Two-membrane cavity optomechanics: linear and non-linear dynamics

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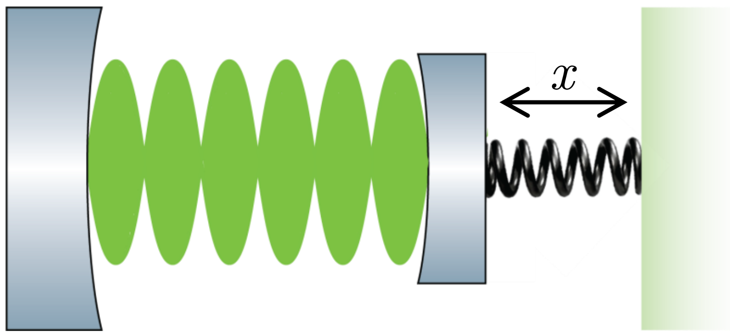
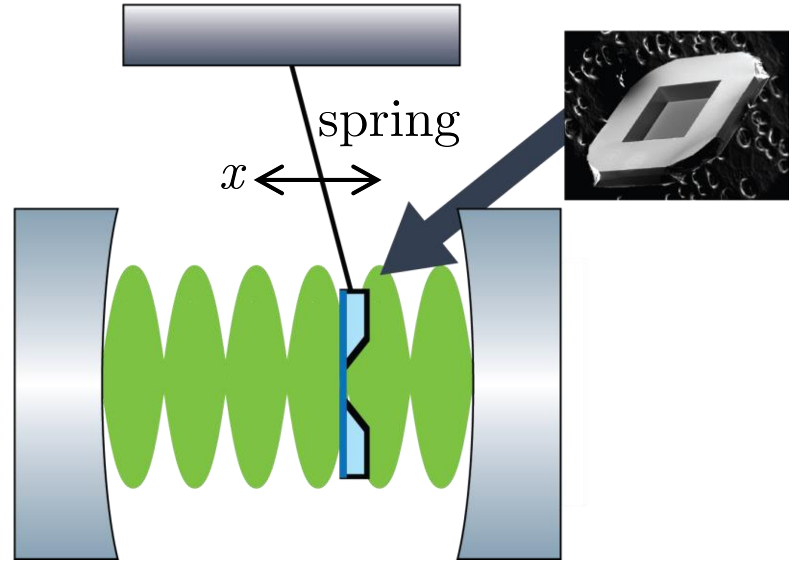
Optomechanics

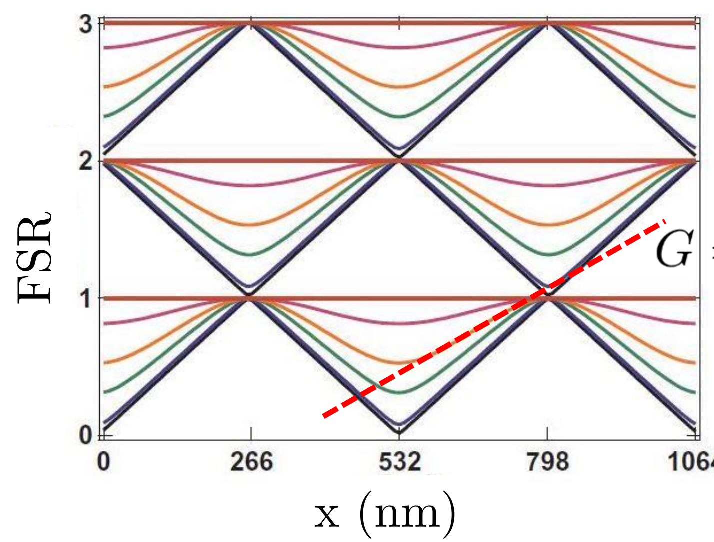


$$\omega_{cav} = \omega_0 \left(1 - \frac{x}{L}\right)$$

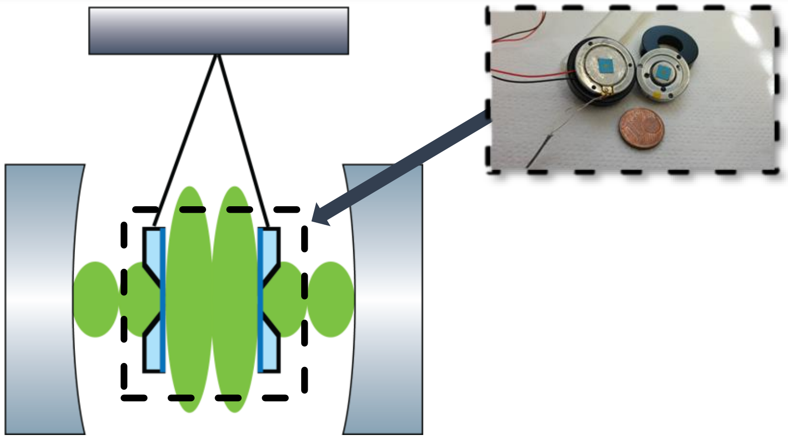
Radiation pressure couples the cavity radiation field to the mechanical motion.

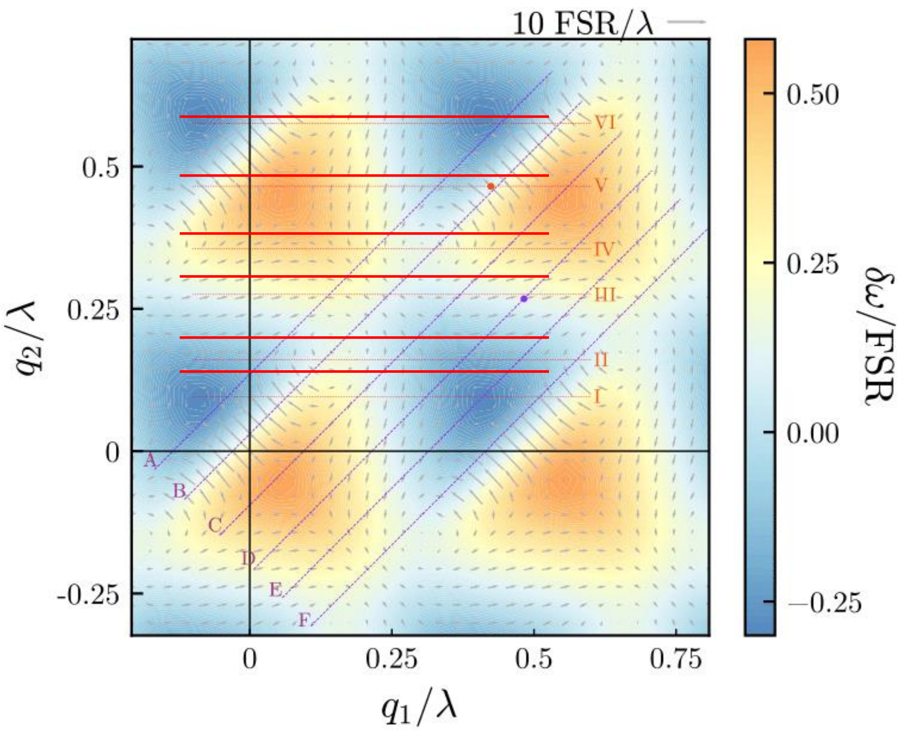
$$G = \frac{d\omega_{cav}}{dx} = \frac{\omega_0}{L}$$





Optomechanical coupling strength





$$R_m < 1 \qquad |G_j^{max}| = \frac{1}{1-\sqrt{R_m}}|G_{sing}^{max}|$$

$$R_m \sim 1 \qquad |G_j^{sat}| = 2\pi c/(\lambda_0 L_c)$$

$$R_m \sim 0.4 \longrightarrow |G_j^{max}| \sim 2.72|G_{sing}^{max}|$$

Advantages:

- Strong coupling regime
- Energy transfer and entanglement
- Synchronization

- **Piergentili P. et al., Two-membrane cavity optomechanics, New J. Phys. 20 083024, 2018, https://doi.org/10.1088/1367-2630/aad85f**
- **Perspective: Jan Gieseler, *New J. Phys.* 20 101001, 2018, https://doi.org/10.1088/1367-2630/aae3c0**

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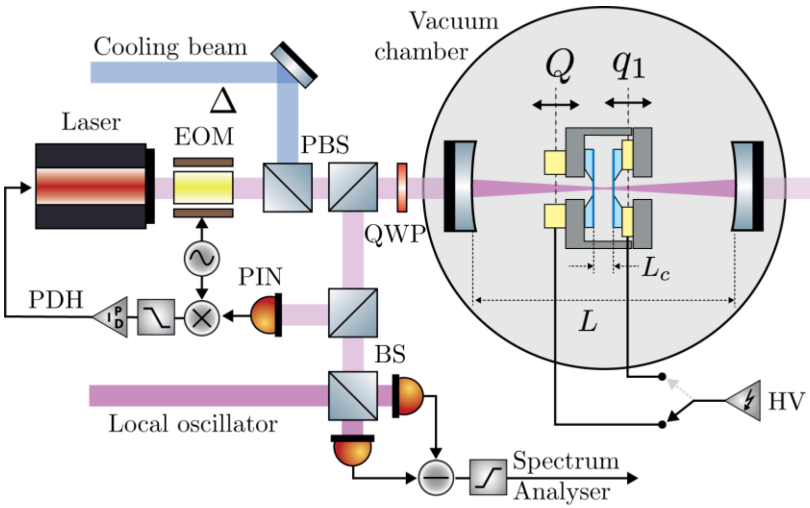
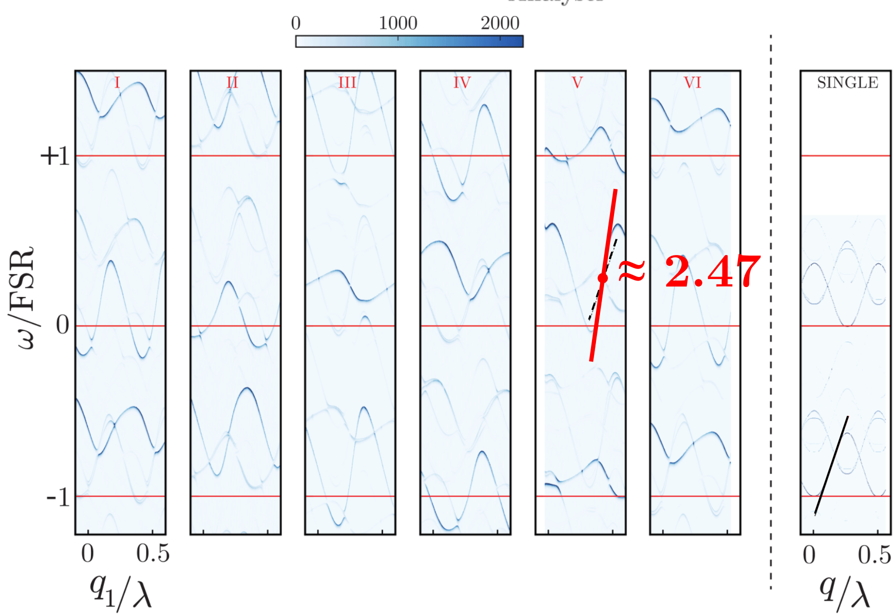
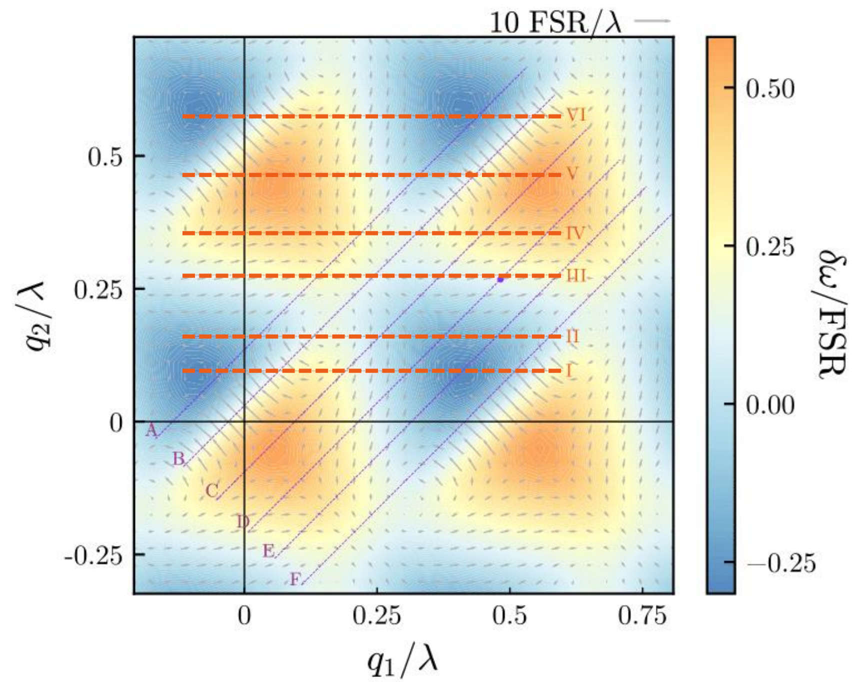


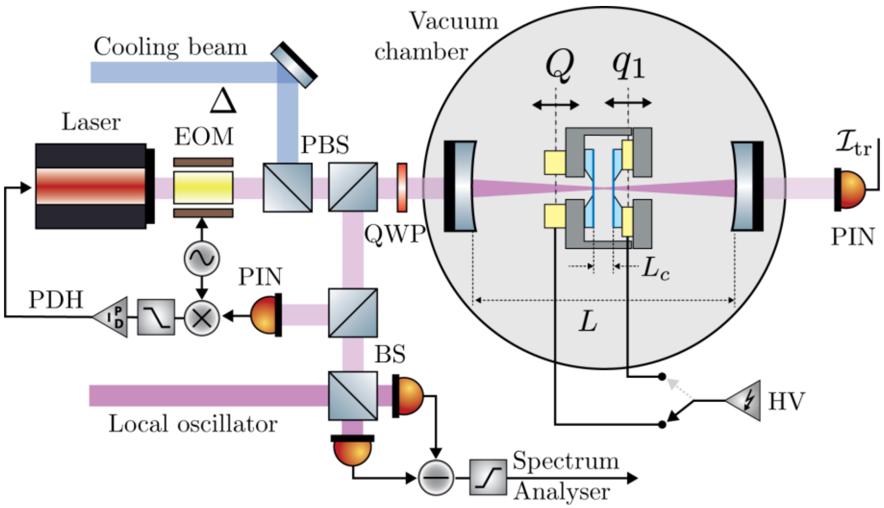


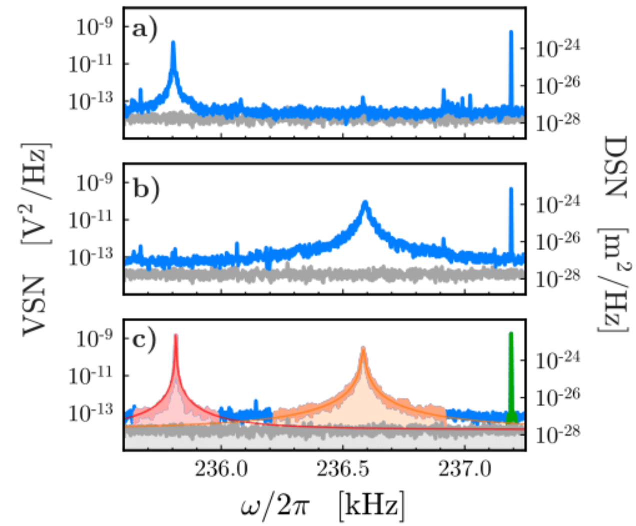


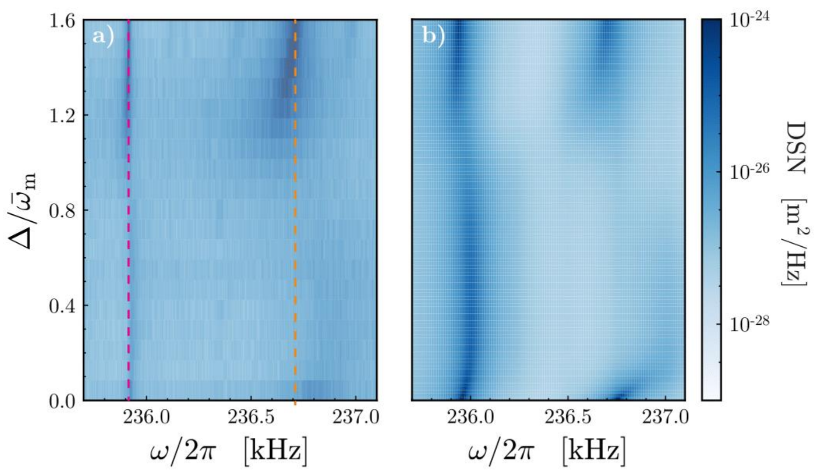
$$G_{sing}^{max} \sim 2\pi \times 3.47 \text{ MHz nm}^{-1}$$

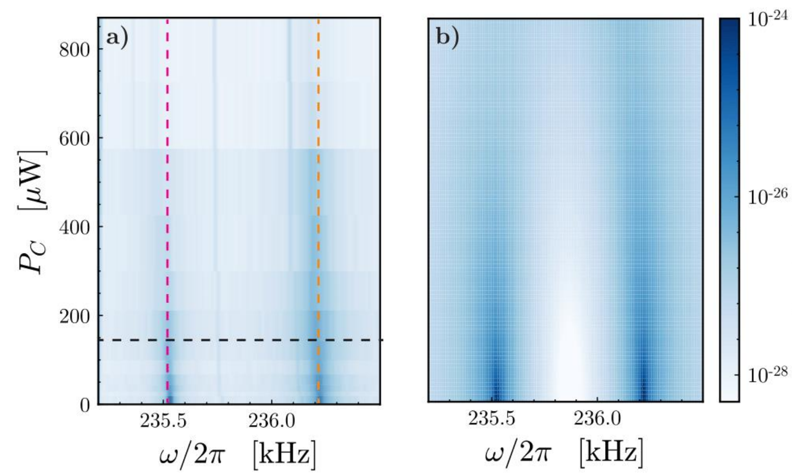
$$G_{q_1}^{max} \sim 2\pi \times 8.59 \text{ MHz nm}^{-1}$$

Tunable coupling and laser cooling



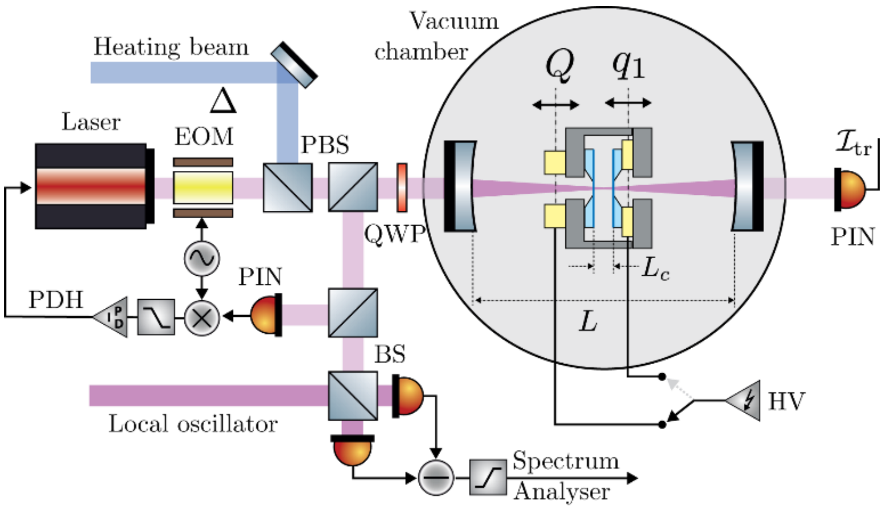


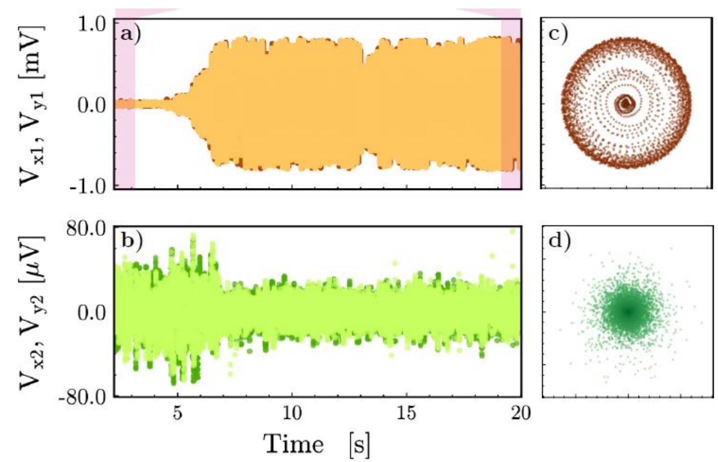


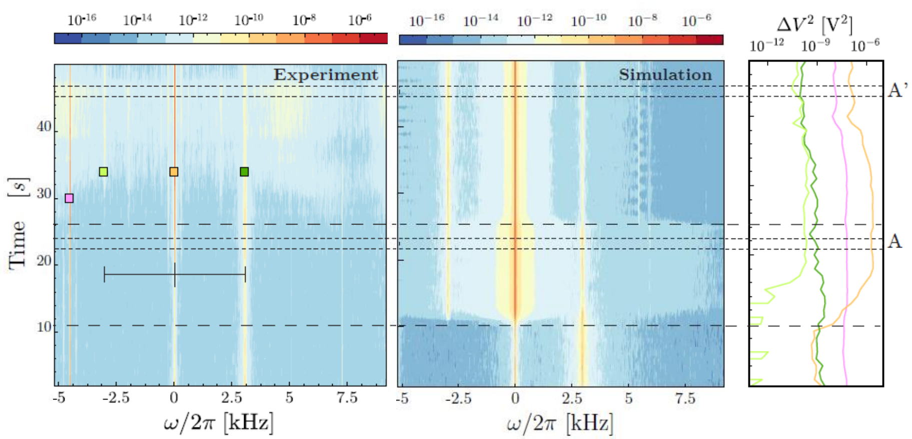


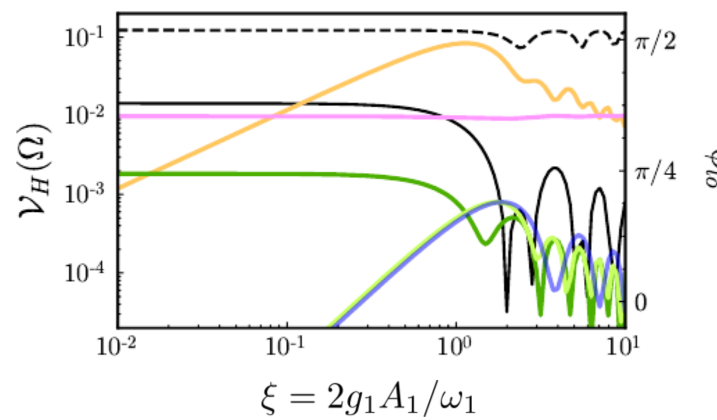
Two-membrane cavity optomechanics: non-linear dynamics

Laser heating - onset of synchronization









- **Li W., Piergentili P . et al., Phys. Rev. A 101, 013802 (2020)**
- **Piergentili P. et al., Two-membrane cavity optomechanics: non-linear dynamics, New J. Phys. 23, 073013 (2021)**

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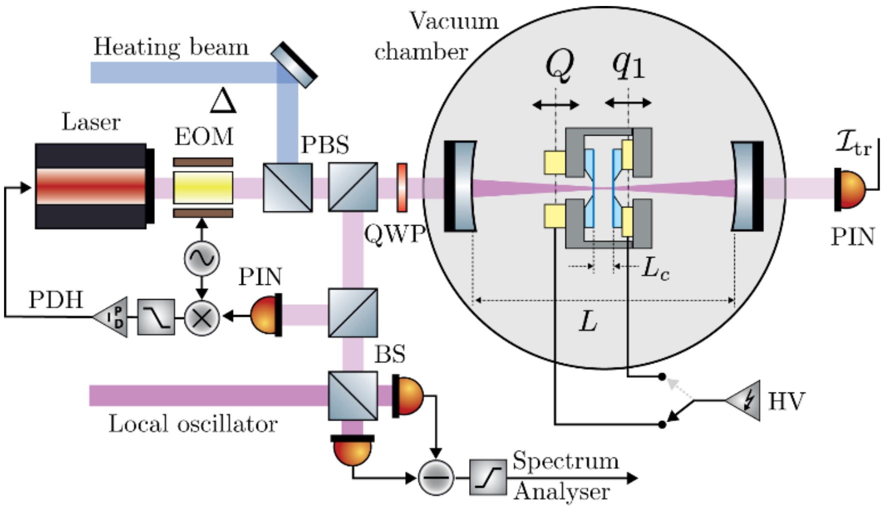

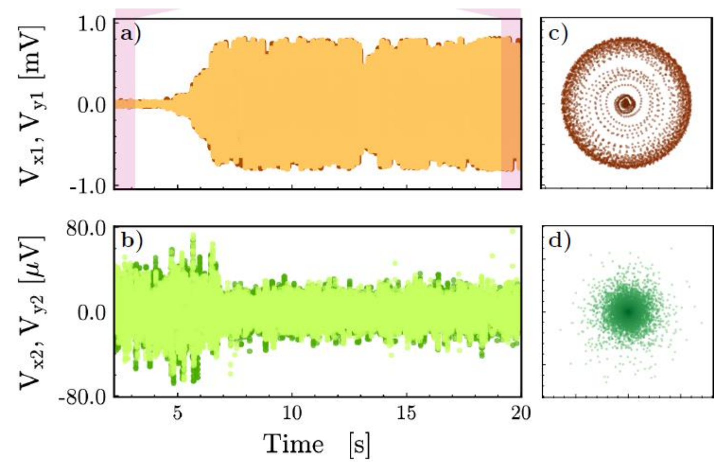

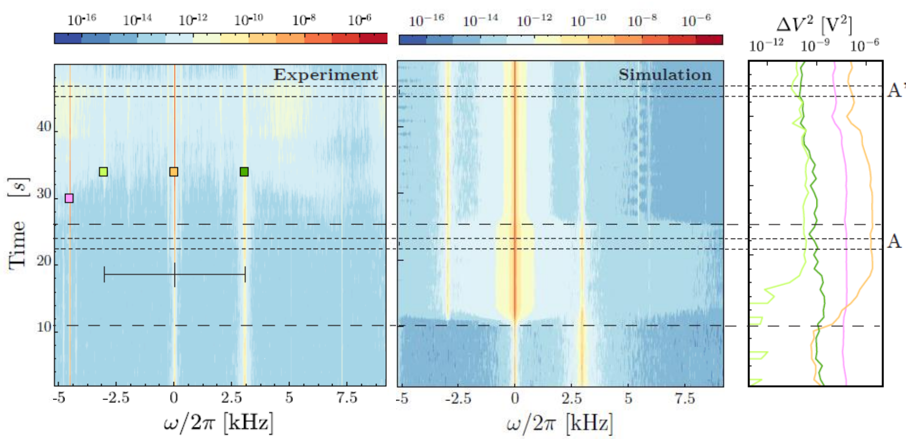

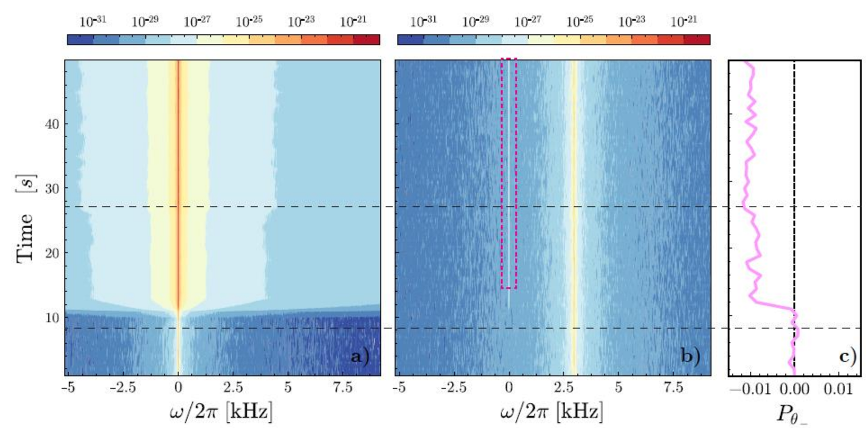

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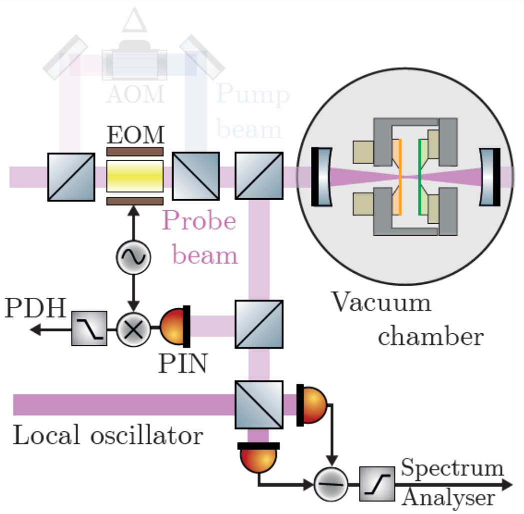
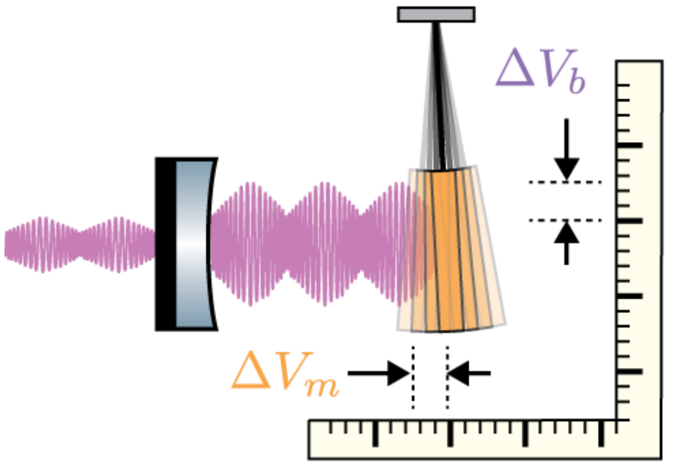
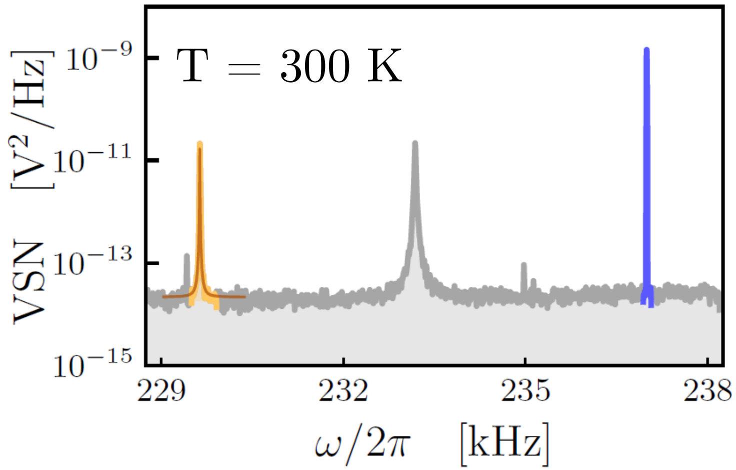
Determination of the single-photon optomechanical coupling

Optomechanical coupling rate determination





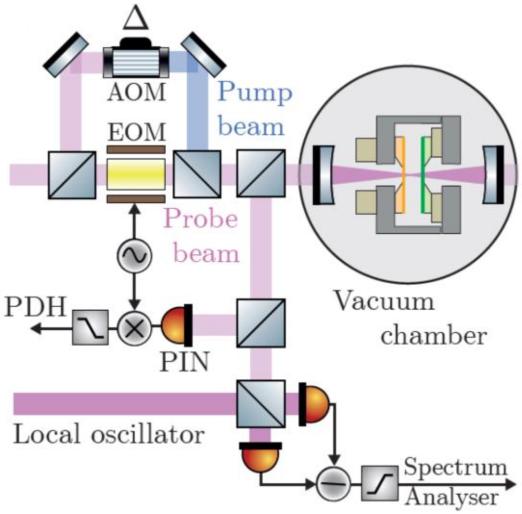


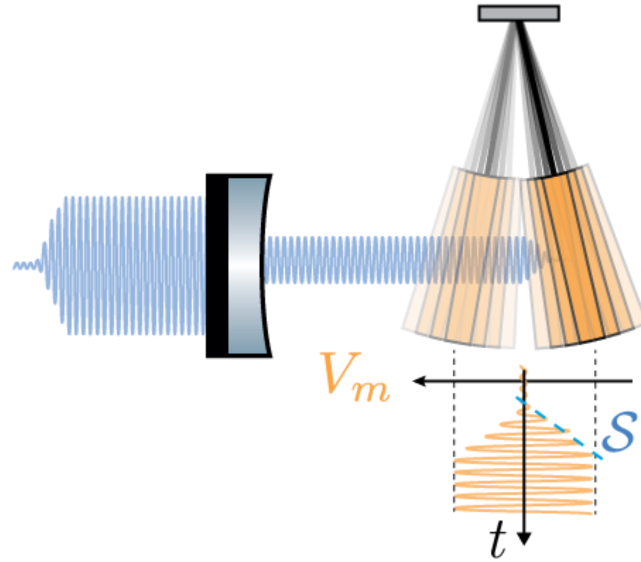
$$g_0 = \frac{1}{\sqrt{2\bar{n}_m}} \frac{\beta\omega_b}{\sqrt{2}} \sqrt{\frac{\Delta V_m^2}{\Delta V_b^2} \mathcal{K}} = 2\pi \cdot 0.327(33)\,\text{Hz}$$

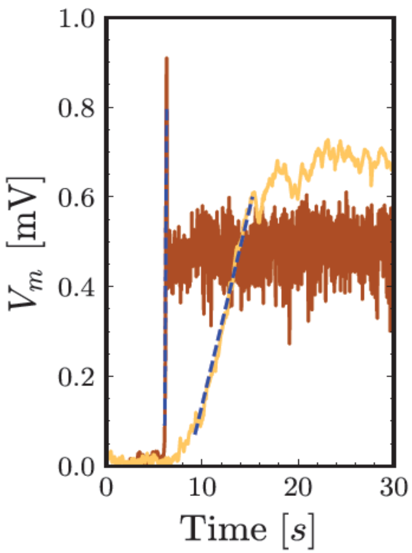
- Need to know the temperature.
- Requires calibration of the EOM.

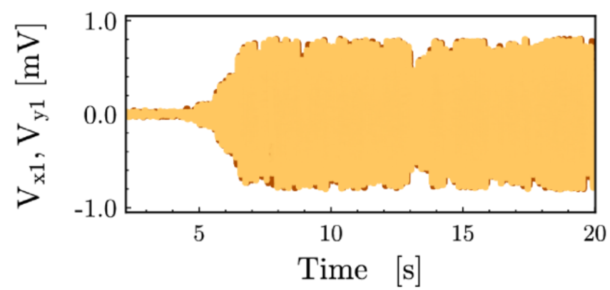
- **Gorodetksy M. L. et al, Determination of the vacuum optomechanical coupling rate using frequency noise calibration, Opt. Express 18, 22 2010**

Optomechanical coupling rate determination



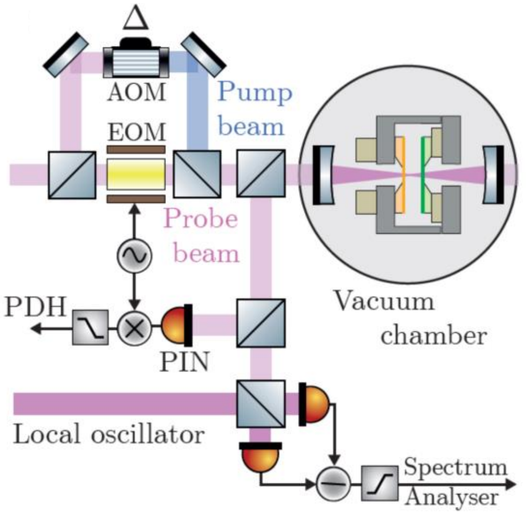


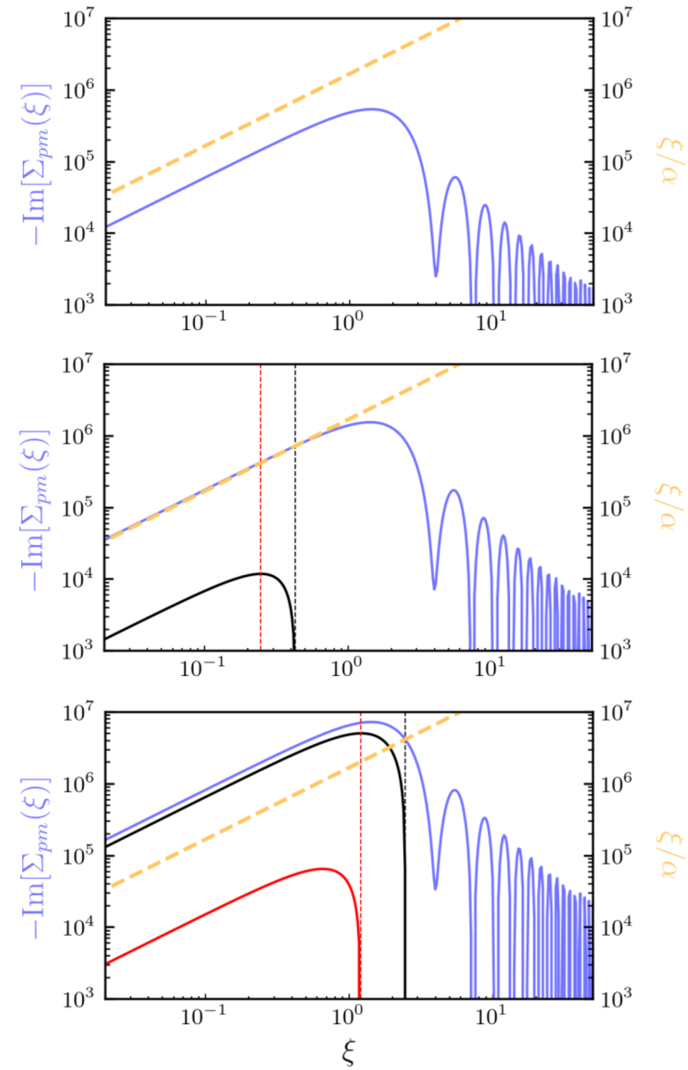




- **Piergentili P. et al, Absolute Determination of the Single-Photon Optomechanical Coupling Rate via a Hopf Bifurcation, Phys. Rev. Applied 15, 034012 2021**

Optomechanical coupling rate determination





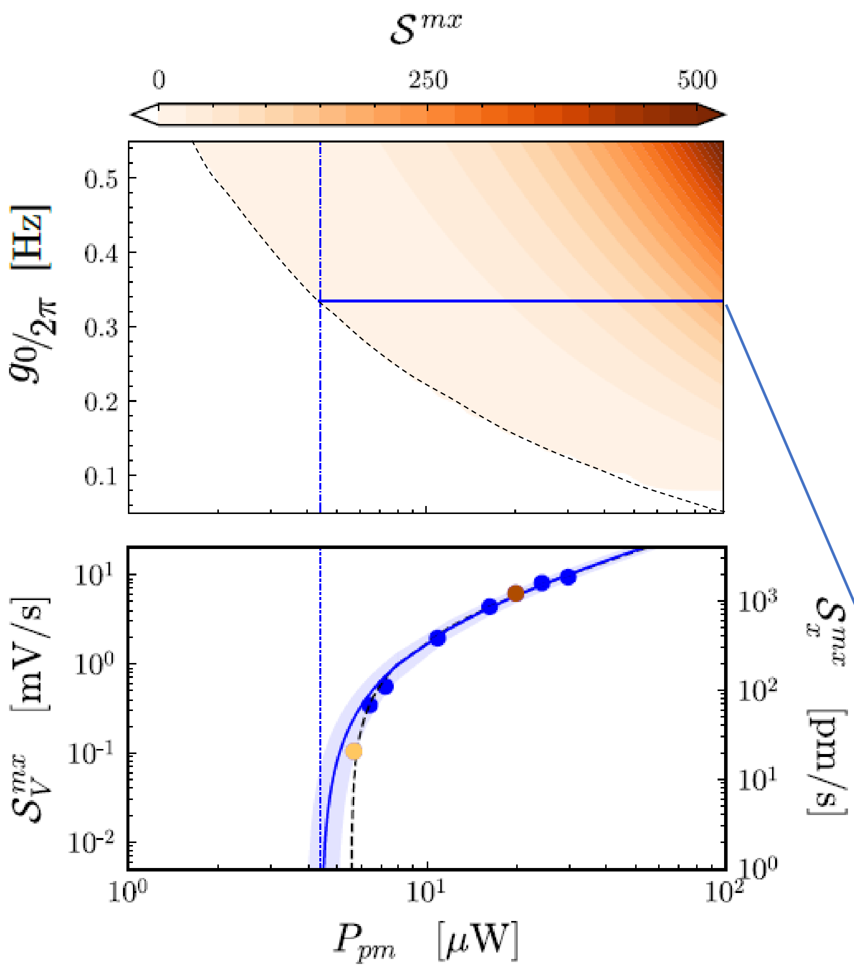
$$\dot{\xi}(t) = -\xi - \frac{2g_0^2}{\gamma_m\omega_m}\,\mathrm{Im}\Big[E_{pm}^2\Sigma_{pm}(\xi) + E_{pr}^2\Sigma_{pr}(\xi)\Big]$$

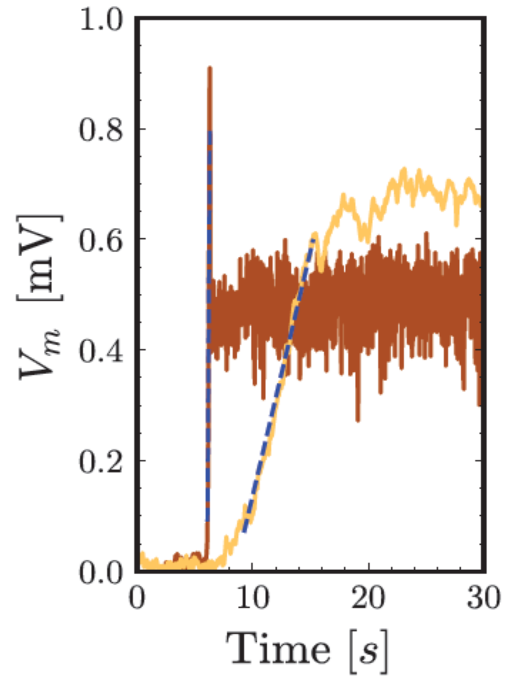
$$\frac{\gamma_m\omega_m}{2g_0^2}\,\xi = -\,\mathrm{Im}\Big[E_{pm}^2\Sigma_{pm}(\xi)\Big]$$

$$E_{pm} = \sqrt{2\kappa_{in}P_{pm}/\hbar\omega_L}$$

$$\Sigma_{pm}(\xi) = \sum_n \frac{J_n(-\xi)J_{n+1}(-\xi)}{[\mathrm{i}n\omega_m - \mathcal{W}_i][-\mathrm{i}(n+1)\omega_m - \mathcal{W}_i^\star]}$$

Optomechanical coupling rate determination

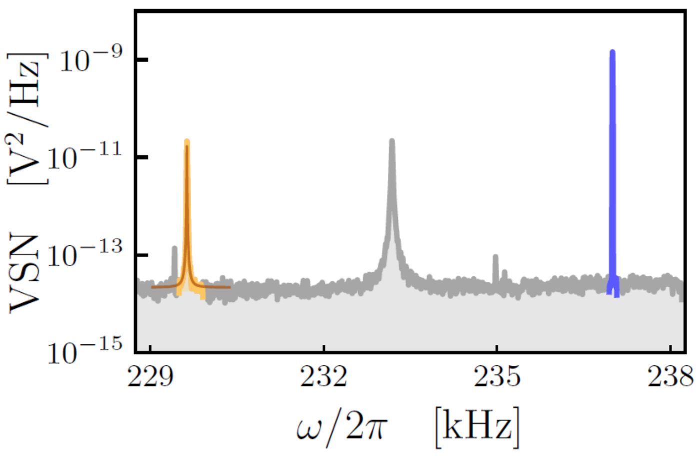




$$g_0^2 = (2\pi)^2 \frac{0.497\,\mathrm{Hz}^2\,\mu\mathrm{W}}{P_{pm}^{th}[\mu W]}$$

$$g_0 = 2\pi \cdot 0.336(13)\,\mathrm{Hz}$$

Optomechanical coupling rate determination



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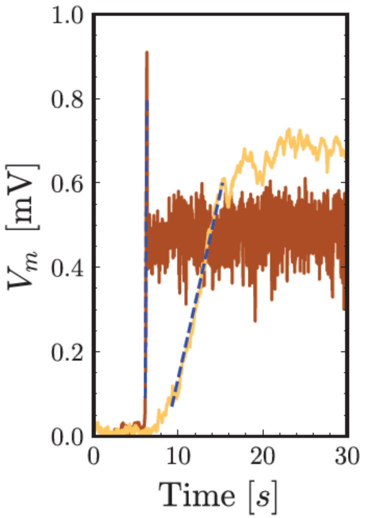


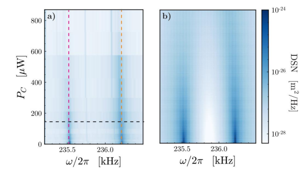
$$g_0 = 2\pi \cdot 0.336(13)\,\text{Hz}$$

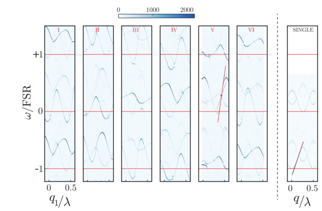
- No external calibration needed
- No need to know the temperature
- Applicable to any system where a Hopf bifurcation occurs

- Piergentili P. et al, Absolute Determination of the Single-Photon Optomechanical Coupling Rate via a Hopf Bifurcation, Phys. Rev. Applied 15, 034012 2021

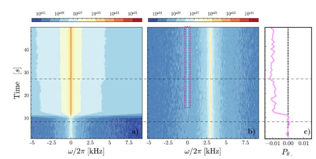
Conclusions

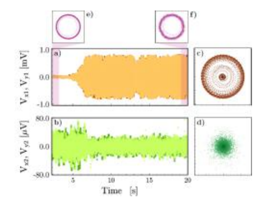
- Enhanced the optomechanical coupling strength by a factor ≈ 2.47 respect to the single membrane case.

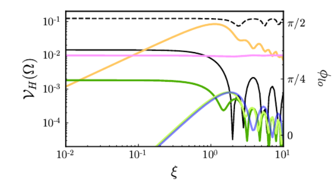




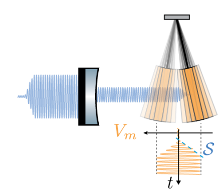
- Optical heating of the fundamental modes of the membranes and onset of synchronization.

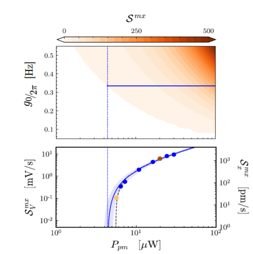






- Non-linear dynamics of the optomechanical system.





- New method for the determination of optomechanical coupling rate.