2} n_c}{(\Gamma_{eff}/2)^2 + (\Delta - \Omega_m)^2}$$

**Change in the electromagnetic resonance freq.**




$$\Delta\omega_{om} = \frac{\Gamma_{eff} g_0^{\ 2} n_c (\Delta - \Omega_m)}{(\Gamma_{eff}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{eff} g_0^{\ 2} n_c (\Delta + \Omega_m)}{(\Gamma_{eff}/2)^2 + (\Delta - \Omega_m)^2}$$

**Modified cavity response**

$$S_{11}(\omega) = 1 - \frac{\kappa_{ex}}{(\kappa_0 + \kappa_{ex} + \kappa_{om})/2 + i(\omega_c + \Delta\omega_{om} - \omega)}$$

A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett*. **113,** 023604 (2014)

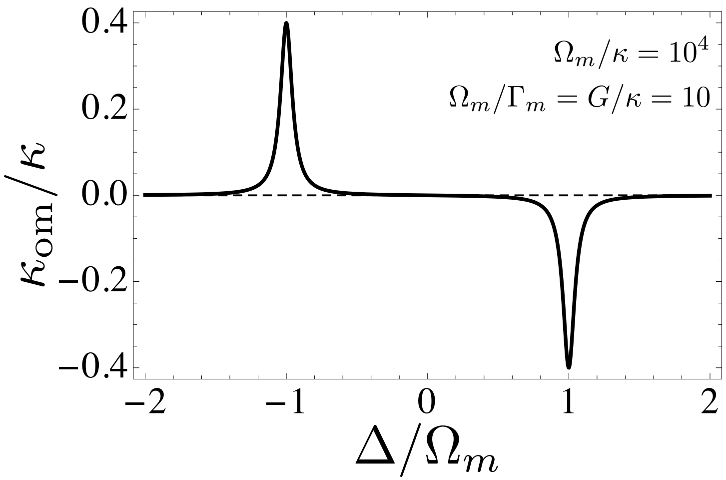
# The reversed dissipation regime

**Reversed dissipation** hierarchy : $\kappa \ll \Gamma_m$

Mechanics *amplifies* electromagnetic mode on blue sideband

$\Gamma_{eff} \rightarrow \kappa_{eff}$

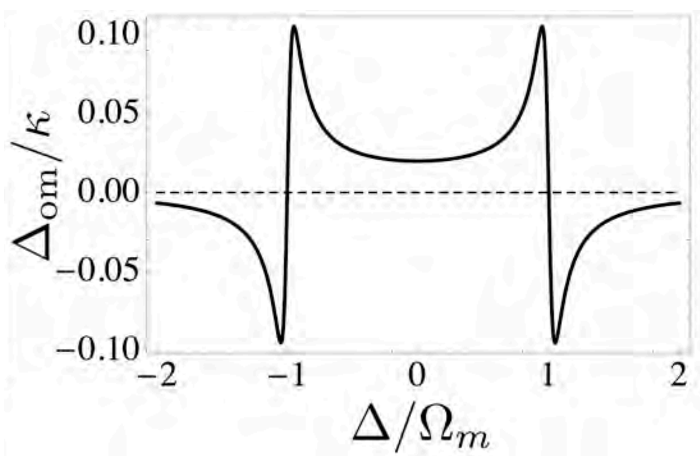
Change in the *mechanical* damping rate, becomes change in the *optical* decay rate.




**Change in the electromagnetic decay rate (mechanical damping)**

$$\kappa_{om} = \frac{\Gamma_{eff} g_0^2 n_c}{(\Gamma_{eff}/2)^2 + (\Delta+\Omega_m)^2} - \frac{\Gamma_{eff} g_0^2 n_c}{(\Gamma_{eff}/2)^2 + (\Delta-\Omega_m)^2}$$

**Change in the electromagnetic resonance freq.**




$$\Delta\omega_{om} = \frac{\Gamma_{eff} g_0^2 n_c(\Delta-\Omega_m)}{(\Gamma_{eff}/2)^2 + (\Delta+\Omega_m)^2} - \frac{\Gamma_{eff} g_0^2 n_c(\Delta+\Omega_m)}{(\Gamma_{eff}/2)^2 + (\Delta-\Omega_m)^2}$$

**Modified cavity response**

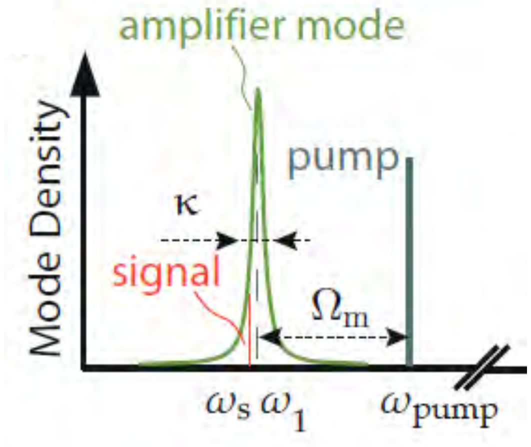
$$S_{11}(\omega) = 1 - \frac{\kappa_{ex}}{(\kappa_0 + \kappa_{ex} + \kappa_{om})/2 + i(\omega_c + \Delta\omega_{om} - \omega)}$$

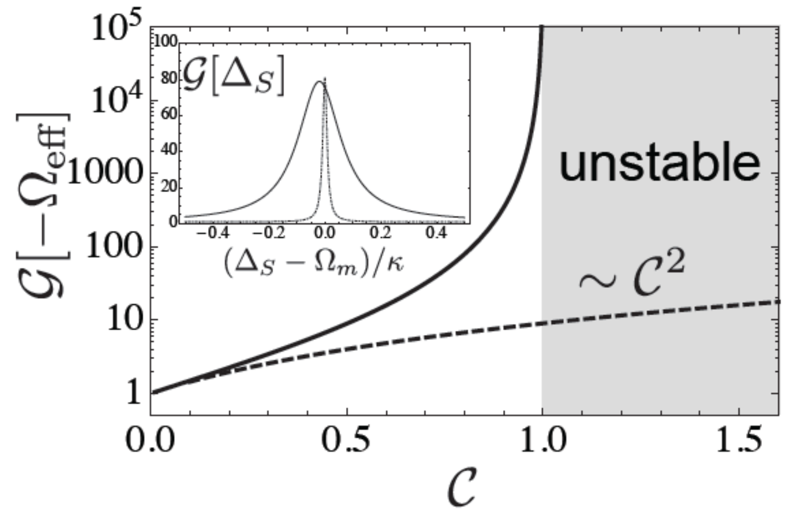
A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett.* **113,** 023604 (2014)

# Amplification in the reversed dissipation regime

Amplification scheme

$\Gamma_m \gg \kappa$




$$\hat{a}_{out} = A(\omega)\hat{a}_{in} + \underbrace{B(\omega)}_{|B| \ll |A|}\hat{a}_{in}^{\dagger} + C(\omega)\hat{b}_{in} + \underbrace{D(\omega)}_{|C| \ll |D|}\hat{b}_{in}^{\dagger}$$

The system operates as a **phase preserving parametric amplifier**

**Gain of the amplifier**

$$\mathcal{G}(\Delta_s) = \left| 1 - \frac{\kappa}{\kappa_{eff}/2 - i(\Delta_s + \Delta_{eff})} \right|^2$$

$$\mathcal{G}(0) = \left| \frac{1+\mathcal{C}}{1-\mathcal{C}} \right|^2$$

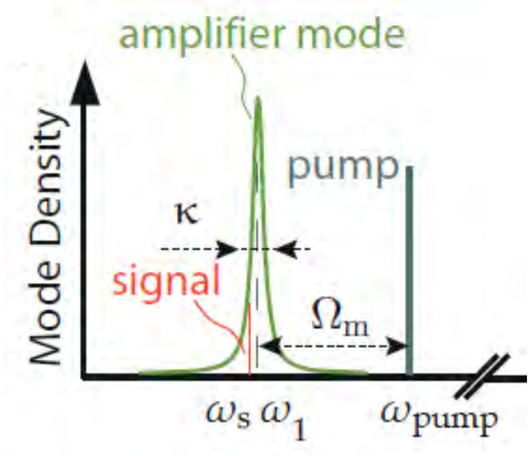
A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett.* **113,** 023604 (2014)
C. M. Caves. *Phys. Rev. D* **26,** 1817 (1982)

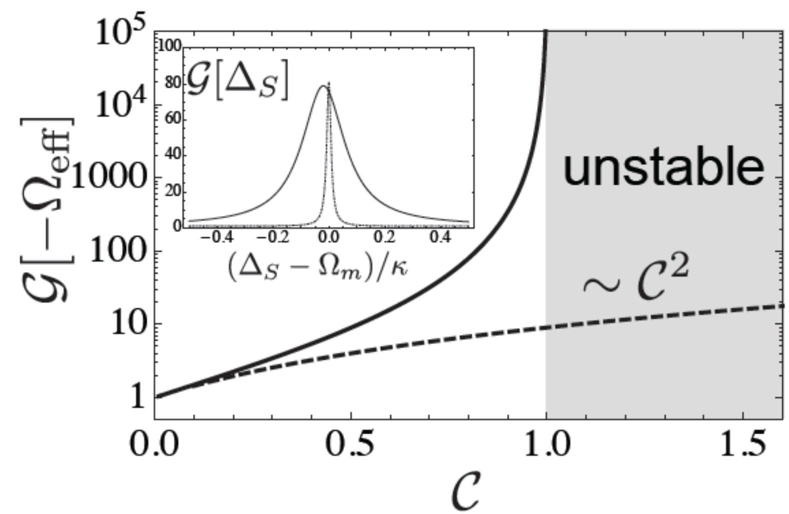
# Amplification in the reversed dissipation regime



Amplification scheme

$\Gamma_m \gg \kappa$




$$\hat{a}_{out} = A(\omega)\hat{a}_{in} + \underbrace{B(\omega)}_{|B|\ll|A|}\hat{a}_{in}^{\dagger} + C(\omega)\hat{b}_{in} + \underbrace{D(\omega)}_{|C|\ll|D|}\hat{b}_{in}^{\dagger}$$

The system operates as a **phase preserving parametric amplifier**

**Noise added by the amplifier**

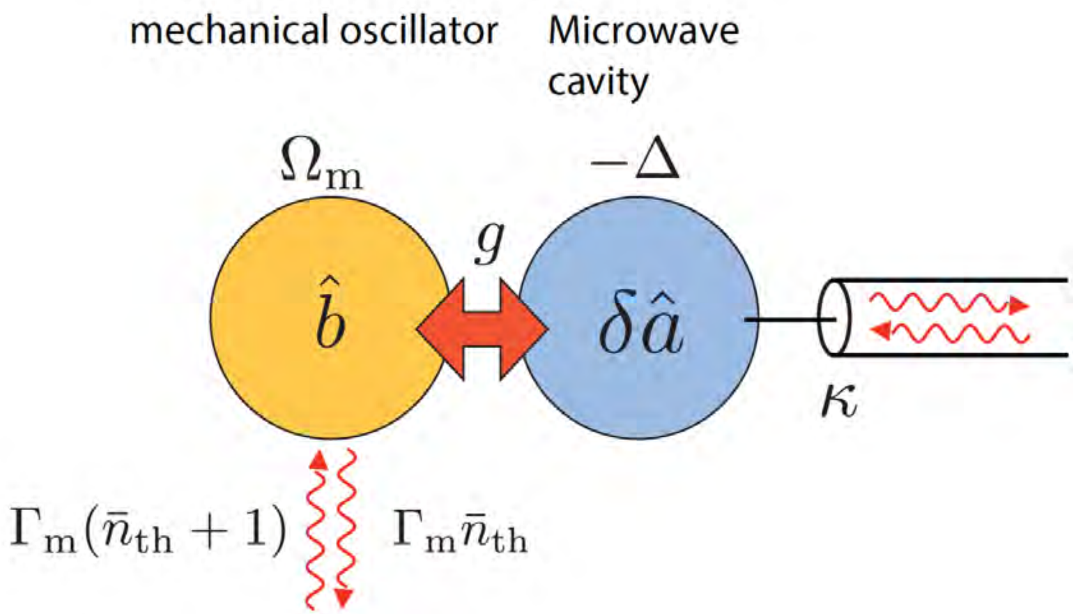
$$\mathcal{N} = (n_{eff} + \tfrac{1}{2})\left|\frac{D(\omega)}{A(\omega)}\right|^2 = \frac{4\mathcal{C}\left(n_{eff} + \frac{1}{2}\right)}{(\mathcal{C}+1)^2} \to n_{eff} + \frac{1}{2}$$

Providing a dissipative but cold mechanical oscillator therefore realizes a **quantum limited phase preserving amplifier** based on a mechanical oscillator

A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett.* **113,** 023604 (2014)
C. M. Caves. *Phys. Rev. D* **26,** 1817 (1982)

# Two-mode implementation of the reversed dissipation regime

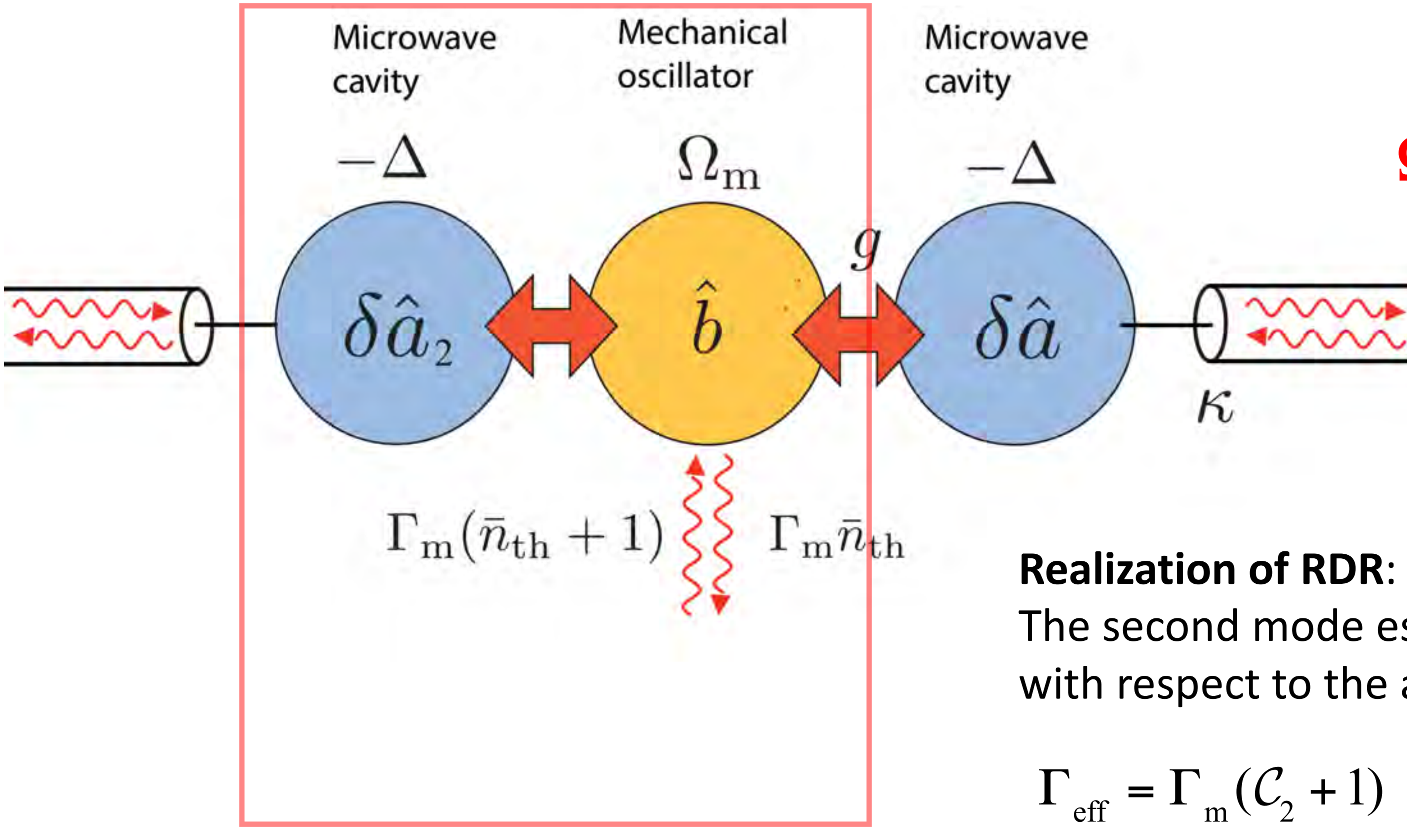
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE




A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett.* **113,** 023604 (2014)

# Two-mode implementation of the reversed dissipation regime

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



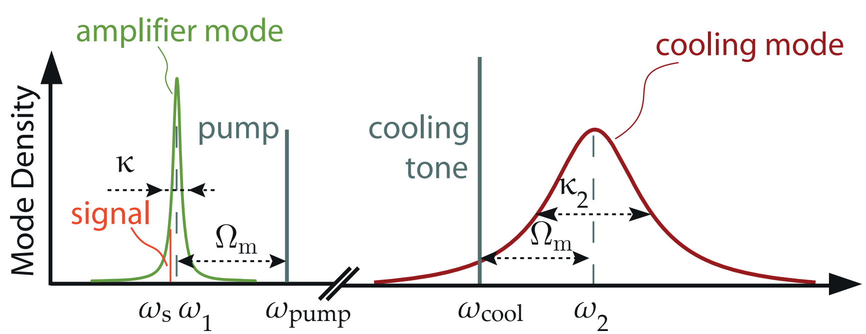

$$\Omega_m \gg \kappa_2 \gg \kappa$$

**Realization of RDR**:
The second mode establishes the RDR with respect to the amplifier mode:

$$\Gamma_{\mathrm{eff}} = \Gamma_{\mathrm{m}}(\mathcal{C}_2 + 1)$$

$$\Gamma_{\mathrm{eff}} \rightarrow \kappa_2 / 2 \gg \kappa$$

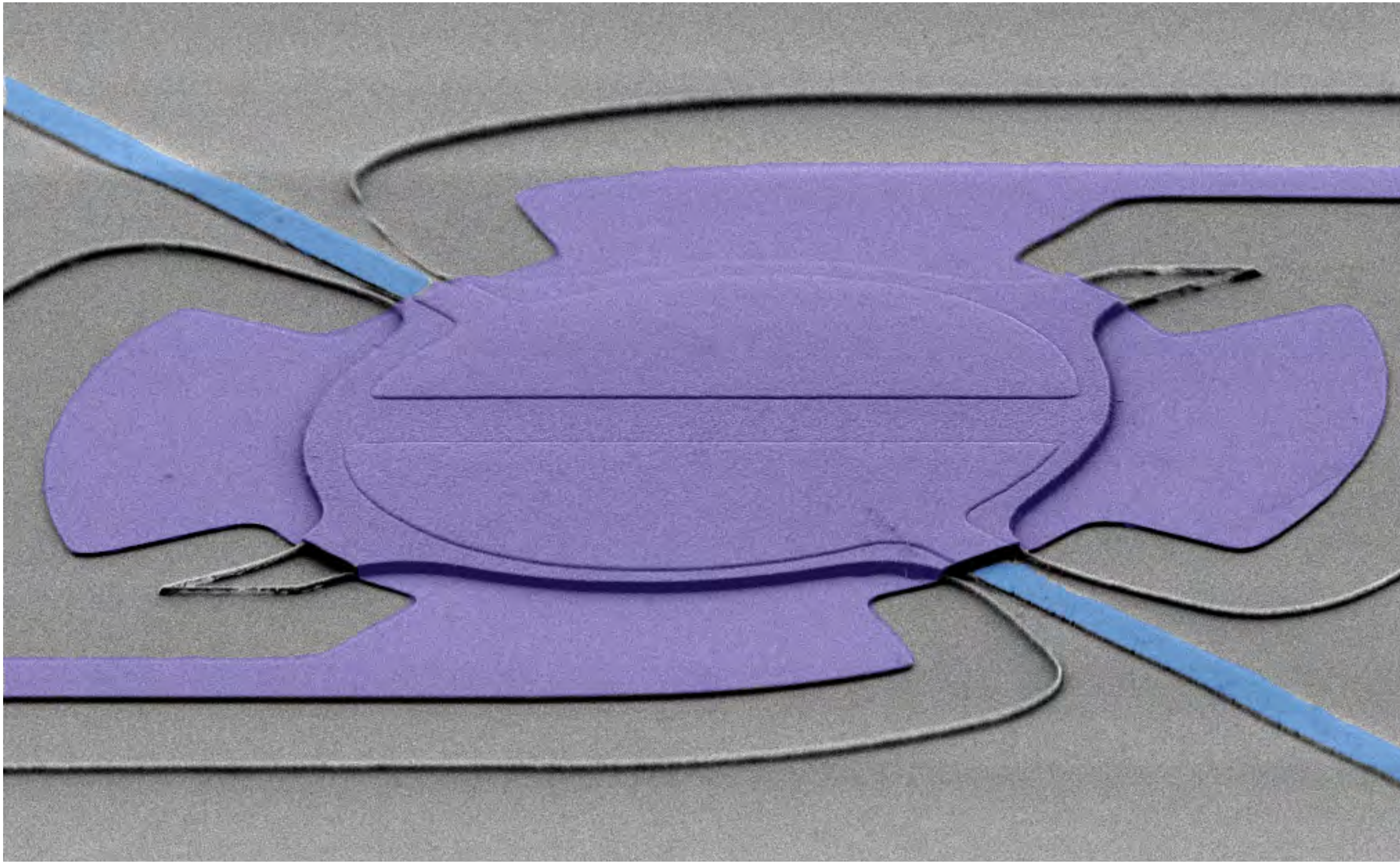
$$\text{for } \mathcal{C}_2 = \frac{4G_2^2}{\kappa_2 \Gamma_{\mathrm{m}}} \gg 1$$




A. Nunnenkamp, V. Sudhir, A. K. Feofanov, A. Roulet, T. J. Kippenberg. *Phys. Rev. Lett.* **113,** 023604 (2014)

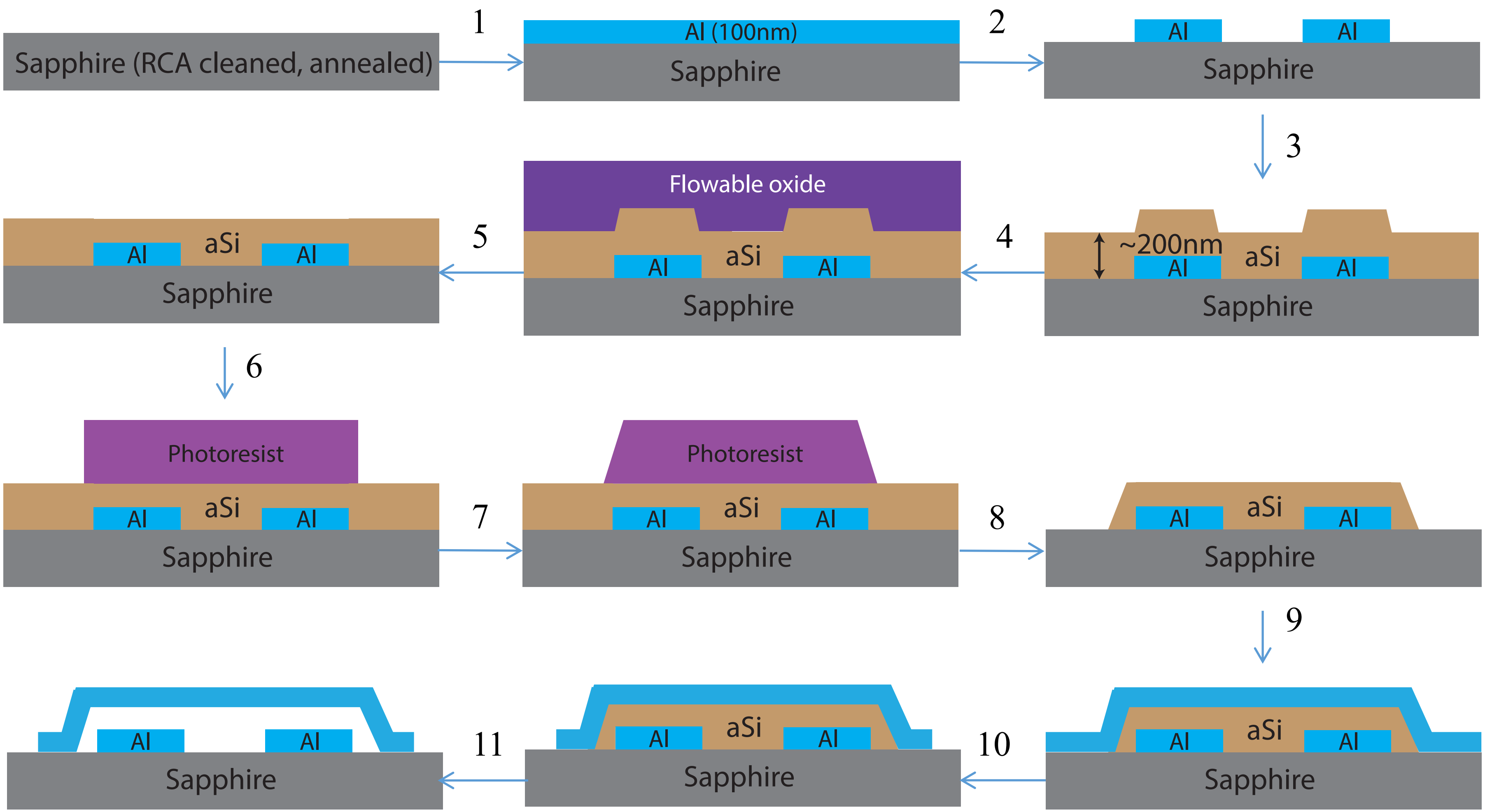
# Circuit design and fabrication

CMi EPFL Center of MicroNanoTechnology



# Process flow – dual-mode circuits

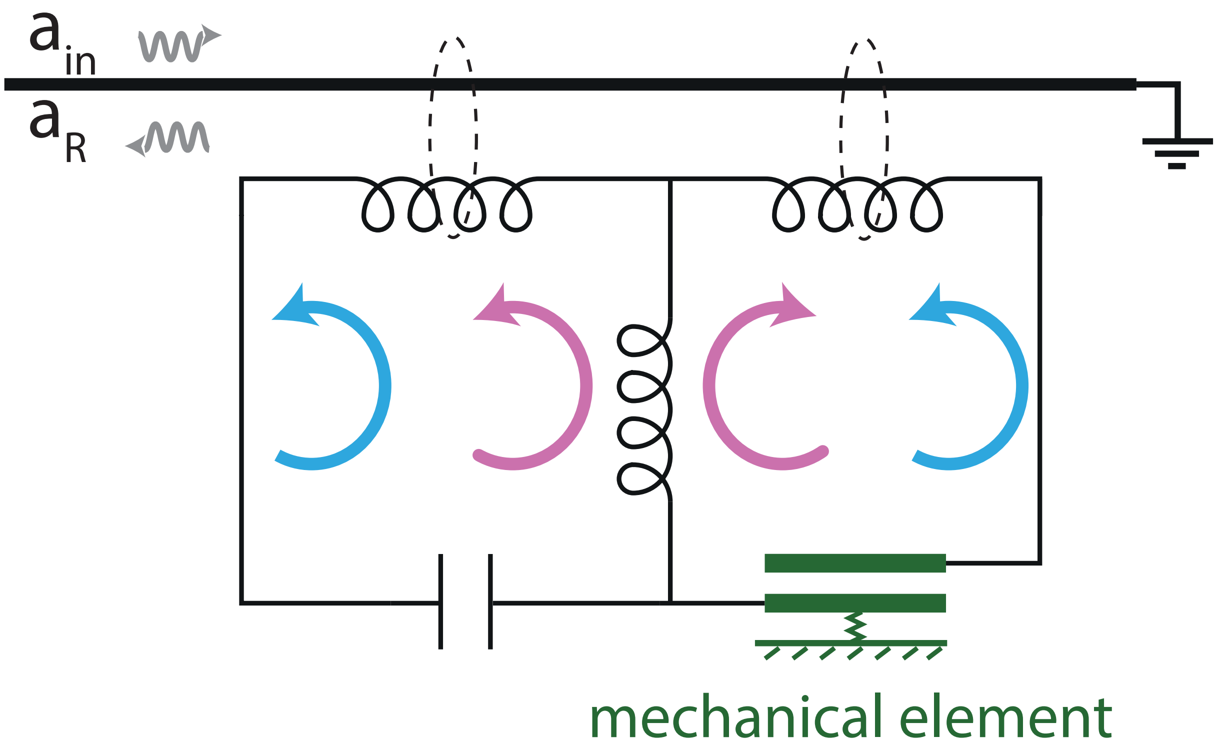
CMi EPFL Center of MicroNanoTechnology

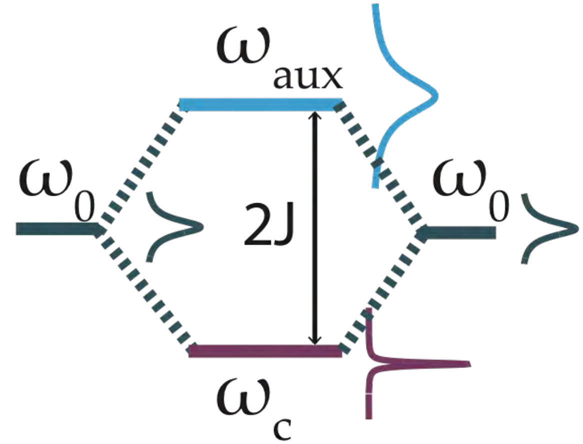



**1, 3, 9:** metal and sacrificial layer (Si) deposition
**2, 8, 10:** metal and Si etch
**4, 5:** planarization of Si layer (for split-plate drums)
**6, 7:** lithography to open Si layer (with reflow)
**11:** releasing the drum capacitor ($XeF_2$)

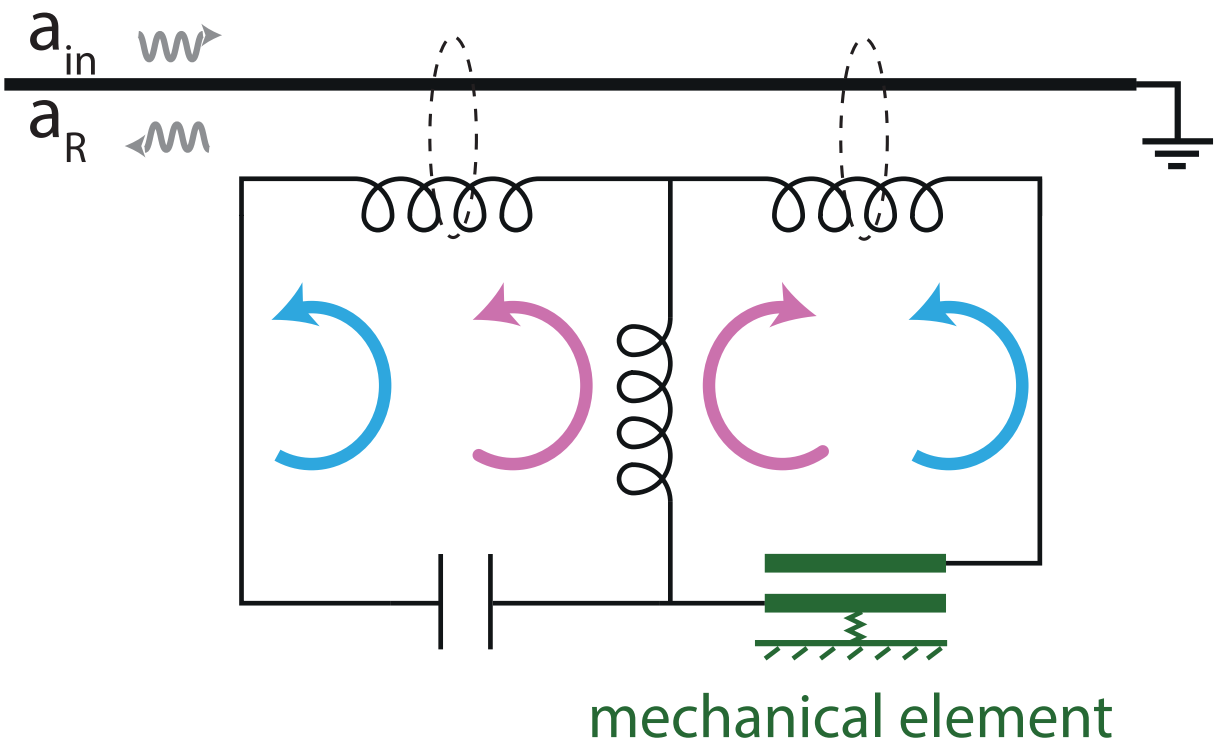
K. Cicak et al. *Appl. Phys. Lett.* **96**, 093502 (2010)

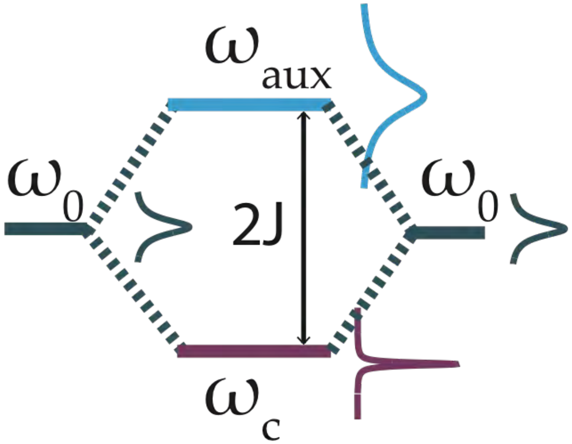
# New approach – hybrid modes



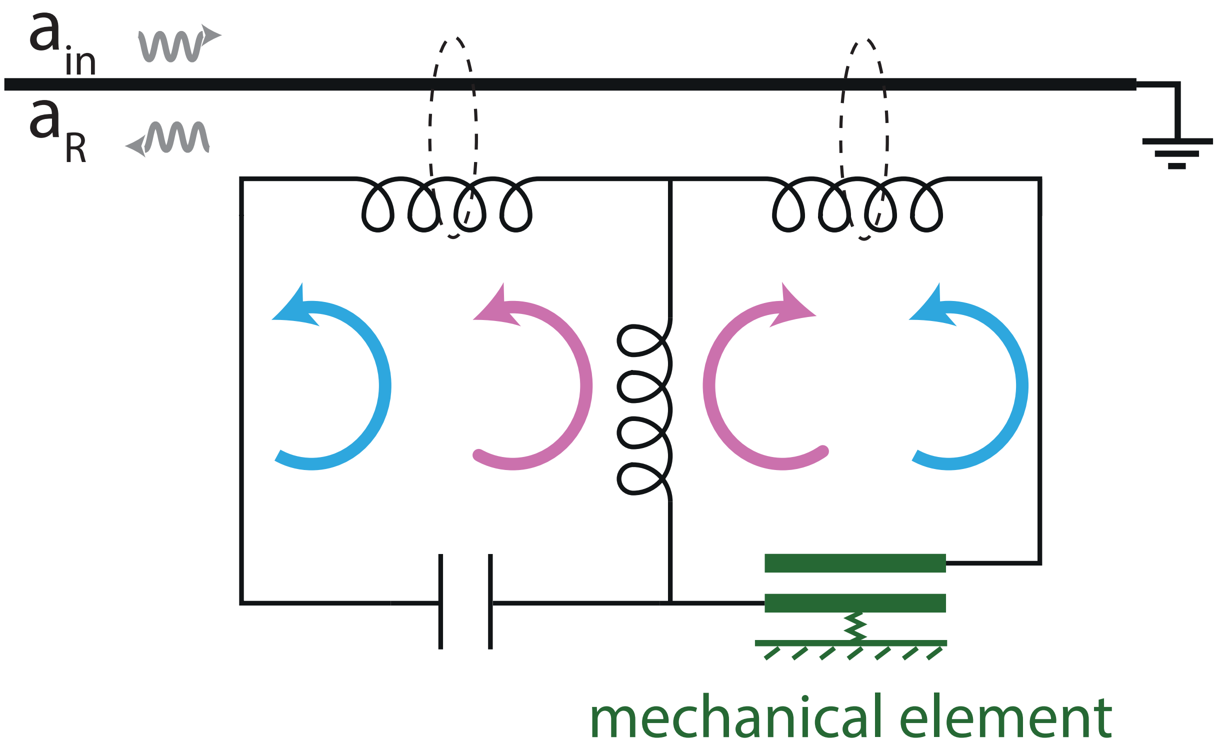
# New approach – hybrid modes

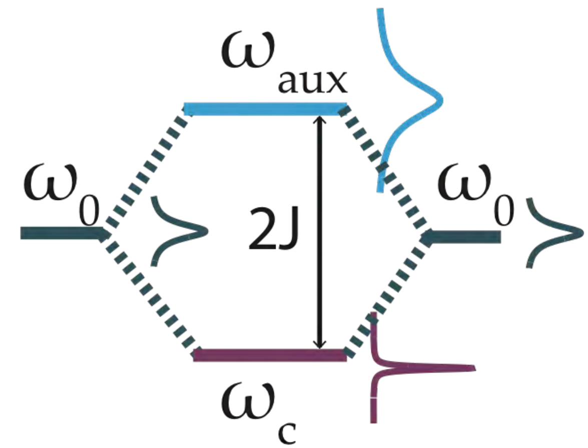



$$\hat{H}_{int} = \hbar J(\hat{a}_1^{\dagger}\hat{a}_2 + \hat{a}_2^{\dagger}\hat{a}_1) + \hbar g_0 \hat{a}_1^{\dagger}\hat{a}_1(\hat{b} + \hat{b}^{\dagger})$$

# New approach – hybrid modes



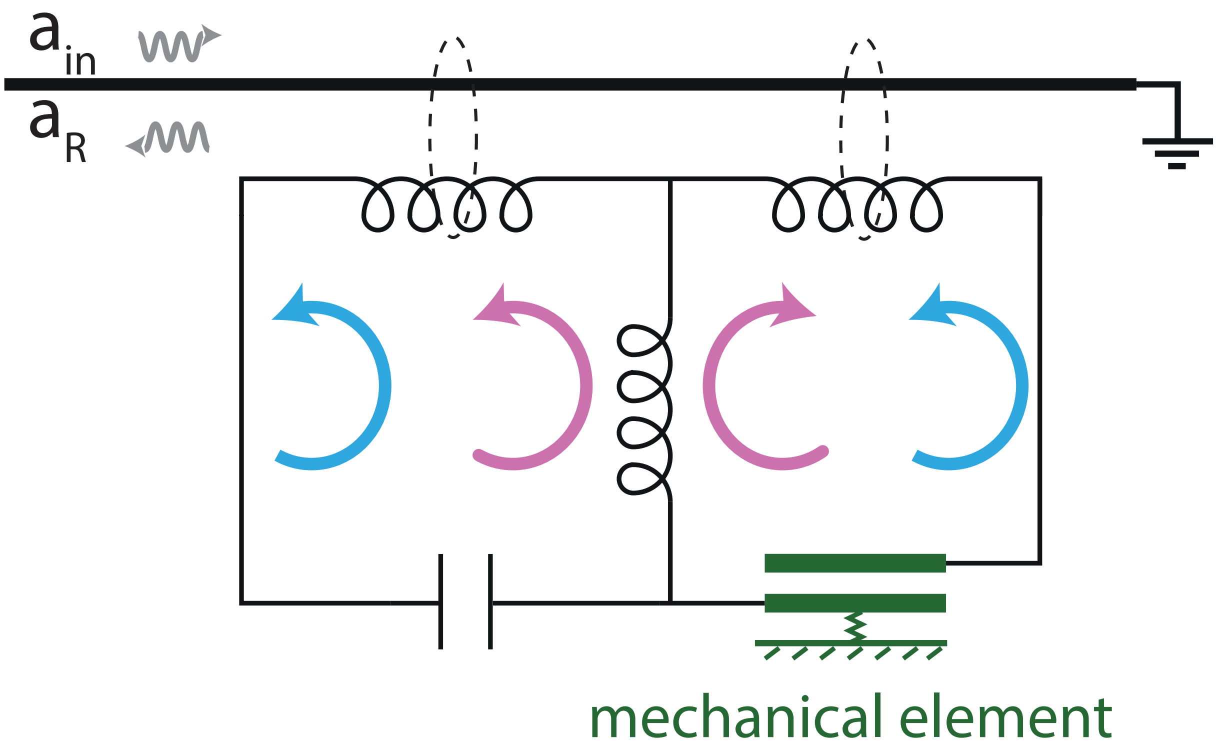



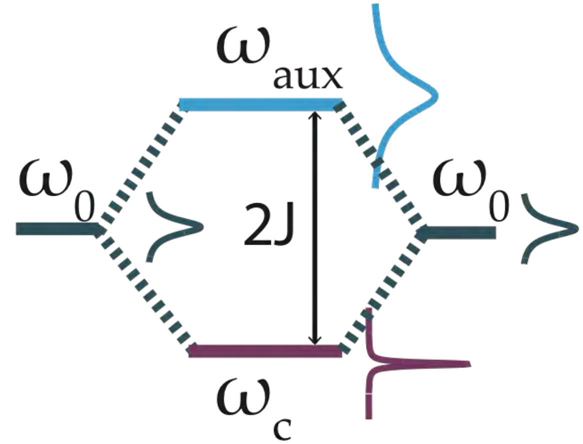

$$\hat{a}_{s,a} = \sqrt{2}^{-1}(\hat{a}_1 \pm \hat{a}_2)$$

$$\hat{H}_{int} = \hbar J(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1) + \hbar g_0 \hat{a}_1^\dagger \hat{a}_1 (\hat{b} + \hat{b}^\dagger)$$

# New approach – hybrid modes

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE



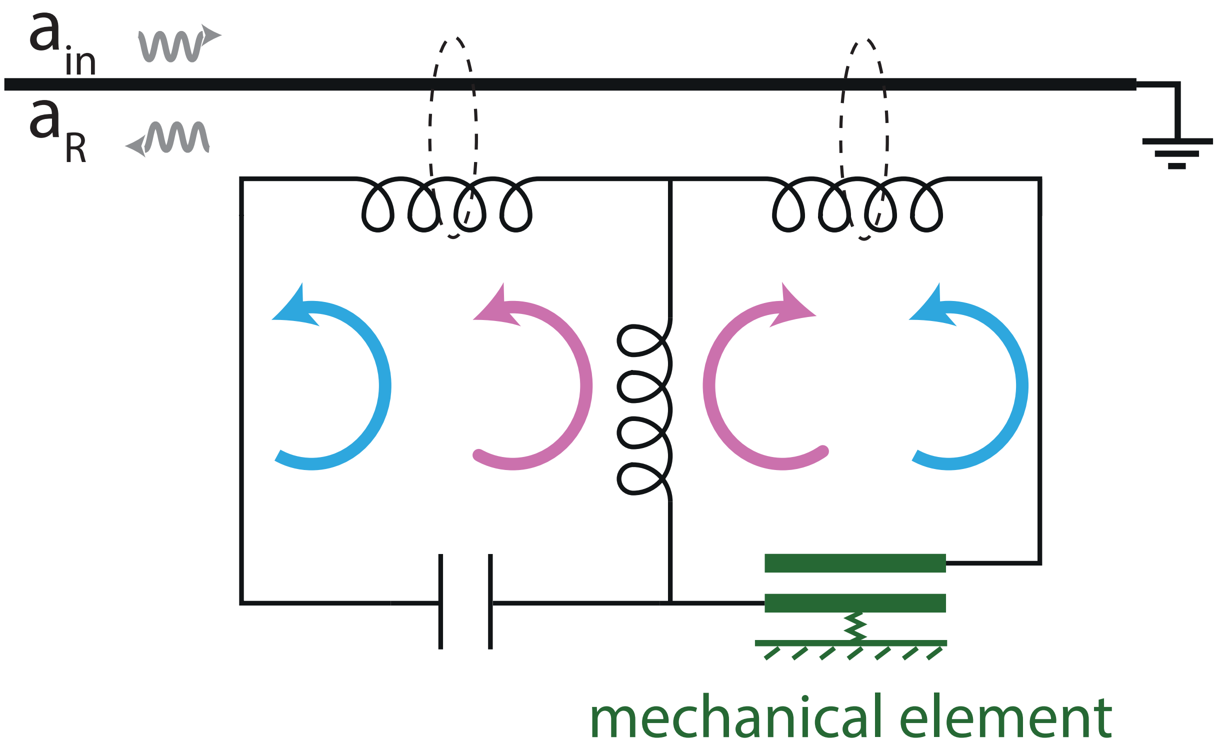

$$\hat{a}_{s,a} = \sqrt{2}^{-1}(\hat{a}_1 \pm \hat{a}_2)$$

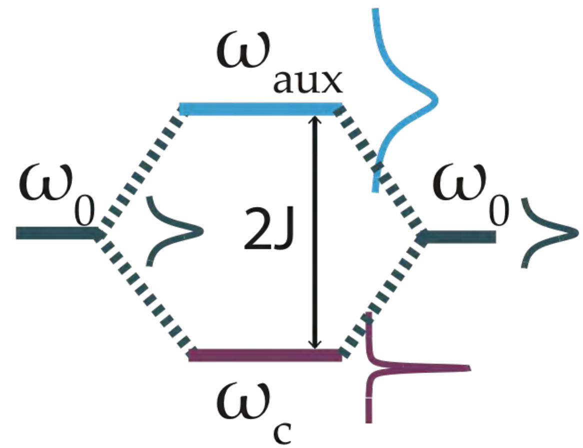
$$\hat{H}_{int} = \hbar J(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1) + \hbar g_0 \hat{a}_1^\dagger \hat{a}_1 (\hat{b} + \hat{b}^\dagger)$$

$$\hat{H}_{int} = \hbar J(\hat{a}_s^\dagger \hat{a}_s - \hat{a}_a^\dagger \hat{a}_a) + \hbar \frac{g_0}{2}(\hat{a}_a^\dagger \hat{a}_a + \hat{a}_s^\dagger \hat{a}_s)(\hat{b} + \hat{b}^\dagger)$$

# New approach – hybrid modes

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE



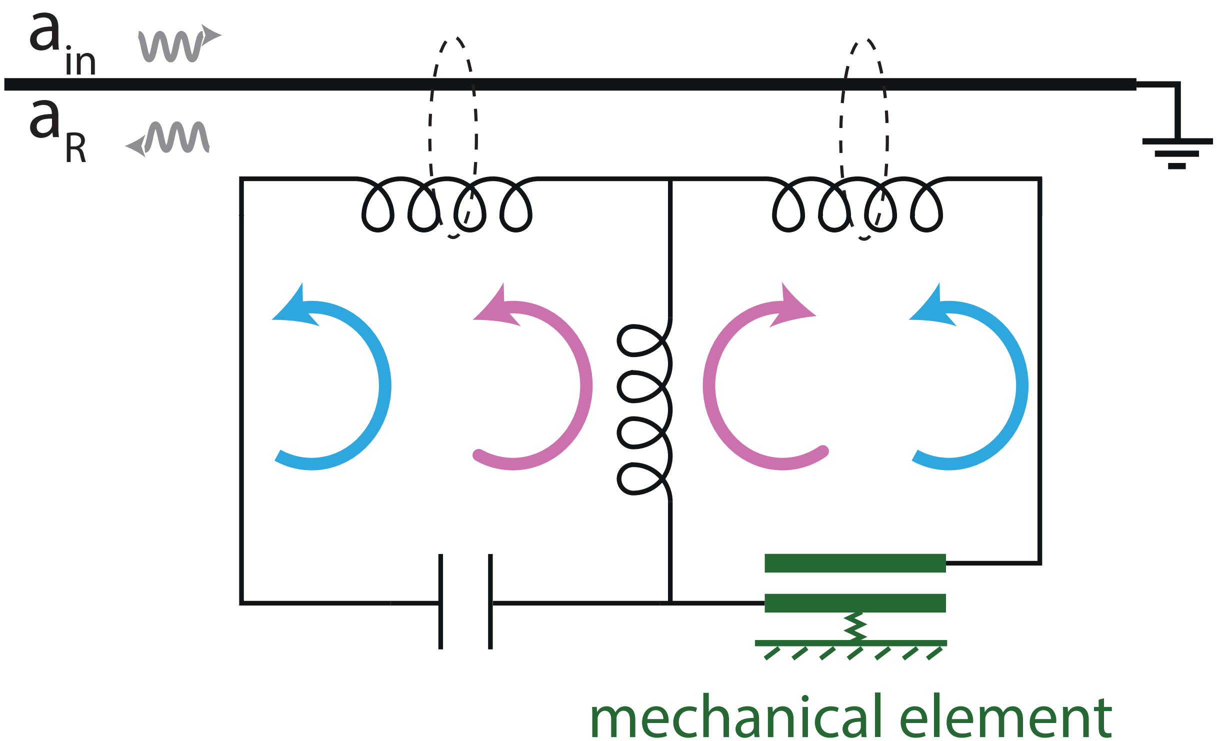

$$\hat{a}_{s,a} = \sqrt{2}^{-1}(\hat{a}_1 \pm \hat{a}_2)$$

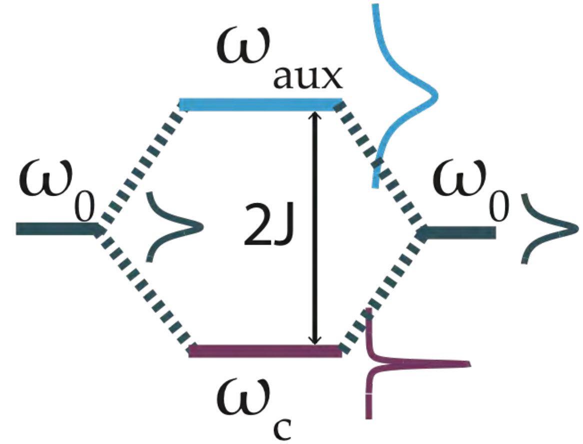
$$\widehat{\mathcal{H}} = \hbar\omega_0\left(\hat{a}_1^\dagger \hat{a}_1 + \hat{a}_2^\dagger \hat{a}_2\right) + \sum_k \hbar\omega_k \hat{c}_k^\dagger \hat{c}_k + \hbar J\left(\hat{a}_1^\dagger \hat{a}_2 + \text{H.c.}\right)$$

$$+\hbar\sum_k\left(g_k^{(1)} \hat{a}_1 \hat{c}_k^\dagger + \text{H.c.}\right) + \hbar\sum_k\left(g_k^{(2)} \hat{a}_2 \hat{c}_k^\dagger + \text{H.c.}\right)$$

# New approach – hybrid modes





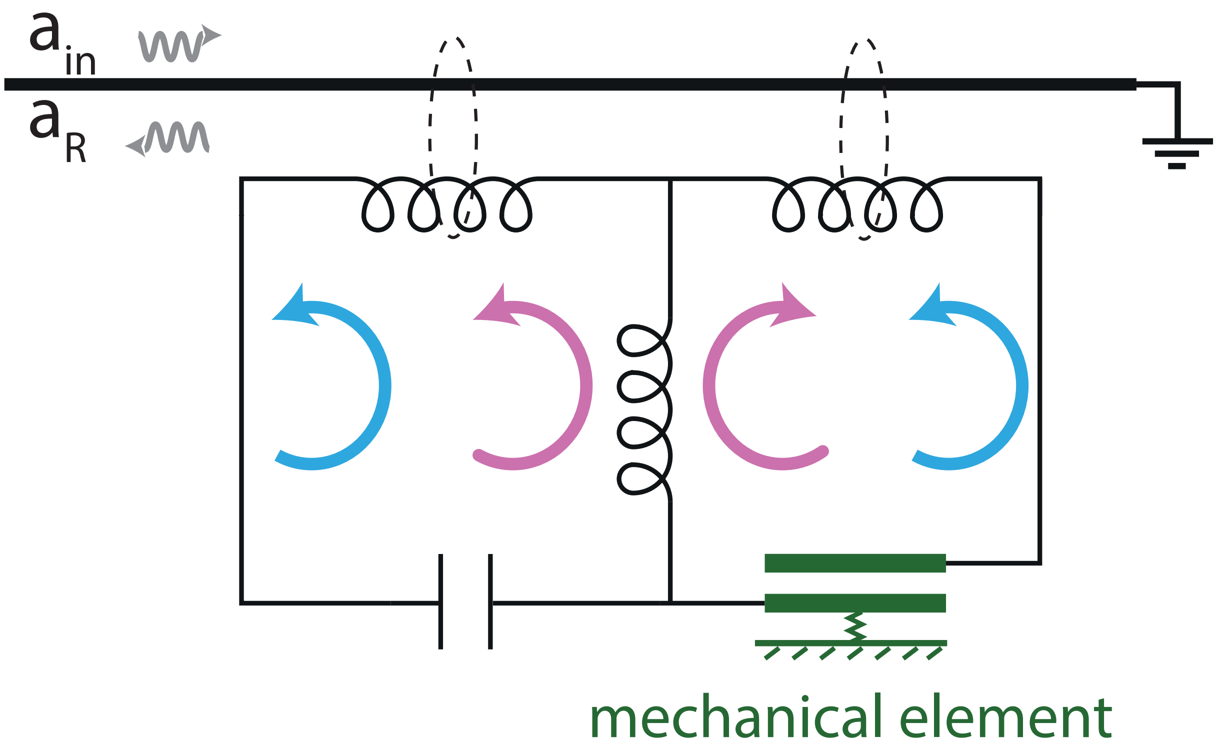

$$\hat{a}_{s,a} = \sqrt{2}^{-1}(\hat{a}_1 \pm \hat{a}_2)$$

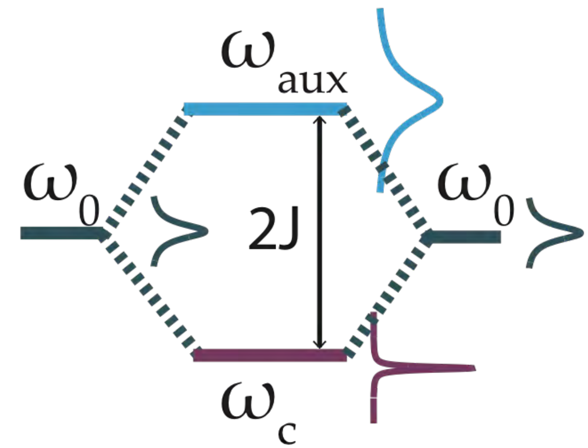
$$\widehat{\mathcal{H}} = \hbar(\omega_0 + J)\hat{a}_s^\dagger \hat{a}_s + \hbar(\omega_0 - J)\hat{a}_a^\dagger \hat{a}_a + \sum_k \hbar\omega_k \hat{c}_k^\dagger \hat{c}_k$$

$$+\hbar\sum_k\left(\frac{g_k^{(1)}+g_k^{(2)}}{\sqrt{2}}\hat{a}_s\hat{c}_k^\dagger + \text{H.c.}\right) + \hbar\sum_k\left(\frac{g_k^{(1)}-g_k^{(2)}}{\sqrt{2}}\hat{a}_a\hat{c}_k^\dagger + \text{H.c.}\right)$$

# New approach – hybrid modes

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



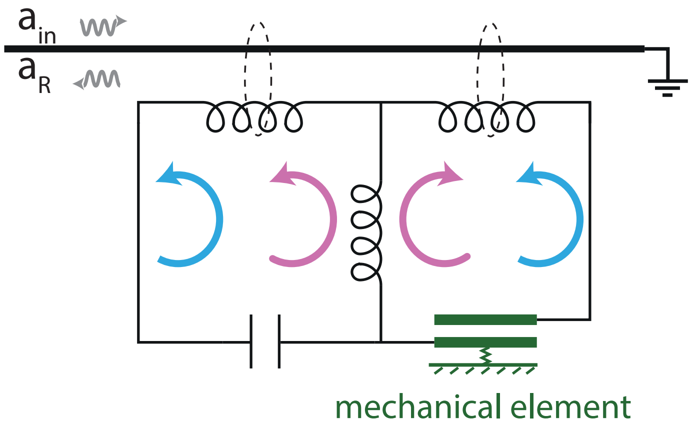




$$\hat{a}_{s,a} = \sqrt{2}^{-1}(\hat{a}_1 \pm \hat{a}_2)$$

$$\widehat{\mathcal{H}} = \hbar(\omega_0 + J)\hat{a}_s^\dagger \hat{a}_s + \hbar(\omega_0 - J)\hat{a}_a^\dagger \hat{a}_a + \sum_k \hbar\omega_k \hat{c}_k^\dagger \hat{c}_k$$
$$+\hbar\sum_k\left(\frac{g_k^{(1)}+g_k^{(2)}}{\sqrt{2}}\hat{a}_s\hat{c}_k^\dagger + \text{H.c.}\right) + \hbar\sum_k\left(\frac{g_k^{(1)}-g_k^{(2)}}{\sqrt{2}}\hat{a}_a\hat{c}_k^\dagger + \text{H.c.}\right)$$

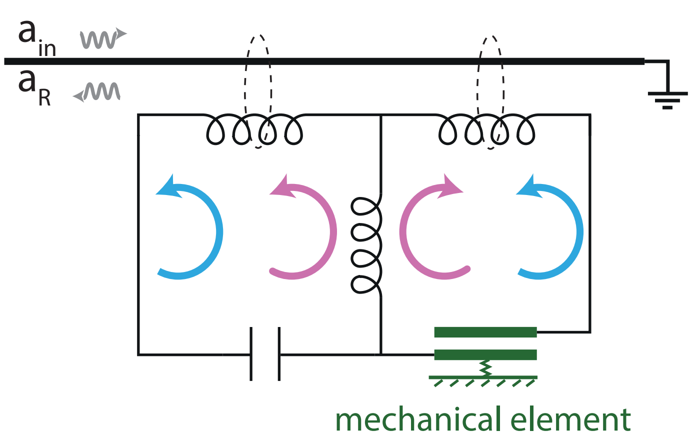
Bright and dark modes due to interference

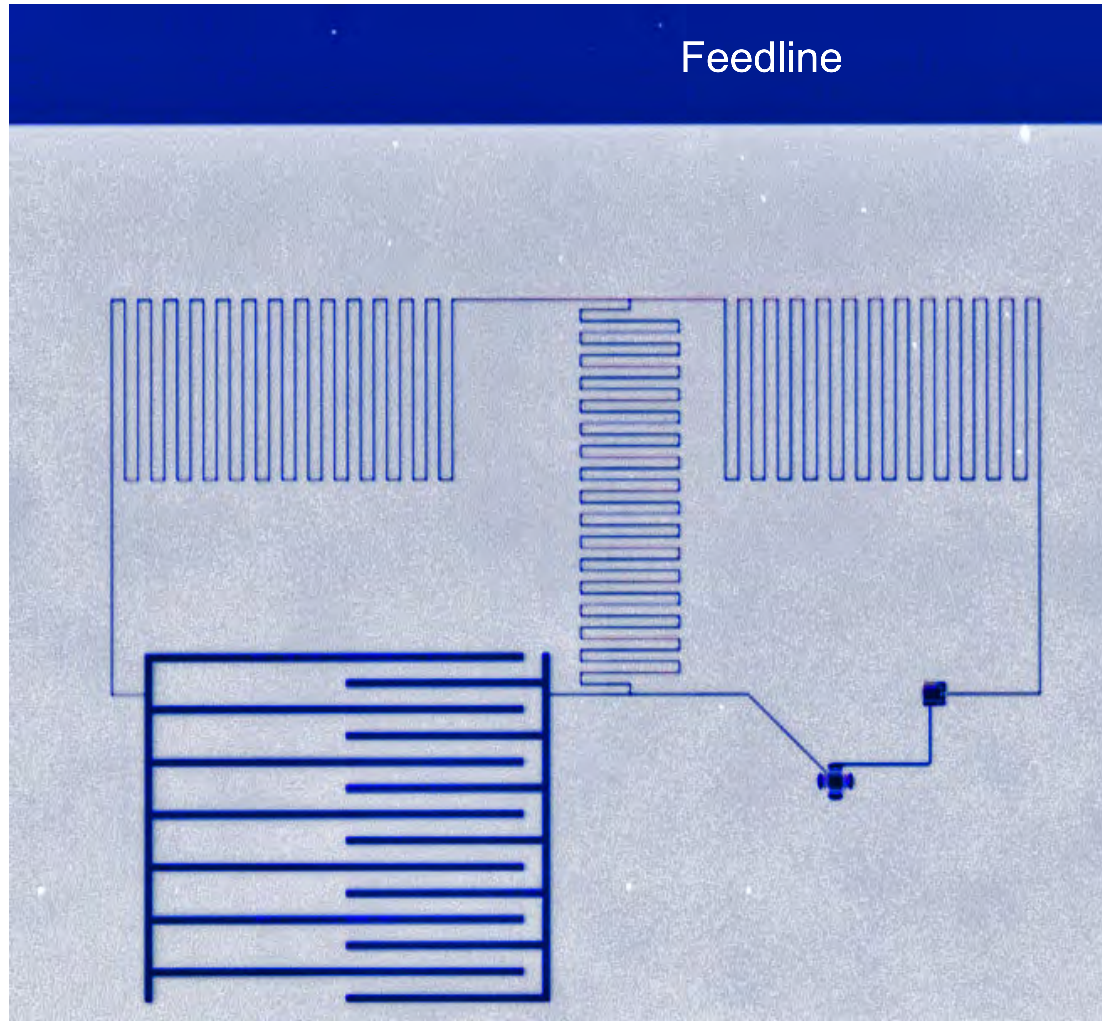
# Circuit layout




L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

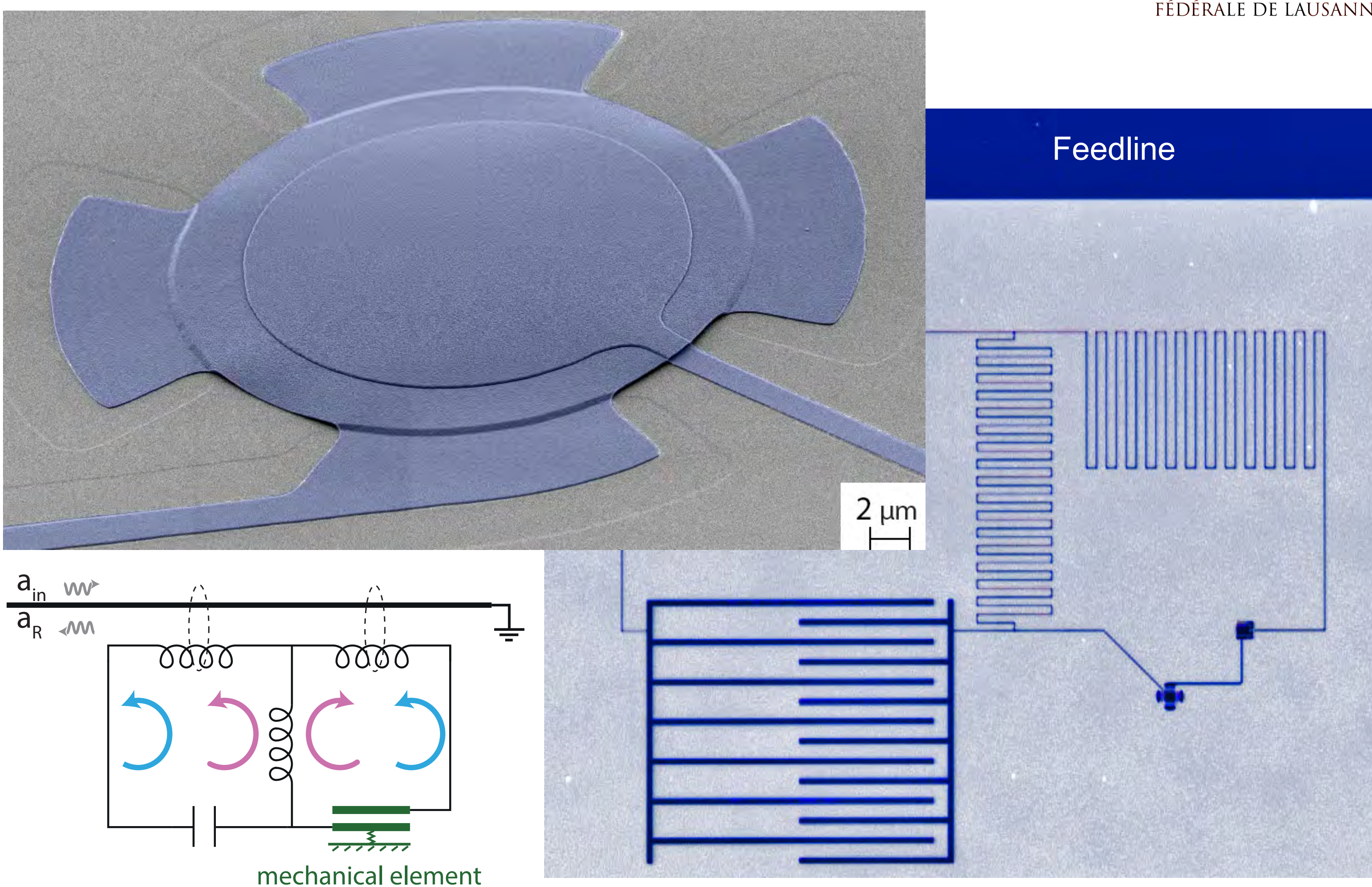
# Circuit layout




L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

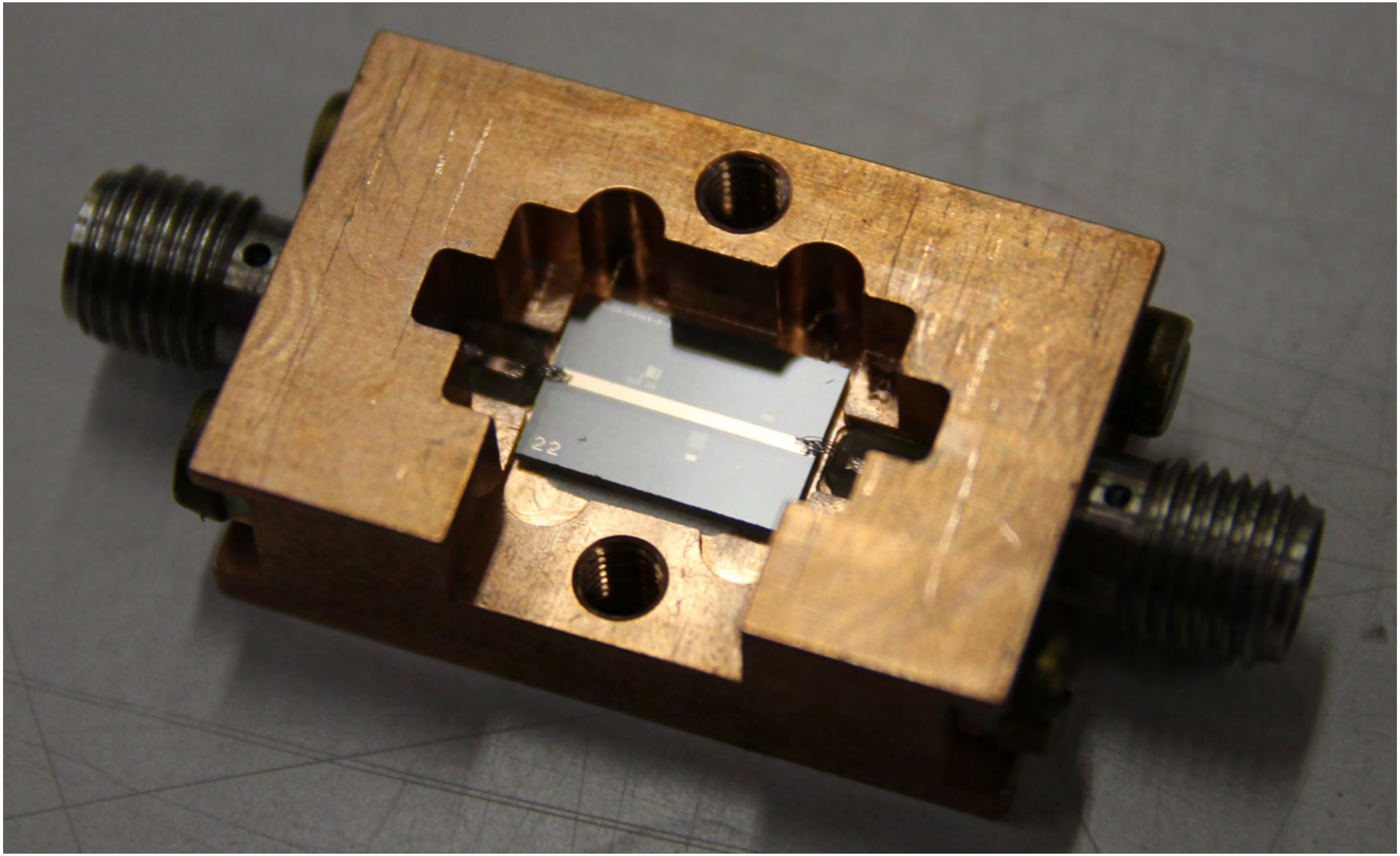
# Circuit layout




L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

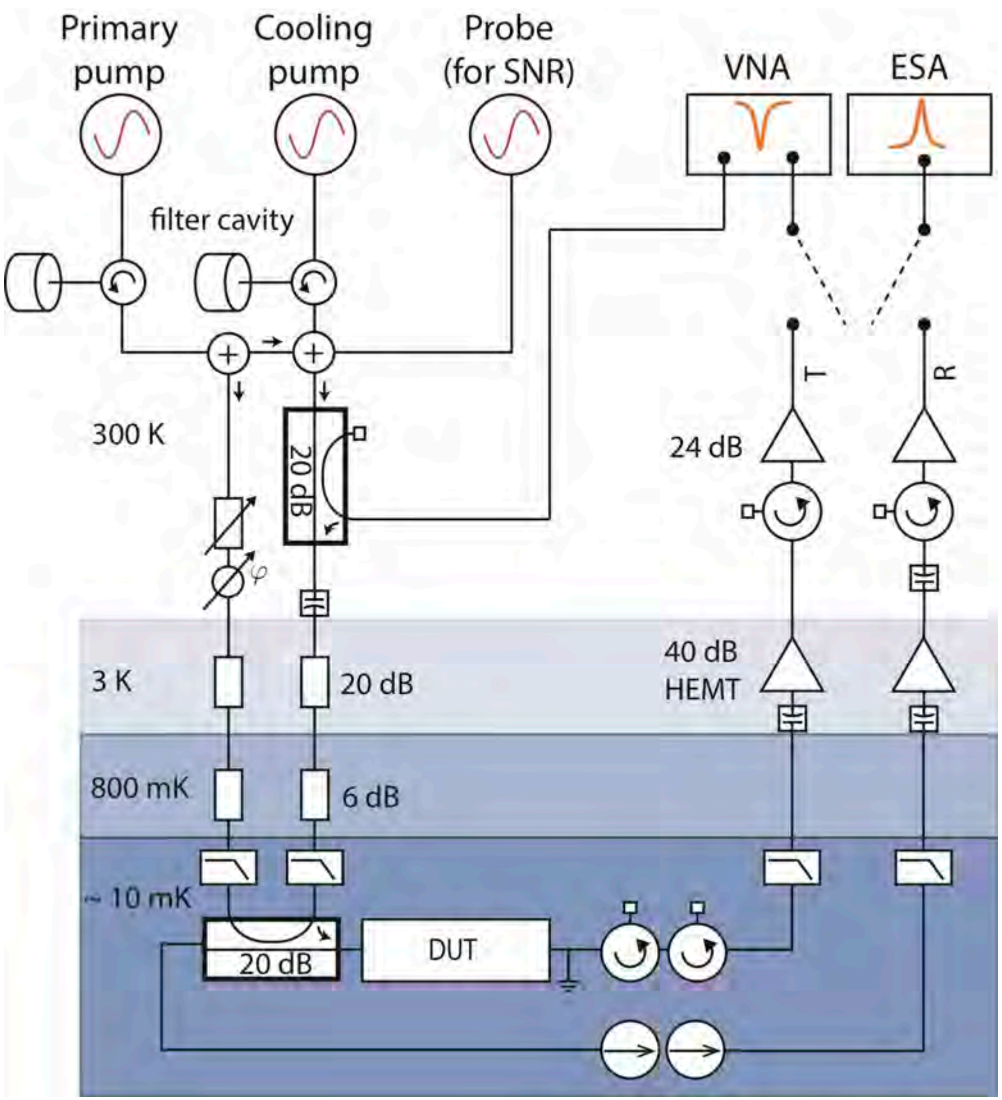
# Measurement setup

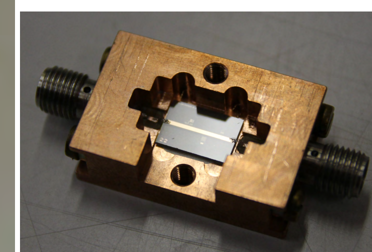
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE



# Measurement setup

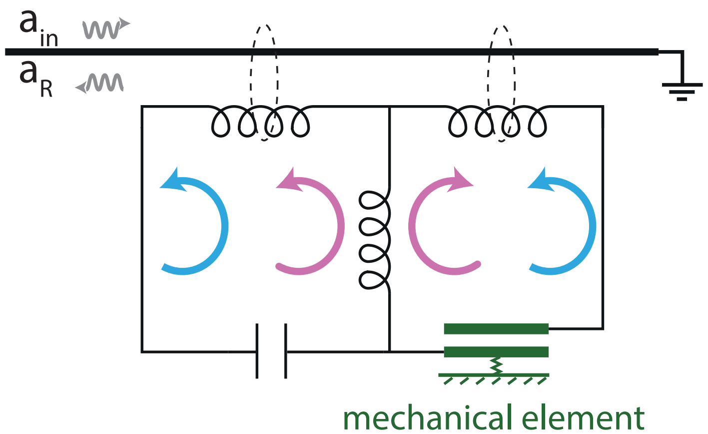
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

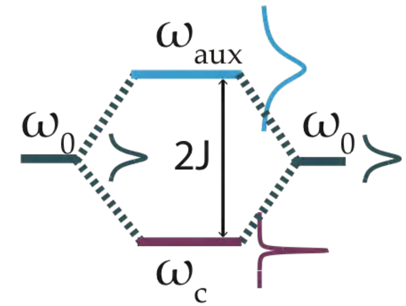


L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

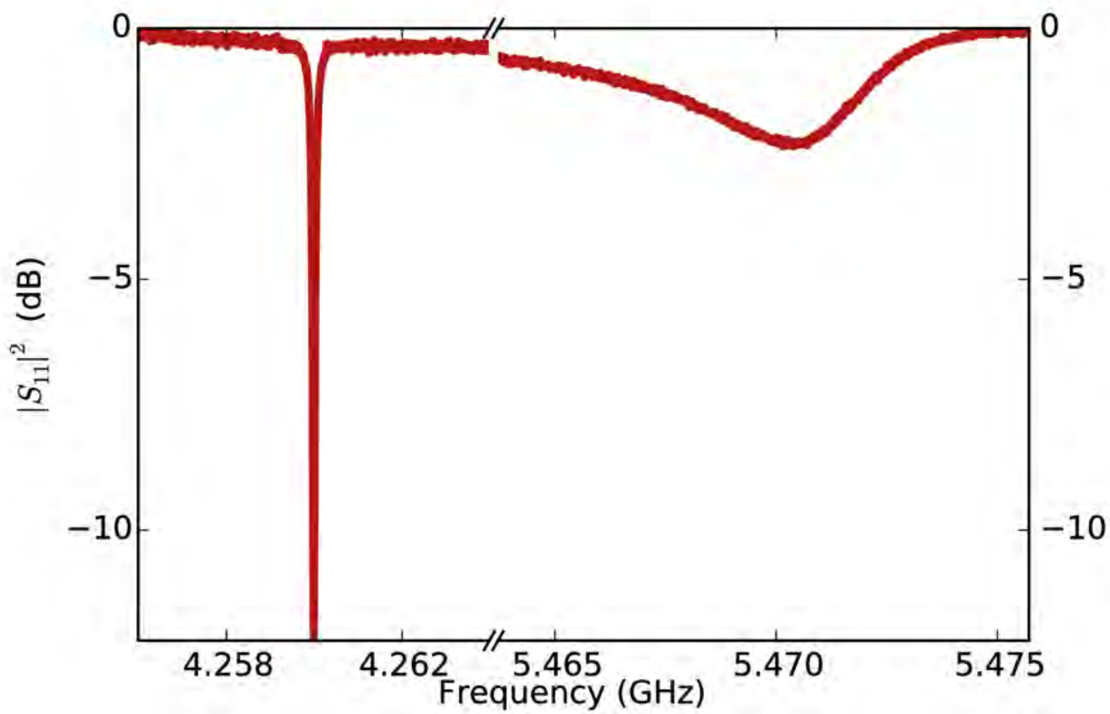
# Device characterization

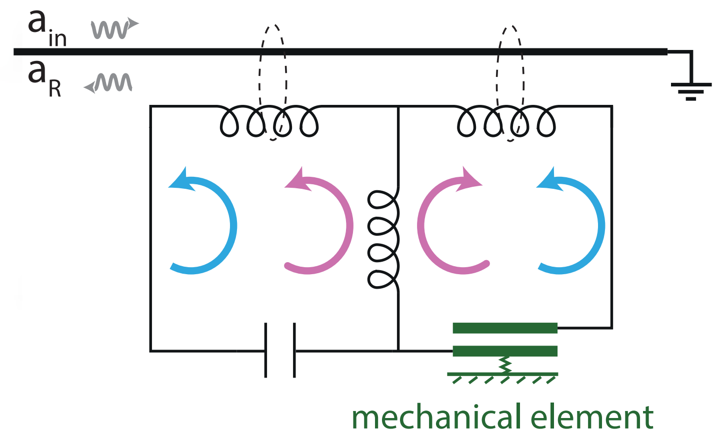


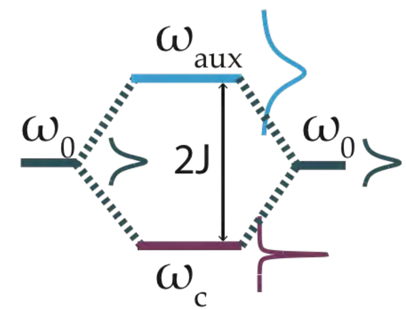




L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Device characterization



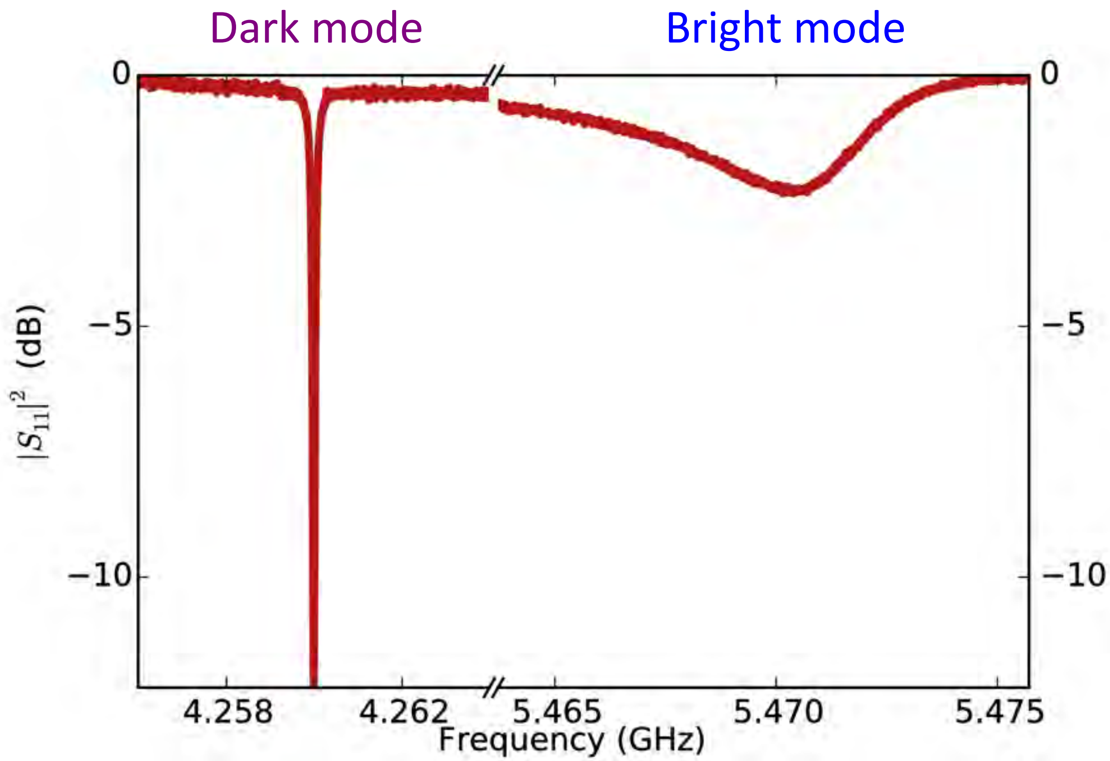



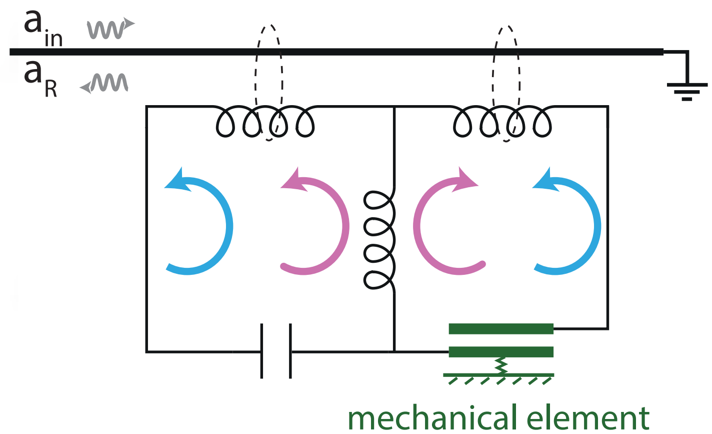



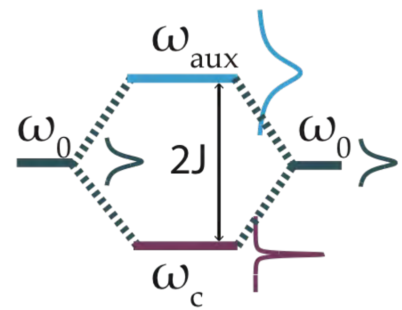

| $\omega_c / 2\pi$ | $\kappa / 2\pi$ | $\omega_{aux} / 2\pi$ | $\kappa_{aux} / 2\pi$ | $\Omega_m / 2\pi$ | $\Gamma_m / 2\pi$ | $g_0 / 2\pi$ |
|---|---|---|---|---|---|---|
| 4.3 GHz | 118 kHz | 5.4 GHz | 4.4 MHz | 5 MHz | ~ 30 Hz | ~ 120 Hz |

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Device characterization



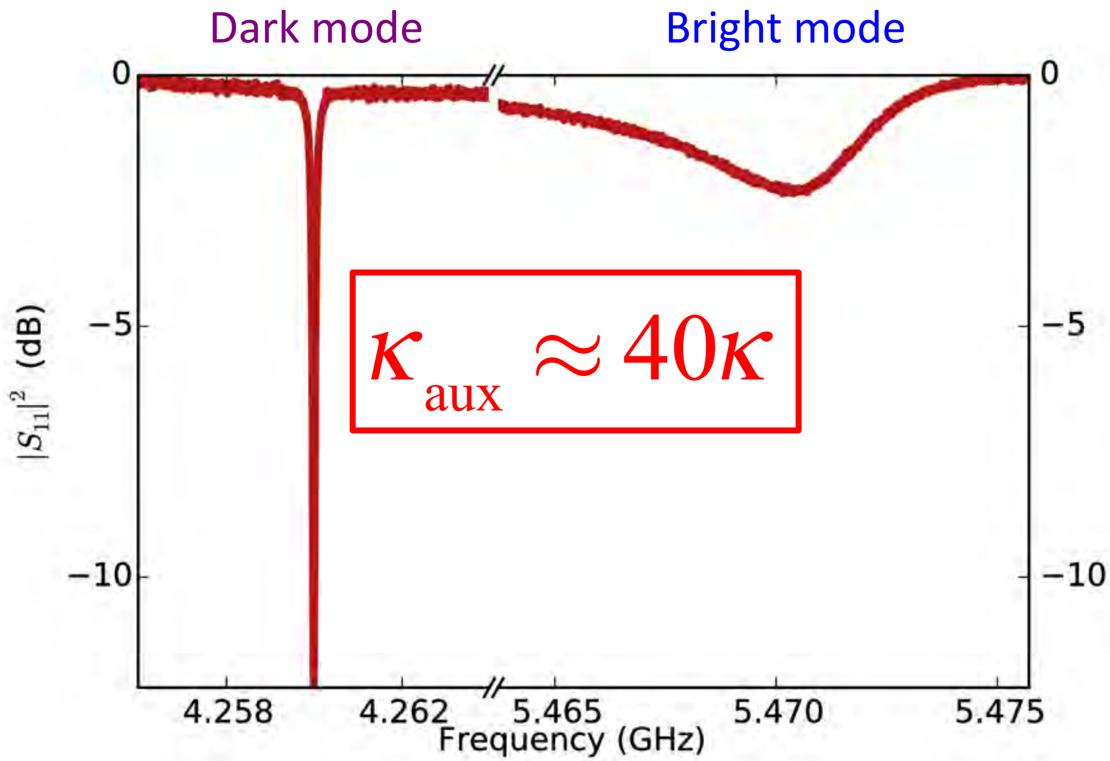



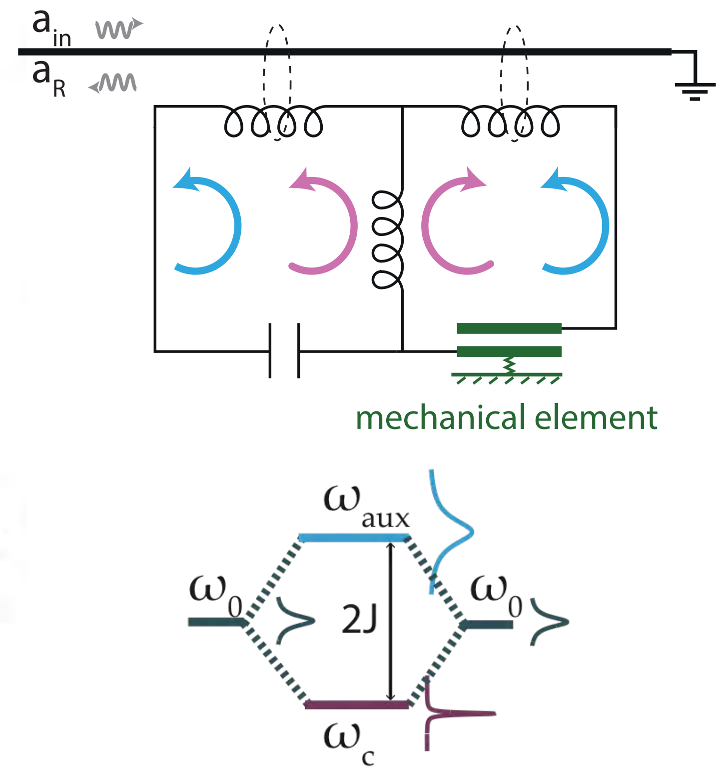




| $\omega_c / 2\pi$ | $\kappa / 2\pi$ | $\omega_{aux} / 2\pi$ | $\kappa_{aux} / 2\pi$ | $\Omega_m / 2\pi$ | $\Gamma_m / 2\pi$ | $g_0 / 2\pi$ |
|---|---|---|---|---|---|---|
| 4.3 GHz | 118 kHz | 5.4 GHz | 4.4 MHz | 5 MHz | ~ 30 Hz | ~ 120 Hz |

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Device characterization



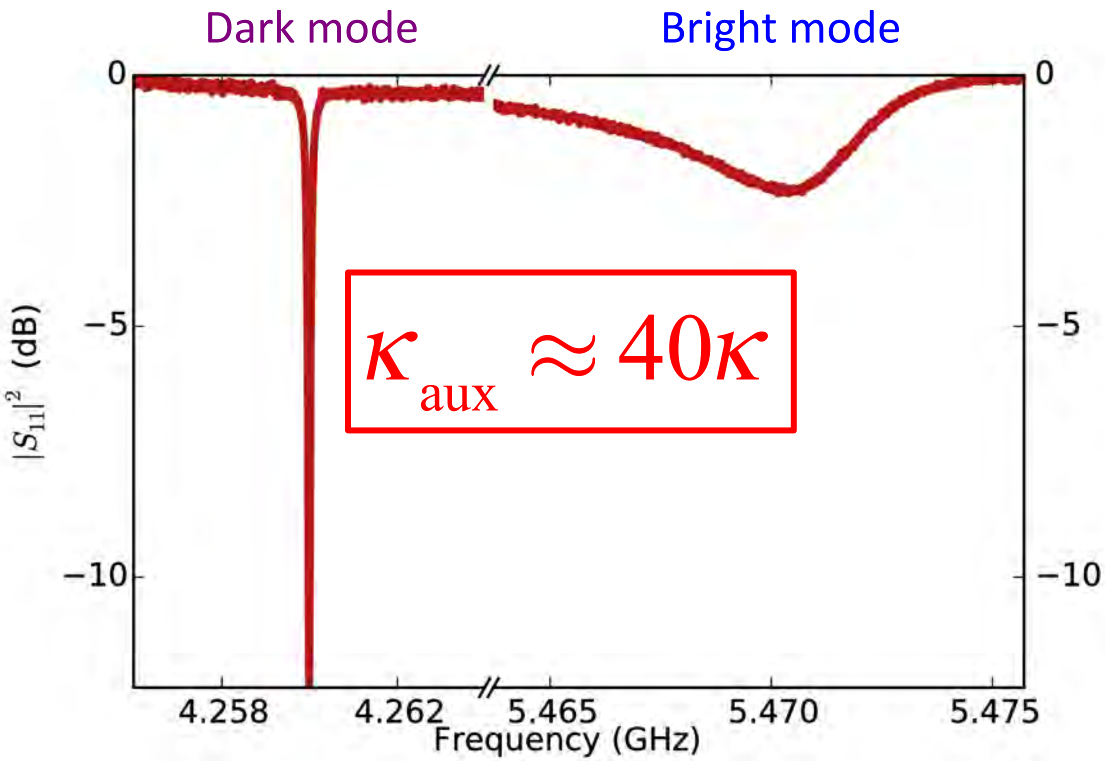



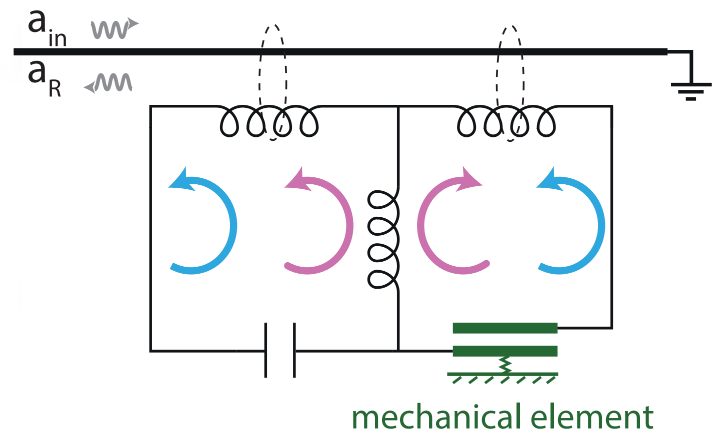

| $\omega_c / 2\pi$ | $\kappa / 2\pi$ | $\omega_{aux} / 2\pi$ | $\kappa_{aux} / 2\pi$ | $\Omega_m / 2\pi$ | $\Gamma_m / 2\pi$ | $g_0 / 2\pi$ |
|---|---|---|---|---|---|---|
| 4.3 GHz | 118 kHz | 5.4 GHz | 4.4 MHz | 5 MHz | ~ 30 Hz | ~ 120 Hz |

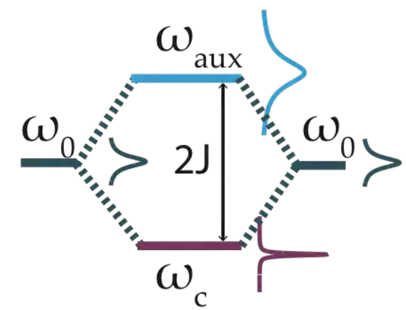
L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Device characterization

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE




| $\omega_c / 2\pi$ | $\kappa / 2\pi$ | $\omega_{aux} / 2\pi$ | $\kappa_{aux} / 2\pi$ | $\Omega_m / 2\pi$ | $\Gamma_m / 2\pi$ | $g_0 / 2\pi$ |
|---|---|---|---|---|---|---|
| 4.3 GHz | 118 kHz | 5.4 GHz | 4.4 MHz | 5 MHz | ~ 30 Hz | ~ 120 Hz |

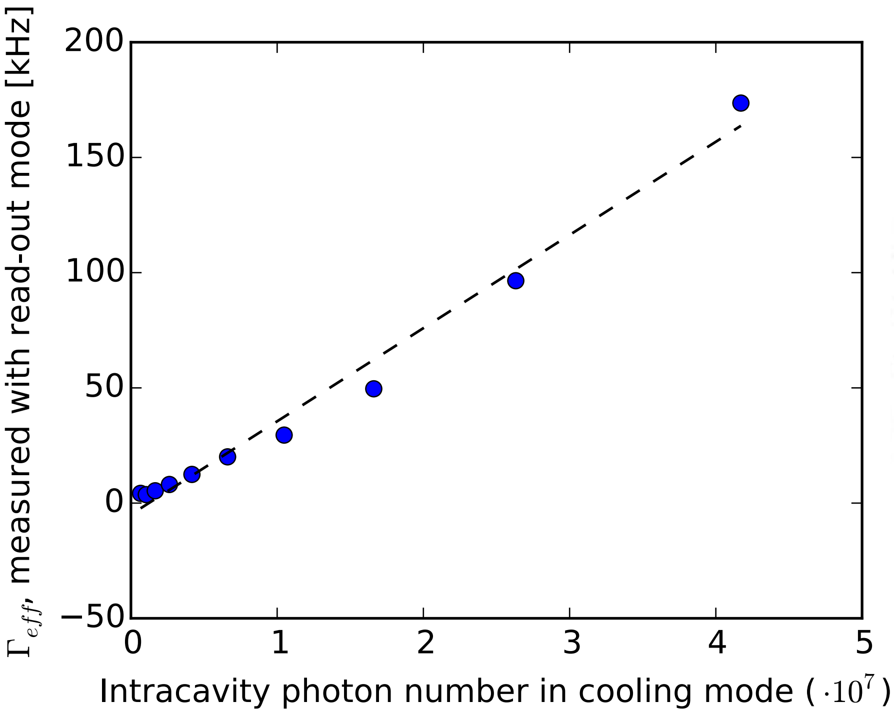
With these parameters we can easily damp the mechanics to $\Gamma_{eff} \sim 2\pi \times 550$ kHz $\approx 5\kappa$

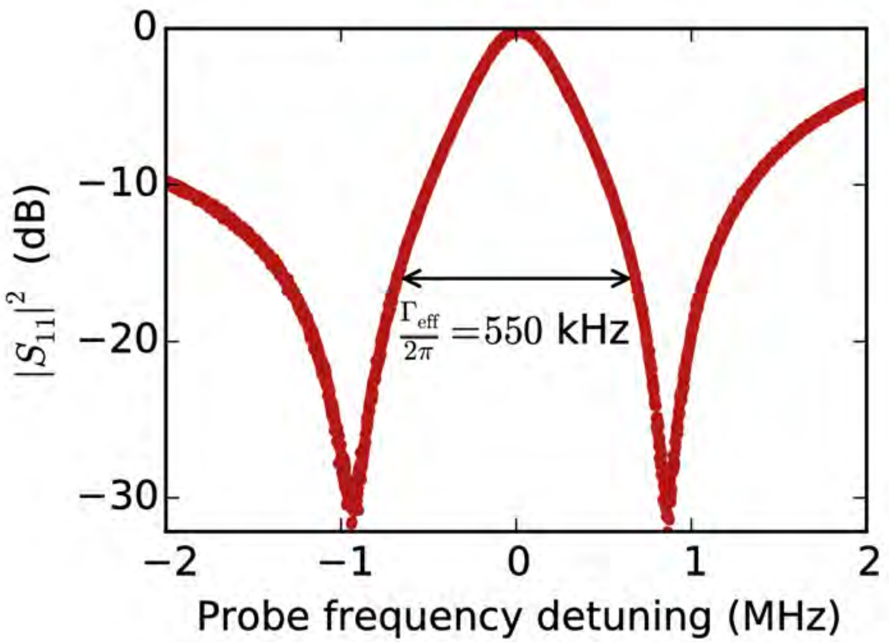
$$\Omega_m \gg \Gamma_{eff} \gg \kappa$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Preparation of a dissipative reservoir

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

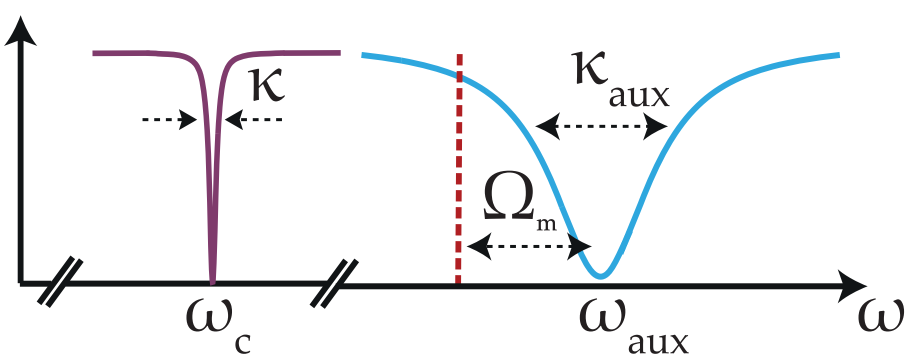



- Prepare of a dissipative reservoir by increasing $\Gamma_{\rm eff}$ / 2π to 550 kHz

- Create close to Markovian dissipative bath for electromagnetic mode

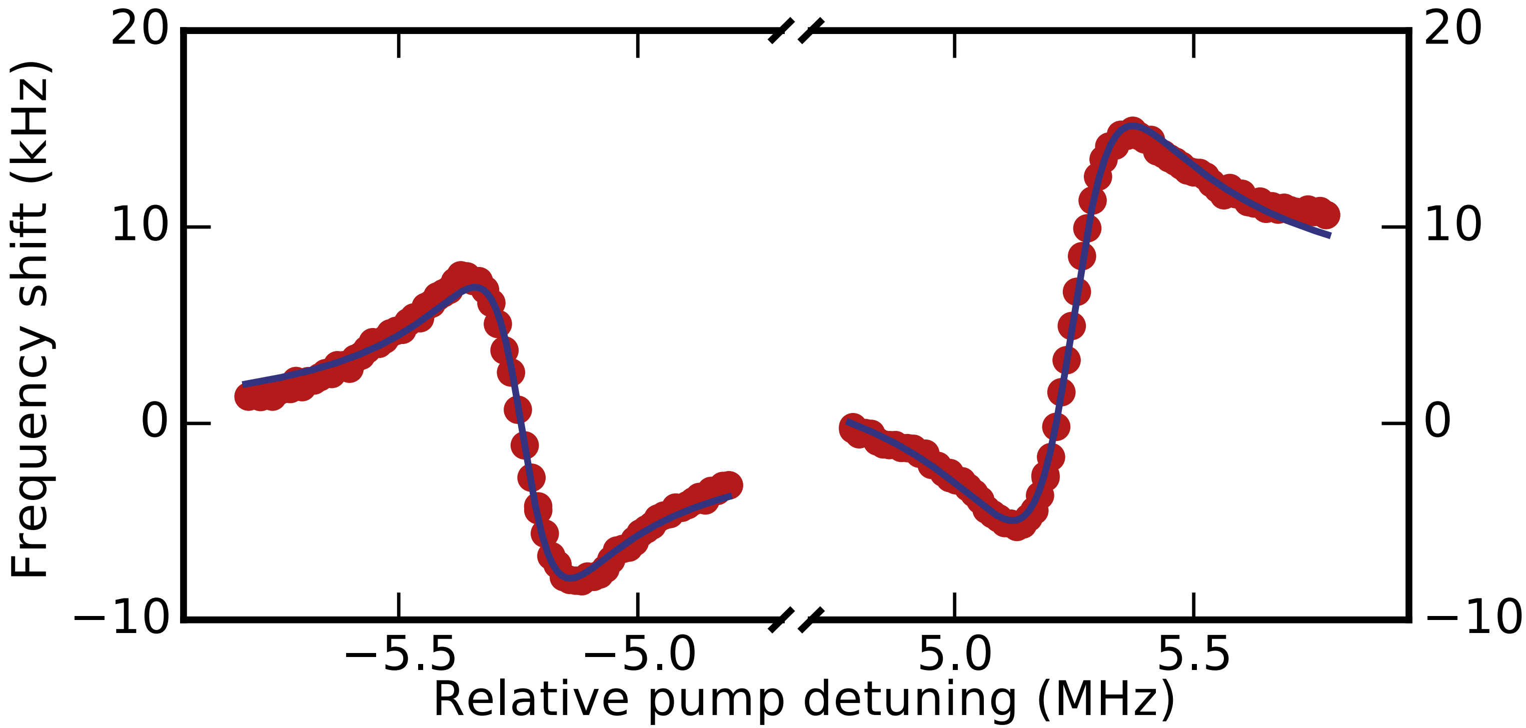
$$\Omega_m \gg \Gamma_{\rm eff} \gg \kappa$$



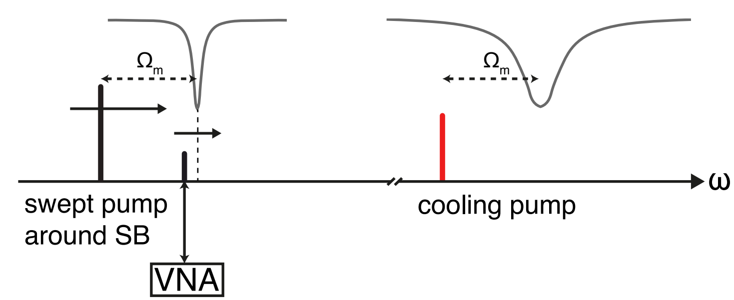

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# “Mechanical” spring effect

Fix pump power (5 dBm) and sweep detuning




$$\Delta\omega_{OM} = \frac{\Gamma_{\text{eff}} g_0^{\,2} n_p (\Delta - \Omega_m)}{(\Gamma_{\text{eff}}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{\text{eff}} g_0^{\,2} n_p (\Delta + \Omega_m)}{(\Gamma_{\text{eff}}/2)^2 + (\Delta - \Omega_m)^2}$$

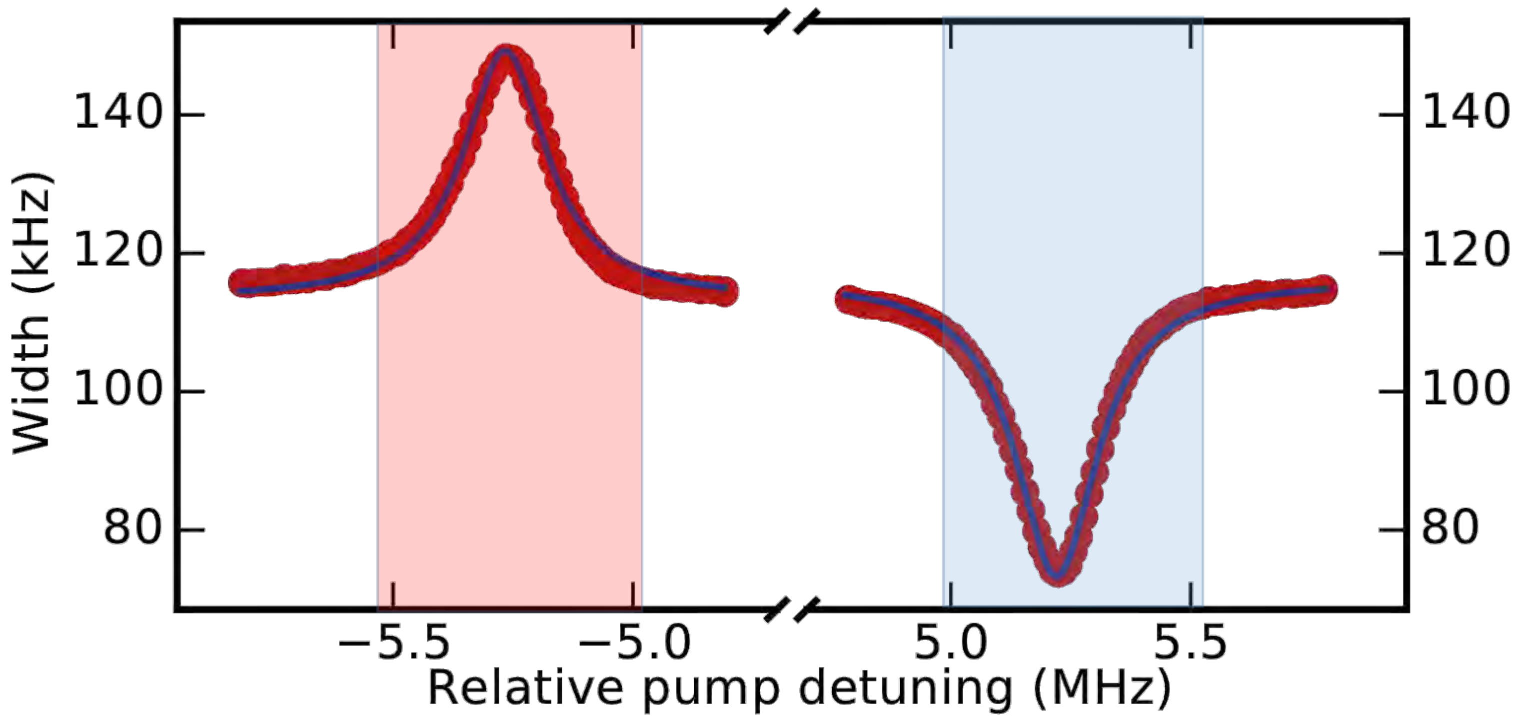



L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

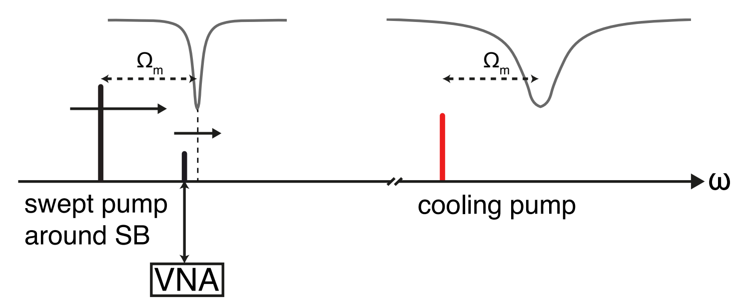
# Electromagnetic dynamical backaction

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Fix pump power (5 dBm) and sweep detuning




$$\kappa_{om} = \frac{\Gamma_{\text{eff}} g_0^{\,2} n_p}{(\Gamma_{\text{eff}}/2)^2 + (\Delta + \Omega_m)^2} - \frac{\Gamma_{\text{eff}} g_0^{\,2} n_p}{(\Gamma_{\text{eff}}/2)^2 + (\Delta - \Omega_m)^2}$$

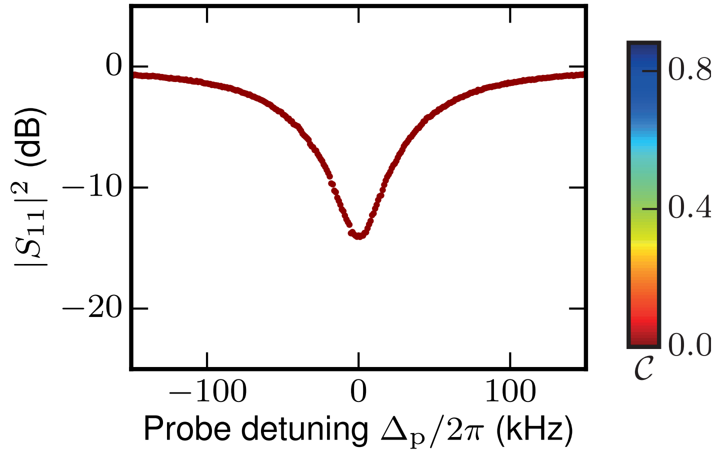


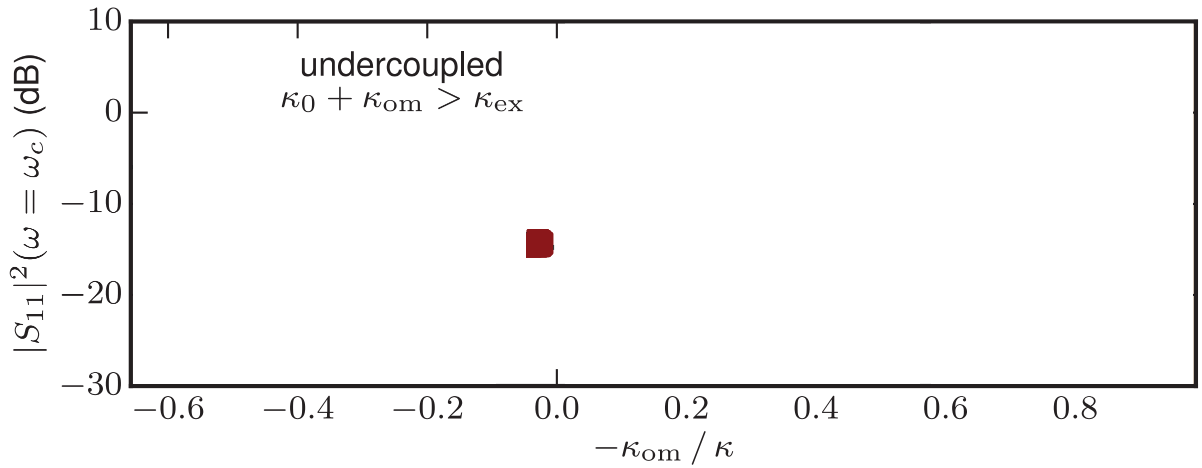

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

$\Delta = -\Omega_m$




$$\kappa_{om} = \pm \mathcal{C}\kappa$$

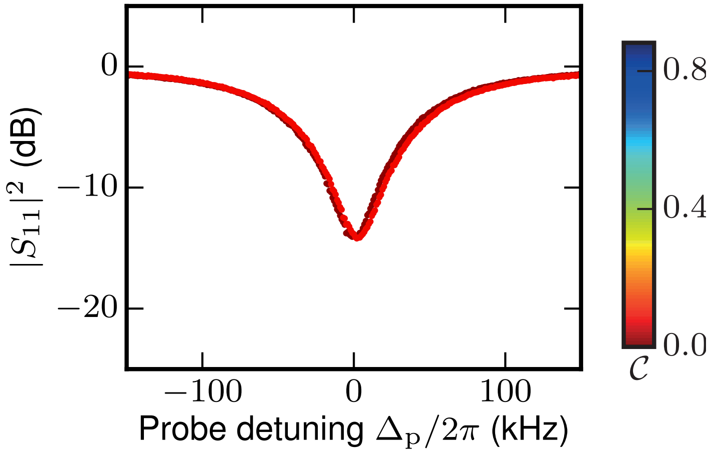
$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

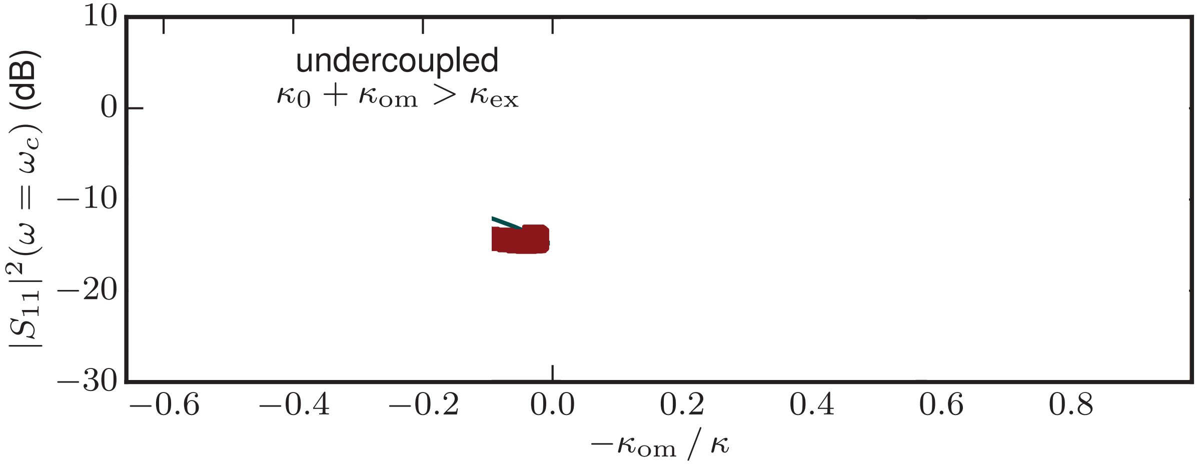
L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

$$\Delta = -\Omega_m$$



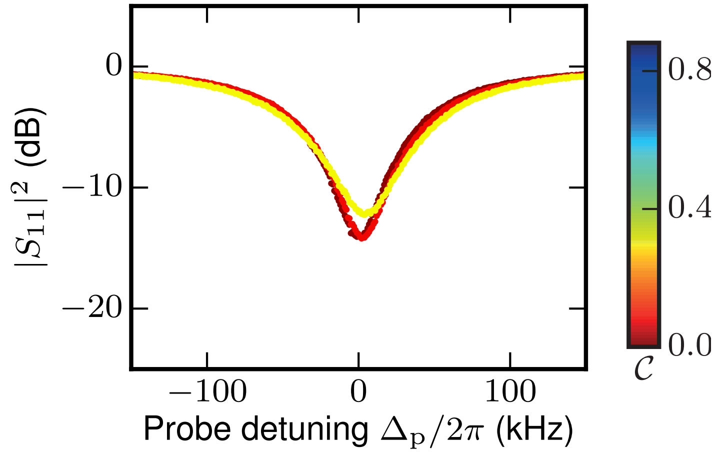

$$\kappa_{om} = \pm\mathcal{C}\kappa$$

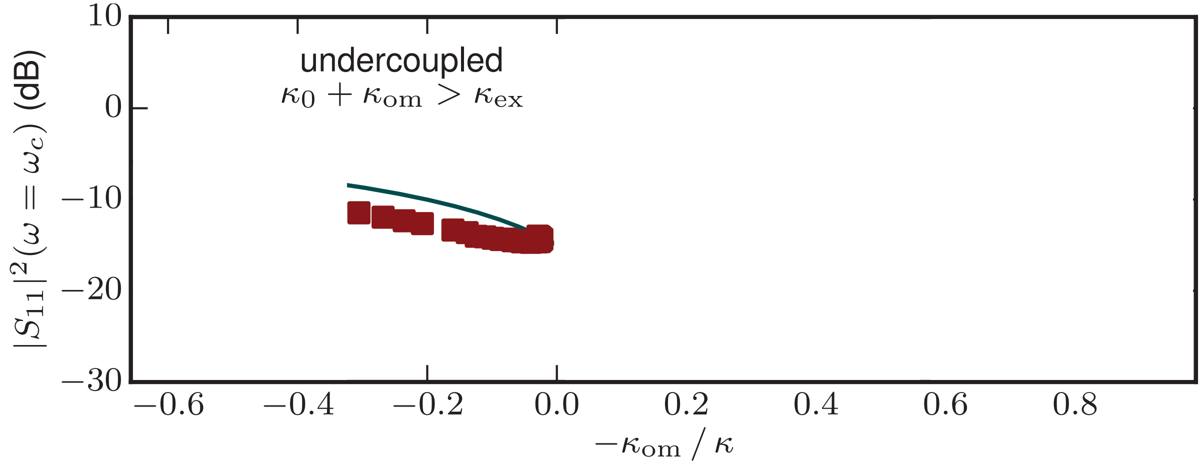
$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

$\Delta = -\Omega_m$



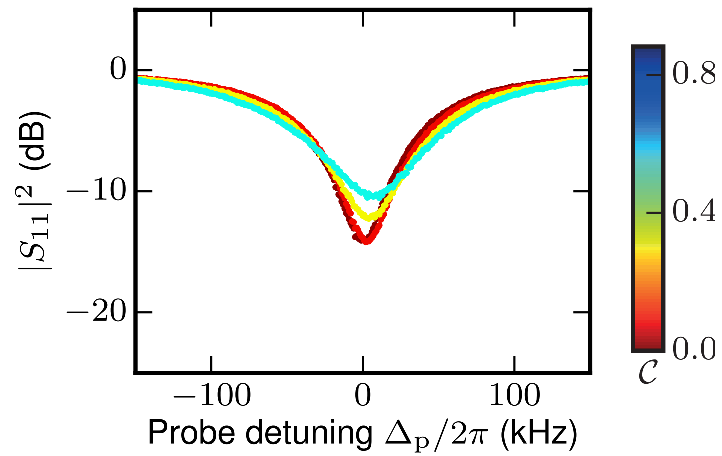

$$\kappa_{om} = \pm \mathcal{C}\kappa$$

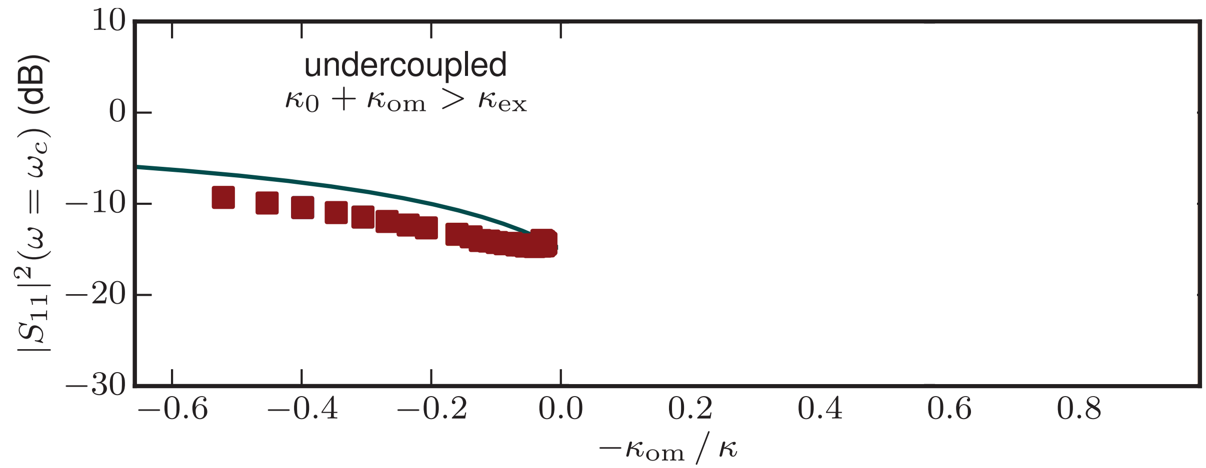
$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

$\Delta = -\Omega_m$



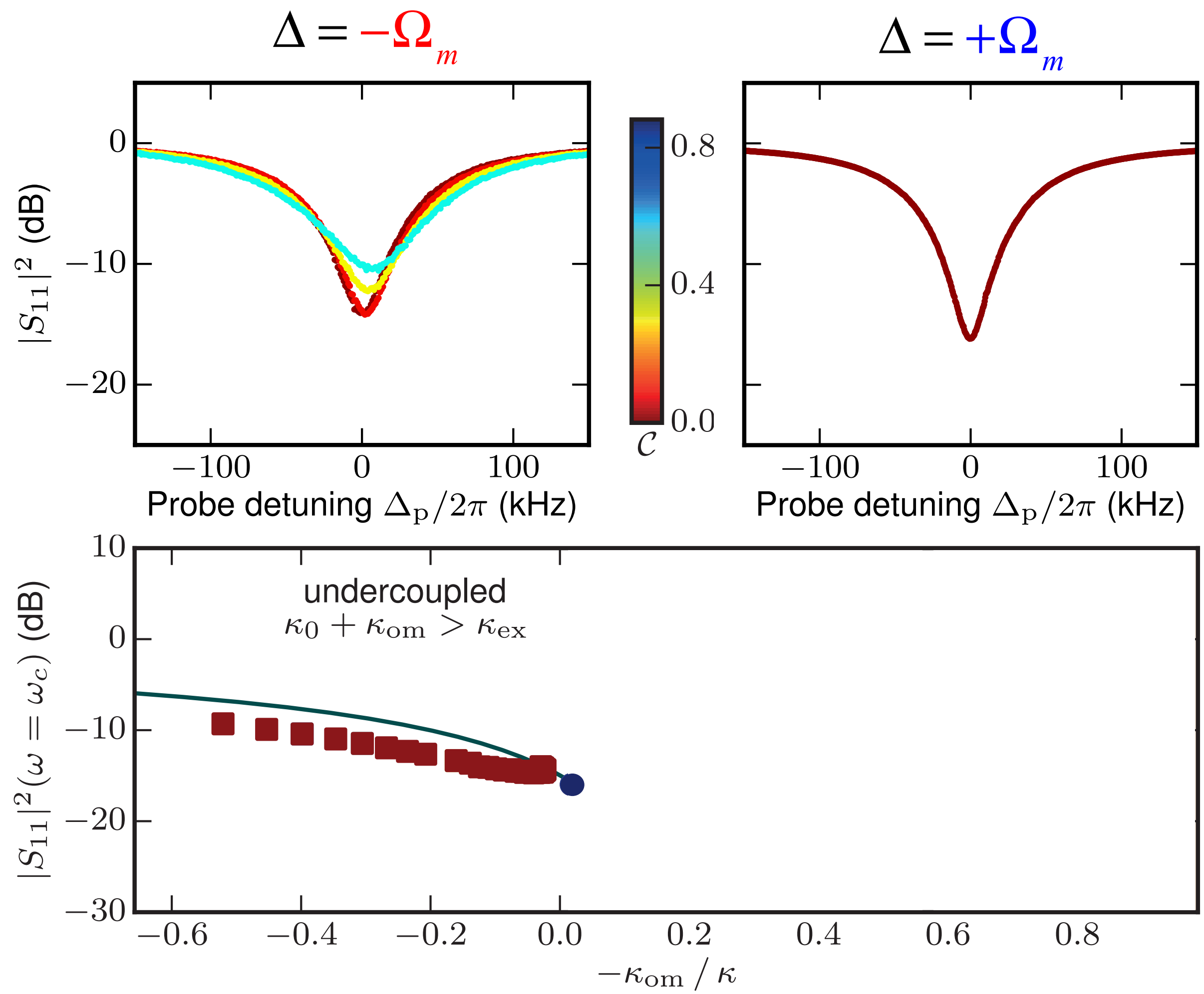

$$\kappa_{om} = \pm\mathcal{C}\kappa$$

$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

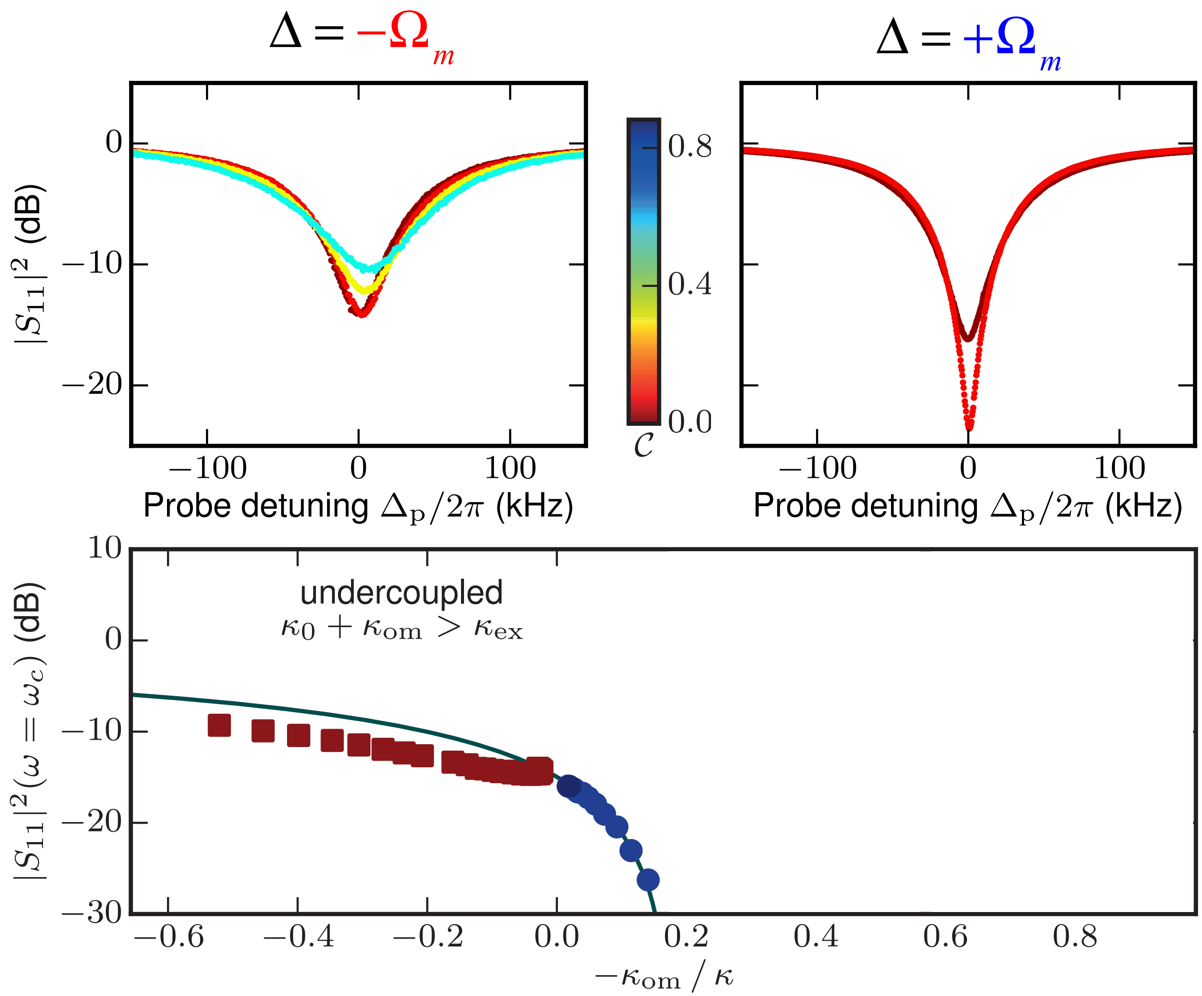



$$\kappa_{om} = \pm \mathcal{C}\kappa$$

$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

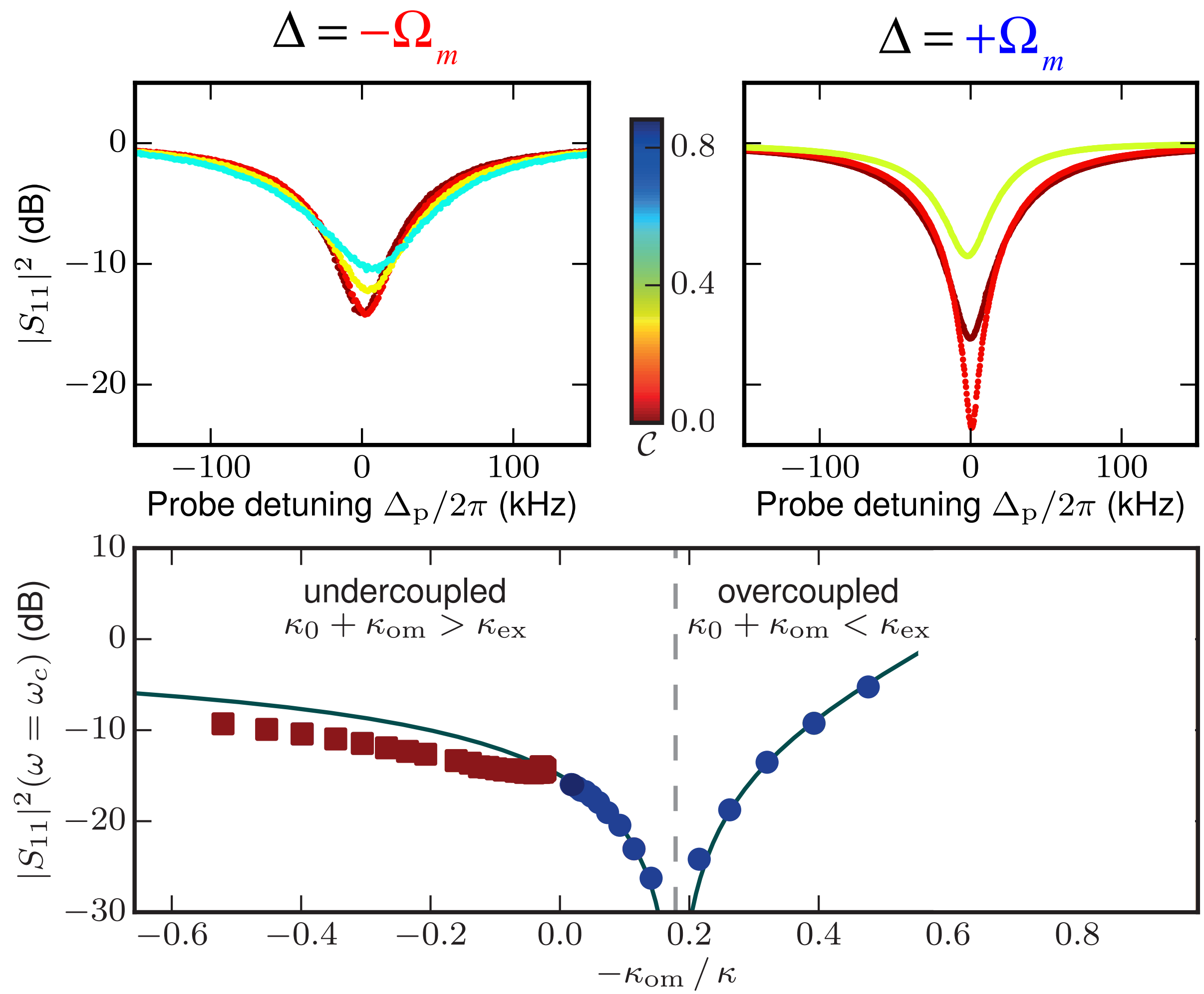



$$\kappa_{om} = \pm \mathcal{C}\kappa$$

$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$


L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

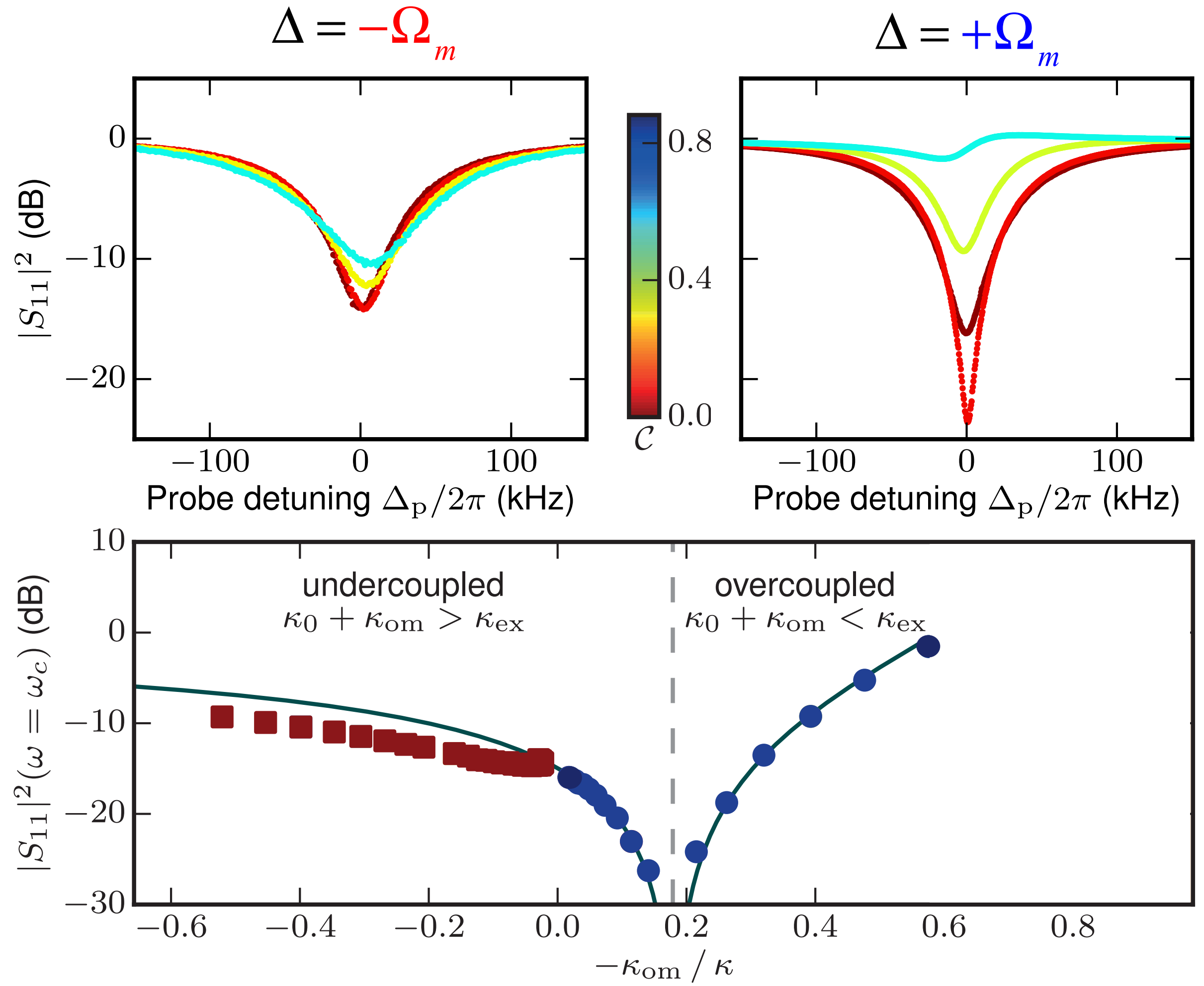



$$\kappa_{om} = \pm \mathcal{C}\kappa$$

$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

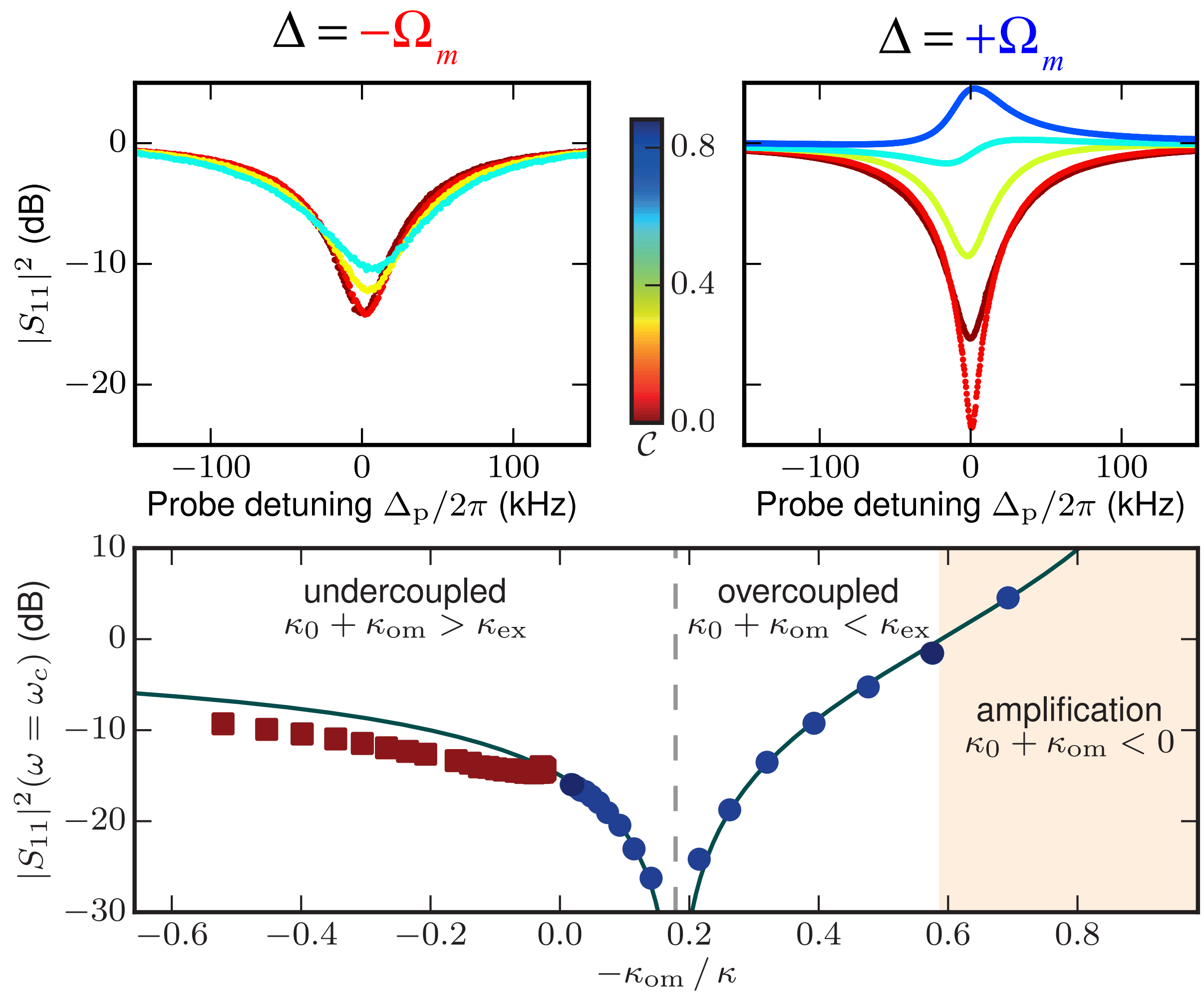



$$\kappa_{\mathrm{om}} = \pm \mathcal{C}\kappa \qquad S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{\mathrm{ex}} + \kappa_{\mathrm{om}}}{\kappa_0 + \kappa_{\mathrm{ex}} + \kappa_{\mathrm{om}}}$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering





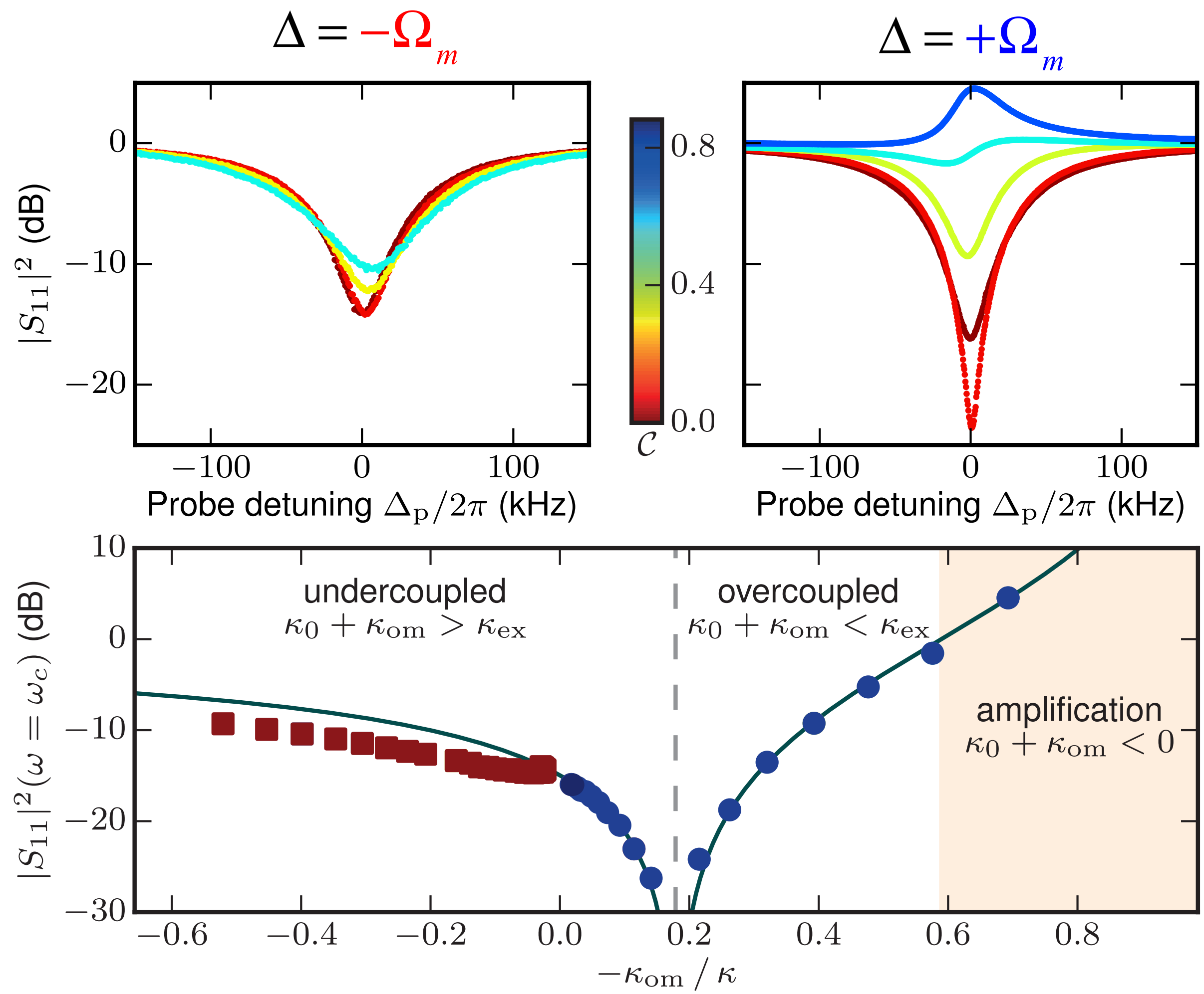

$$\kappa_{om} = \pm \mathcal{C}\kappa$$

$$S_{11}(\omega = \omega_0) = \frac{\kappa_0 - \kappa_{ex} + \kappa_{om}}{\kappa_0 + \kappa_{ex} + \kappa_{om}}$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# (De)amplification by mechanical reservoir engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



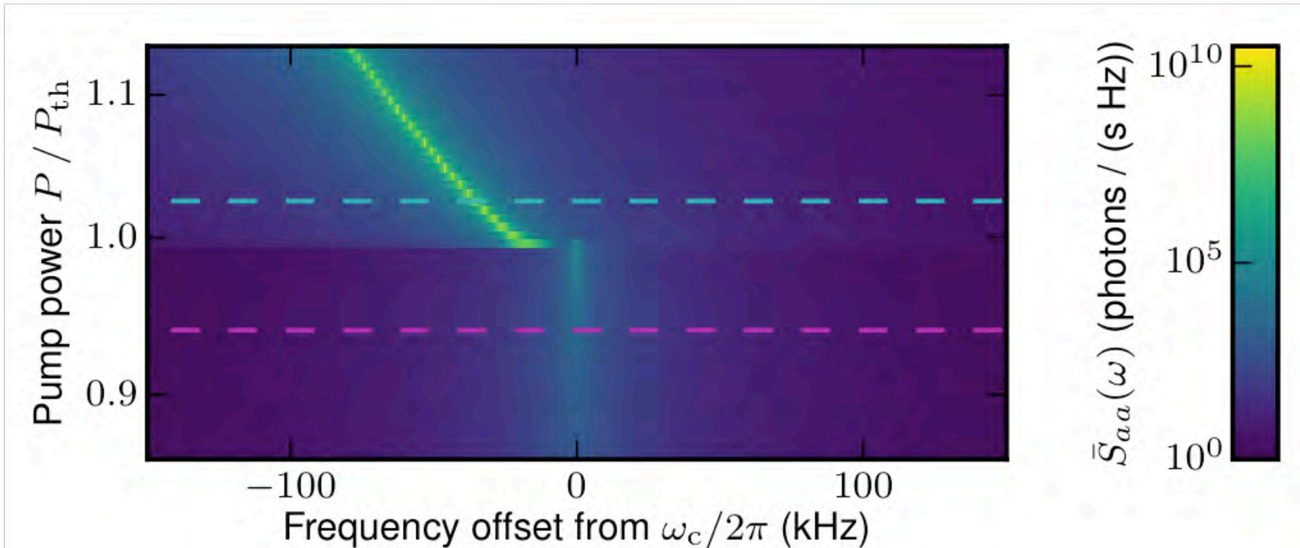

$$\kappa_{\mathrm{om}} = \pm \mathcal{C}\kappa$$

**Demonstrates electromagnetic control over the *cavity damping rate*, via mechanical dissipative reservoir**

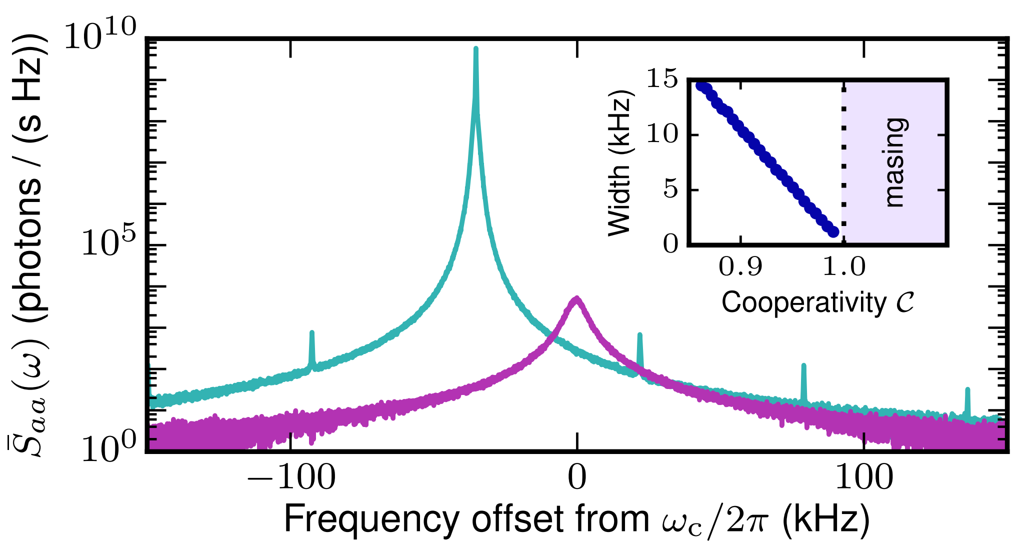
L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Maser using a mechanical dissipative reservoir

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE




- Linewidth narrows as we increase pump power.
- Above threshold, the noise turns into self-sustained oscillations in the cavity.




$$\bar{S}_{aa}(\omega)=\left[1+\frac{\kappa_{ex}(\kappa_{ex}-\kappa_{eff})}{(\frac{\kappa_{eff}}{2})^2+(\omega-\omega_c)^2}\right](n_{in}+\tfrac{1}{2})$$

$$+\frac{\mathcal{C}\kappa_{ex}\kappa}{(\frac{\kappa_{eff}}{2})^2+(\omega-\omega_c)^2}(n_{eff}+\tfrac{1}{2}).$$

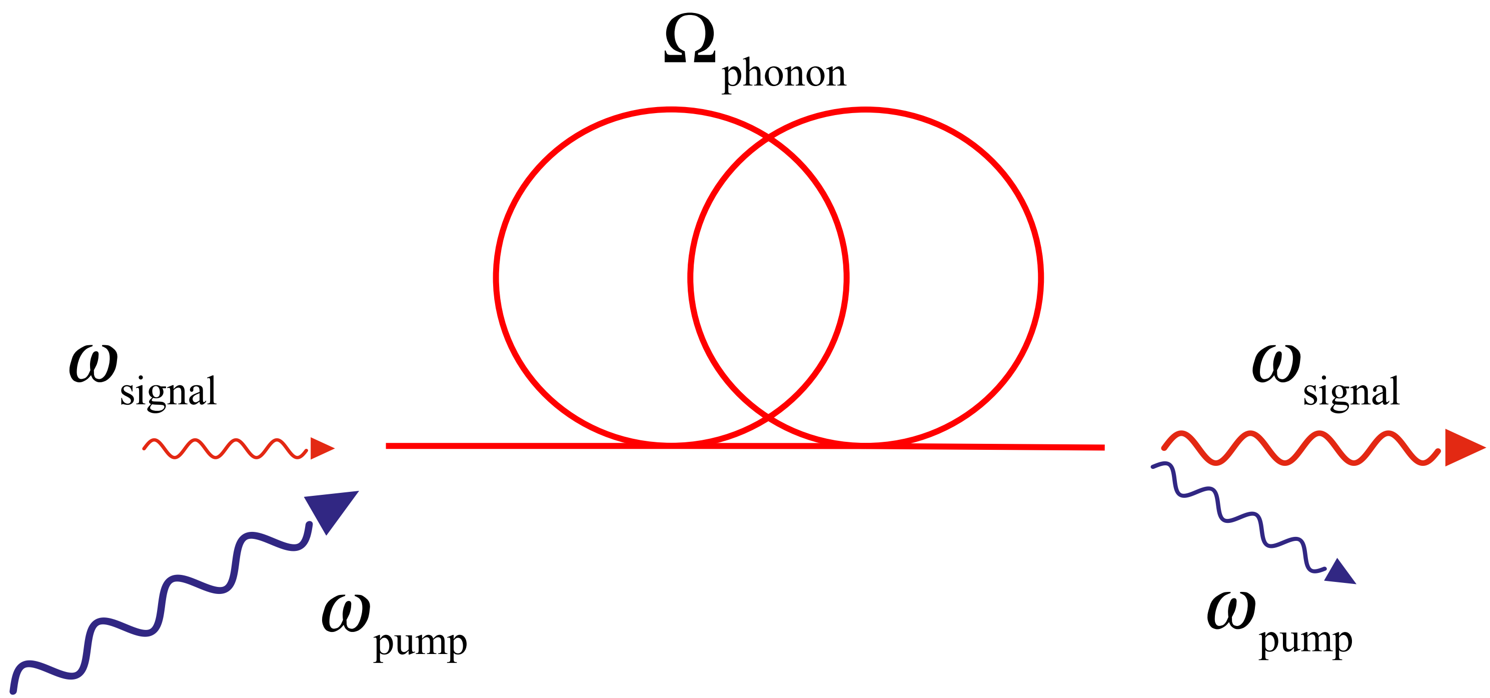
$$\kappa_{eff}=(1-\mathcal{C})\kappa$$

**First observation of dynamical backaction on an *electromagnetic* mode**

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Raman amplifier

Stimulated Raman Scattering (SRS)



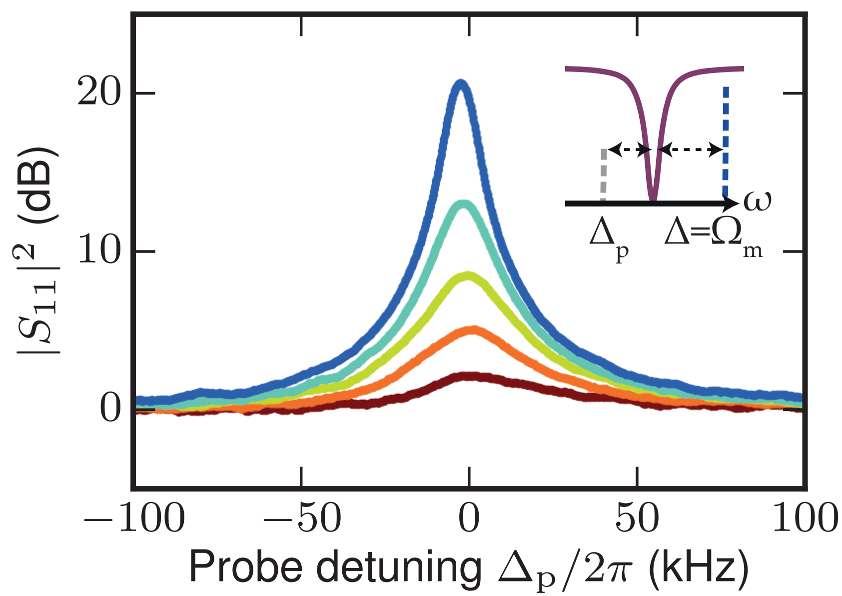

$$\omega_{pump} = \omega_{signal} + \Omega_{phonon}$$

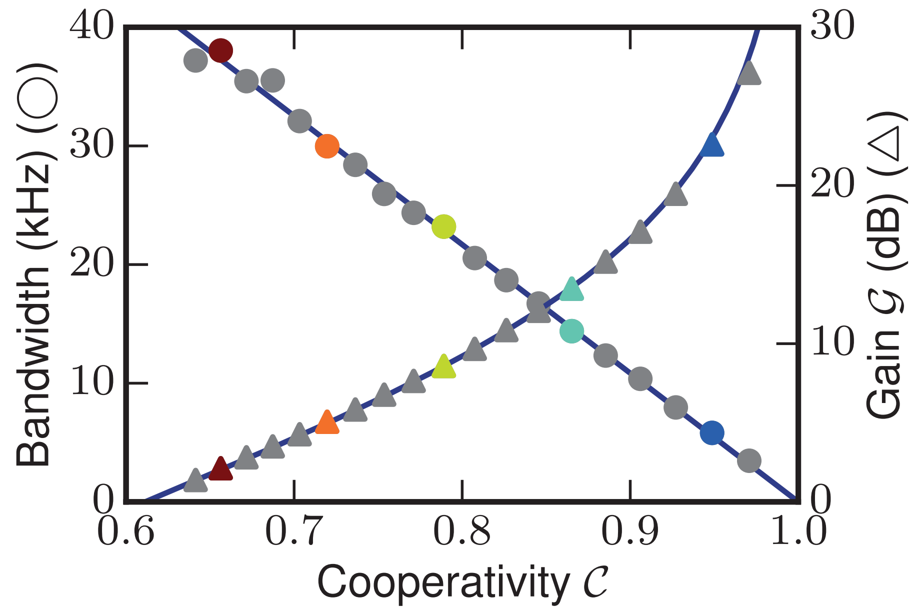
Phonons (*idler mode* population) decay quickly

N. Bloembergen. *Nonlinear Optics*.

# Amplification by mechanical reservoir engineering





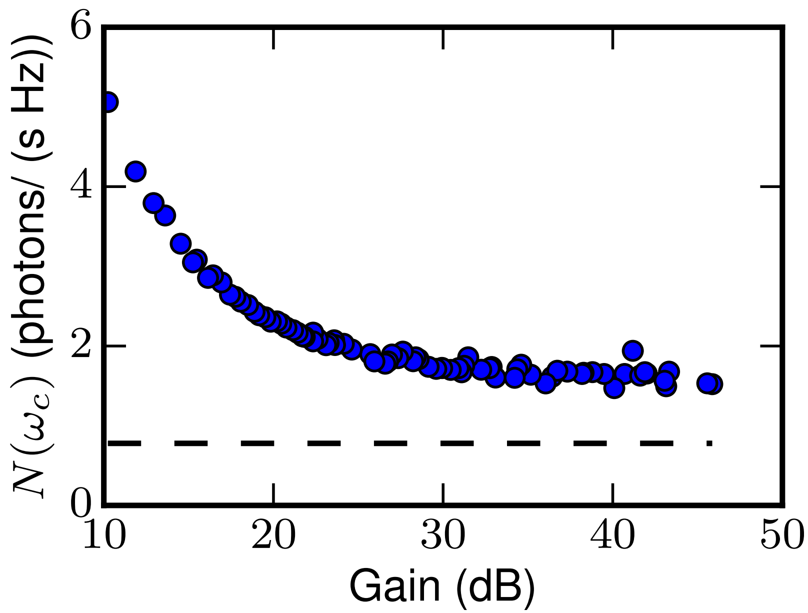



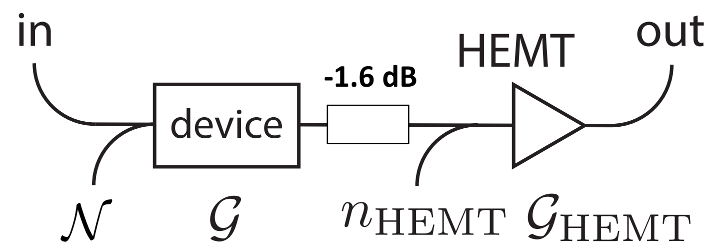

$$\mathcal{G} = \left|S_{11}(\omega_\mathrm{c})\right|^2 = \left|\frac{\left(2\kappa_\mathrm{ex}/\kappa - 1\right) + \mathcal{C}}{1-\mathcal{C}}\right|^2$$

$$\kappa_\mathrm{eff} = (1-\mathcal{C})\kappa$$

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Noise added by the electromechanical amplifier (chip B)




$$N = \mathcal{N} + n_{\mathrm{HEMT}} / (\alpha \cdot \mathcal{G})$$

$$\mathcal{N}_{\mathrm{QL}} = \frac{1}{2} + \frac{\kappa_0}{\kappa_{ex}} \approx 0.78$$

$$\mathcal{N} = \frac{4\mathcal{C}\frac{\kappa_{\mathrm{ex}}}{\kappa}\left(n_{\mathrm{eff}} + \frac{1}{2}\right) + 4\frac{\kappa_{\mathrm{ex}}\kappa_0}{\kappa^2}\cdot\frac{1}{2}}{\left(\mathcal{C} - 1 + \frac{2\kappa_{\mathrm{ex}}}{\kappa}\right)^2}$$

**The system noise is (2.09 ± 0.13) × QL**

$n_{\mathrm{HEMT}}$ **= 22.5 ± 0.25 quanta**

$n_{\mathrm{eff}}$ **= 0.65 ± 0.08 quanta**

L. D. Tóth et al. *Nature Physics* **13**, 787–793 (2017)

# Summary

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

**Realized electromechanics in the reversed dissipation regime**

- Control over electromagnetic cavity properties
  *via cold dissipative mechanical reservoir*
- Near-quantum-limited amplification of microwave field
- Maser action

More generally, realized a **dissipative mechanical reservoir for microwaves**:
a prerequisite for a **new class of dissipative optomechanical interaction**

*Nature Physics* **13**, 787–793 (2017)

# Thank you

L. D. Tóth

N. R. Bernier

A. Nunnenkamp

T. J. Kippenberg