The emerging field of cavity optomechanics focuses on the study of interaction between mechanical degrees of freedom with light to sense and control mechanical motion at mesoscopic and macroscopic scales. In most realizations, an optical cavity is coupled to a mechanical oscillator, such that the cavity provides enhanced sensitivity to the motion of the mechanical oscillator, as well as actuation through radiation pressure or photothermal forces. This interaction enables, for instance, to optically cool the mechanical oscillator close to the quantum mechanical ground state of motion and to prepare and detect quantum states of motion of a macroscopic object. This provides an experimental system to address fundamental questions in quantum mechanics regarding the transition between the classical and quantum regimes in macroscopic systems, and in particular, the role that quantum decoherence plays in this transition.

The aim of this project was to experimentally study optomechanical systems with the required properties to enable optical cooling to this quantum mechanical regime of motion. All experiments performed combine passive cryogenic cooling in a 3He cryostat with optical cooling. Accessing the quantum regime is hindered by the influence of any form of decoherence, in this system materialized as optical and mechanical losses. It is therefore desirable to work with a system with low optical κ and mechanical Γ_m linewidths, describing the energy relaxation rates of the two degrees of freedom. Conversely, the ability to cool and sense the motion of the mechanical resonator scales with the strength of the coupling between the optical and mechanical degrees of freedom, quantified by the single phonon optomechanical coupling constant g_0 measuring the frequency shift of the optical cavity caused by a single phonon of mechanical vibration. It then becomes clear that a good figure of merit to assess the suitability of an optomechanical device to access the quantum mechanical regime is the optomechanical cooperativity $C_0 = \frac{g_0^2}{\kappa \Gamma_m}$, measuring the ratio of optomechanical coupling to optical and mechanical losses. For instance, in systems in the so-called resolved-sideband regime, with optical damping rates below the mechanical resonance frequency, the ratio of initial to final temperature in a sideband cooling experiment scales as $n_c C_0$, where n_c is the intracavity photon number. This factor also describes the signal-to-noise ratio of such a device to sense its quantum zero-point fluctuations, and the sensitivity of the device to the quantum fluctuations of the light, the so-called quantum back-action. Finally, $\frac{n_c}{n_{th}} C_0$, where n_{th} is the number of quanta in the thermal bath, measures the ability to quantum-coherently swap quantum states from the optical mode to the mechanical mode, hence allowing the preparation of quantum states of macroscopic motion.

A good optomechanical system developed in the host group prior to this project is the silica microtoroidal resonator. These devices support whispering gallery optical modes which couple to the radial breathing mode of the microtoroid. Light is evanescently coupled into these structures by launching light into a tapered optical fiber placed in close proximity. Experiments in the group showed that these devices could be cooled to down to 1.7 phonons and quantum states could be swapped quantum coherently between the optical mode and the mechanical mode. Further experiments in this direction were hindered by severe technical problems due to acoustic vibrations caused by the cryostat. In particular, vibrations arising from the internal cryogenic liquid flow caused jitter in the position of the optical fiber used to couple light in and out of the resonator, leading to severe fluctuations in the intracavity power, hence to jitter in most experimental parameters, making experiments unfeasible. Significant efforts were undertaken to undermine these problems including passive and active stabilization, leading to unsuccessful results.

A new kind of sample was designed, consisting of an integrated doubly-clamped high-stress silicon nitride nanobeam evanescently coupled to a silica microdisk resonator. Such structures are advantageous in several respects. First, it allowed solving the cryostat vibration problem described above. As the mechanical resonator is not in physical contact with the optical cavity, the optical fiber used to couple light into the device can now be put in contact with the cavity without degrading the mechanical quality factor of the nanobeam, and the full integration enables easy operation in a cryostat. Second, high-stress silicon nitride is known to provide high mechanical quality factors. A new fabrication technique developed in the group together with precise engineering of the geometrical parameters of the structures gave rise to device with very high optomechanical coupling parameters of up to $g_0 = 2\pi \times 20$ kHz, mechanical damping rates of $\Gamma_m = 2\pi \times 6$ Hz and optical linewidths of $\kappa = 2\pi \times 200$ MHz, leading to a cooperativity of $C_0 = 0.33$. This outstanding unprecedented value makes feasible several experiments, including the observation of quantum back-action and feedback cooling to the quantum regime, both of which were attempted in the course of this project. The frequency of the fundamental vibrational mode of the oscillator is $\Omega_\mathrm{m} = 2\pi \times 4.3$ MHz. Hence, for this mode, the system is said to be in the bad-cavity regime, $\kappa \gg \Omega_\mathrm{m}$.

Feedback cooling is a technique by which the displacement of the oscillator is measured, and a force proportional to the derivative of this displacement, the oscillator velocity, is applied to the oscillator in a closed feedback loop. In our system, both sensing and force actuation are performed optically, by means of the optomechanical coupling. It is the preferred cooling technique in systems in the bad-cavity regime, for which sideband cooling is not possible. We performed an experiment to study the fundamental and technical limitations of feedback cooling in this system. In this context, we note that the requirements to feedback cool a mechanical resonator to its ground state is equivalent to the ability to resolve zero-point fluctuations of the oscillator position faster than the mechanical decoherence rate, a condition that we term *quantum coherent position sensing*.

In a long set of experiments performed with this system, we were capable of cooling the fundamental mechanical mode of the nanostring to 5-10 phonons, currently only limited by classical heating induced by the absorption of light from the sensing laser (Figure 1). A manuscript describing these results is under preparation and will soon be submitted for publication.

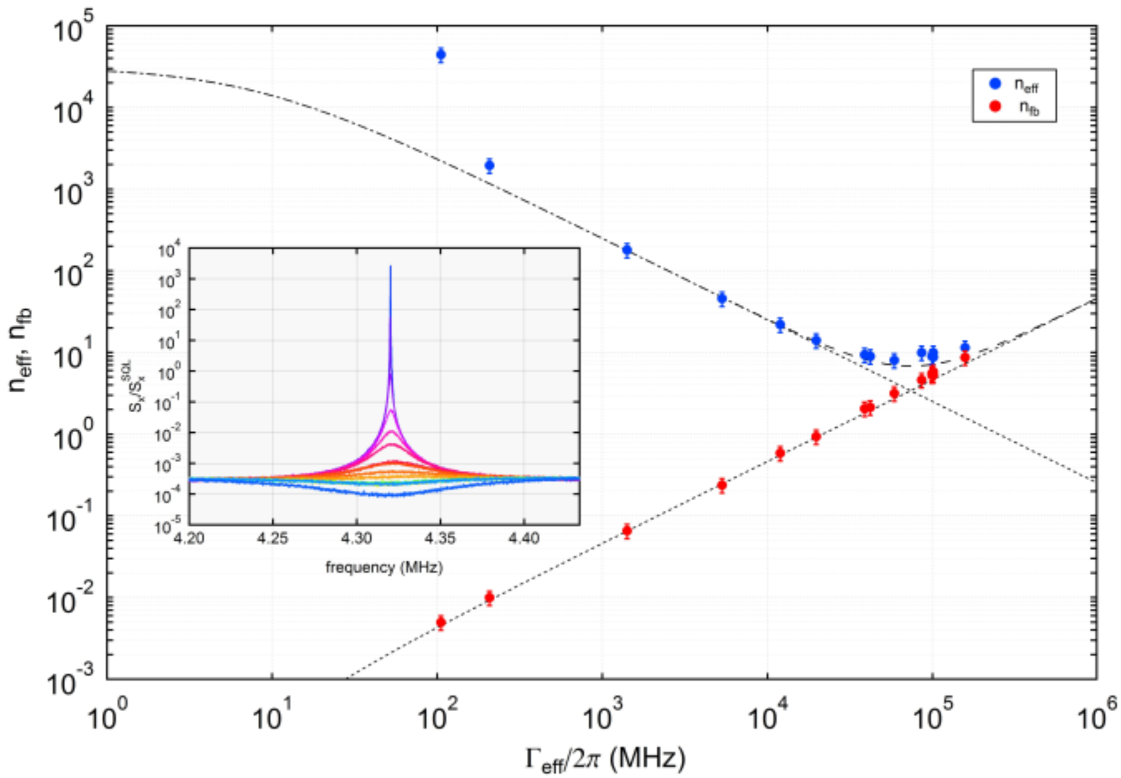

Figure 1: Optical feedback cooling of a nanobeam resonator. Effective mode occupation is plotted vs the induced damping rate (blue) and the induced heating due to feed back of detection noise (red). The final occupation is limited by the onset of heating due to the reinjection of measurement noise, that sets in when the mechanical displacement fluctuation amplitude reach the noise floor level. Inset: plot of the mechanical noise spectra for different feedback gain settings, showing the onset of noise squashing arising due to the reinjection of measurement noise.

The same parameter regime enables to observe the effects of the quantum character of light on the mechanical oscillator, the so-called radiation pressure shot-noise (RPSN), or its effect on the position measurement of the oscillator, the quantum back-action. In essence, if light impinges on a mechanical oscillator, e.g. to measure its position, the quantum fluctuations of this light, or *shot noise*, impart momentum on the oscillator, leading to an effective driving force and heating. This fundamental character of quantum measurements leads to an ultimate limit in the sensitivity achievable in a position measurement. Furthermore, back-action evasion schemes can be implemented to surpass this limitation. Hence, the experimental study of this effect has obvious fundamental and applied implications. The effect has not been accessible in experiments until very recently, and our system is a very good candidate.

In our setup, we performed pump-probe experiments to observe RPSN heating of a strong pump laser on the displacement fluctuations measured with a second week probe laser. To distinguish this quantum-mechanical effect from classical absorptive heating, both of which lead to the same experimental signature, we monitor the mode temperature of several higher order mechanical resonances, apart from the fundamental 4.3 MHz mode, which should be less amenable to radiation pressure, while having a similar absorptive heating contribution. Such experiments showed that significant heating arises from optical absorption, while only 20-30% can be attributed to RPSN. In this context, current development is being undertaken in the device fabrication process to reduce the contribution of absorptive heating, and the next generation of samples will enable a cleaner experiment.

Minimizing mechanical losses is essential for most optomechanical experiments. In glassy materials at low temperatures, mechanical losses are ultimately limited by phonon scattering by defect states present in all amorphous materials, which can be satisfactorily modeled as two-level systems (TLS). These TLS couple to the strain field, leading to mechanical attenuation. In its most basic form, the absorption arises from a resonant process, in which a single mechanical phonon is resonantly absorbed by the TLS. In addition, they possess a dipole moment and hence also couple to the electromagnetic field.

In this context, we have embarked in a project to observe this fundamental absorption contribution with two envisioned objectives. First, the TLSs can be driven with a radio-frequency field to saturate them and suppress phonon absorption and mechanical losses. Second, if the strain field extends over a sufficiently small volume it couples to single TLSs. This scenario would enable to study the prospects of using an optomechanical system for quantum control of phononic two-level quantum systems.

For the experimental implementation, it is necessary to employ a high frequency optomechanical resonantor with low clamping losses. Indeed, the resonant absorption process is known to have a significant contribution at frequencies of the order of a gigahertz. In addition, all other sources of loss mask the observation of these effects. Hence, we fabricated silica spherical resonators with large mechanical resonance frequency (600 MHz) and supported by needle pillars for suppressed clamping losses. After several fabrication and characterization iterations, we obtained a sample with mechanical frequencies of up to 700 MHz and clamping losses below 20 kHz. We performed theoretical calculations to estimate the expected resonant absorption losses to be of the order of 30 kHz at 0.4K, achievable with our 3He cryostat. Hence, this sample makes the observation of these effects feasible and we will soon perform low temperature measurements.

Aside from the aforementioned experimental projects, I also took part in a theoretical study to assess the possibility to prepare, store and readout a single phonon Fock state in a cavity optomechanical system. Calculations and simulations taking into account mechanical and optical decoherence showed that this is feasible with a state-of-the-art optomechanical system consisting of a phoXonic crystal cavity, a device that confines and colocalizes both optical and acoustic waves using a periodically structured nanobeam. This work led to a publication in Physical Review Letters.