Summary of results & achievements

In these 4 years we have constructed from scratch and completed an advanced cavity-QED system, which is now performing single atom-single photon interactions, focusing on the demonstration of photon-photon interactions.

In the following I describe the capabilities we have developed, and the experimental results we have obtained with these capabilities.

Our experimental setup and mode of operation.

Our experimental setup relies on the coupling of single ultra-cold ^{87}Rb atoms to fiber-coupled high-Q microtoroid resonators. Specifically, as depicted in Fig. 1A, in our system we release laser-cooled ^{87}Rb atoms from a magneto-optical trap (MOT), a few mm above a chip with microtoroid resonators.

Light is coupled to one of the microtoroids through a tapered optical fiber. The fiber-cavity coupling ($\boldsymbol{\kappa_{ex}}$) is controlled by using piezo-based positioning system (AttoCube) to control the distance between the tapered fiber and the microtoroid, or by selecting a specific contact point between the fiber and microtoroid surface. The coupling results from overlap between the evanescent fields of the tapered fiber and the whispering-gallery mode (WGM) of the microtoroid. Phase matching between the modes is achieved by varying the position of the microtoroid along the tapered fiber (thereby changing the diameter of the tapered fiber next to the microtoroid) until we can achieve critical coupling, namely a situation in which the coupling is equal to the internal losses and so all the input light is coupled to the resonator, and the on-resonance transmission in the fiber drops to nearly zero. As atoms are released from the MOT, a few fall close enough to the microtoroid surface to interact with the evanescent field of the WGM (see inset of Fig. 1A).

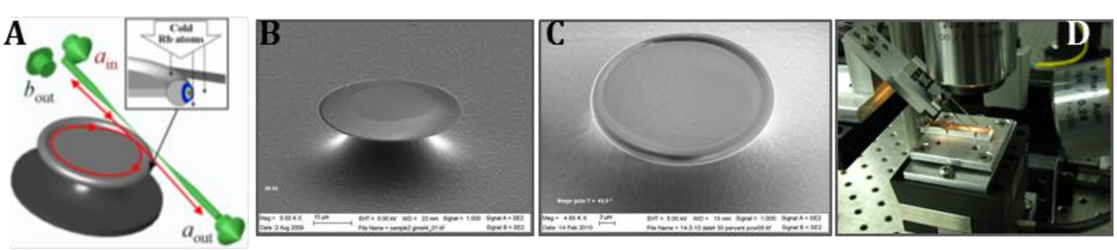

Fig. 1: A) simplified depiction of the experimental apparatus. B),C) microtoroids before and after the laser reflow process. D) small part of the out-of-chamber coupling setup.

Ultrahigh-Q microtoroids and compact and stable coupling system

In my group today we fabricate such microtoroids at quality factors $>5\cdot10^8$, corresponding to line-widths narrower than 1 MHz. Such state-of-the-art line-widths are well beyond sufficient for our purposes, as they are is smaller than the 3 MHz natural linewidth of the D2 transition of ^{87}Rb.

Specifically, The microtoroids are fabricated from Silicon wafers topped with a thin layer of silica. The silica is etched away by wet etching, leaving circular "islands" at varying radii (20-120 μm). A second step of etching is performed to remove most of the silicon supporting the silica, resulting in a silica disk resting upon a silicon pillar (see Fig. 1B-C). The final stage is done by reflowing the silica by heating it using a CO2 laser.

Coupling light to WGM microresonators requires tapering of an optical fiber until it is thinner than the optical wavelength so it could couple a single guided mode to the microtorid by overlapping their evanescent fields. We achieve this by pulling the fiber in a computer-controlled fashion above a hydrogen flame. Considerable effort has been invested to ensure we can repeatedly attain tapered fibers with high transmission (>90%), and yet keep their length to a minimum (a few mm), to allow stability and compatibility with our cavity-QED apparatus.

The tapered part of the fiber is located close to the microtorid at a distance that is piezo-controlled and stabilized to within ~10nm. The entire coupling setup was designed to be compact and robust to fit into the cavity-QED assembly below the MOT, and includes piezo benders that control the strain in the tapered part.

Advanced setup for fast (~ns) manipulation and control of ultracold atoms

To deliver atoms to within ~200nm from the microtoroid surface our setup includes a magneto-optical trap (MOT) of ~3·108 87Rb atoms, polarization-gradient cooled to sub-Doppler temperature of ~7μK, with microwave fields for spectroscopy and hyperfine level manipulation, and far-off resonance blue-detuned beams to guide their fall towards the microresonator. This ensures a delivery of cold atoms to within the evanescent field of the WGM, yet we do not intend at this point to trap the atoms; this task is currently the focus of at least a couple of research groups worldwide, and was not achieved yet due to the great difficulty of providing both an attractive force to attract the atoms to the WGM,

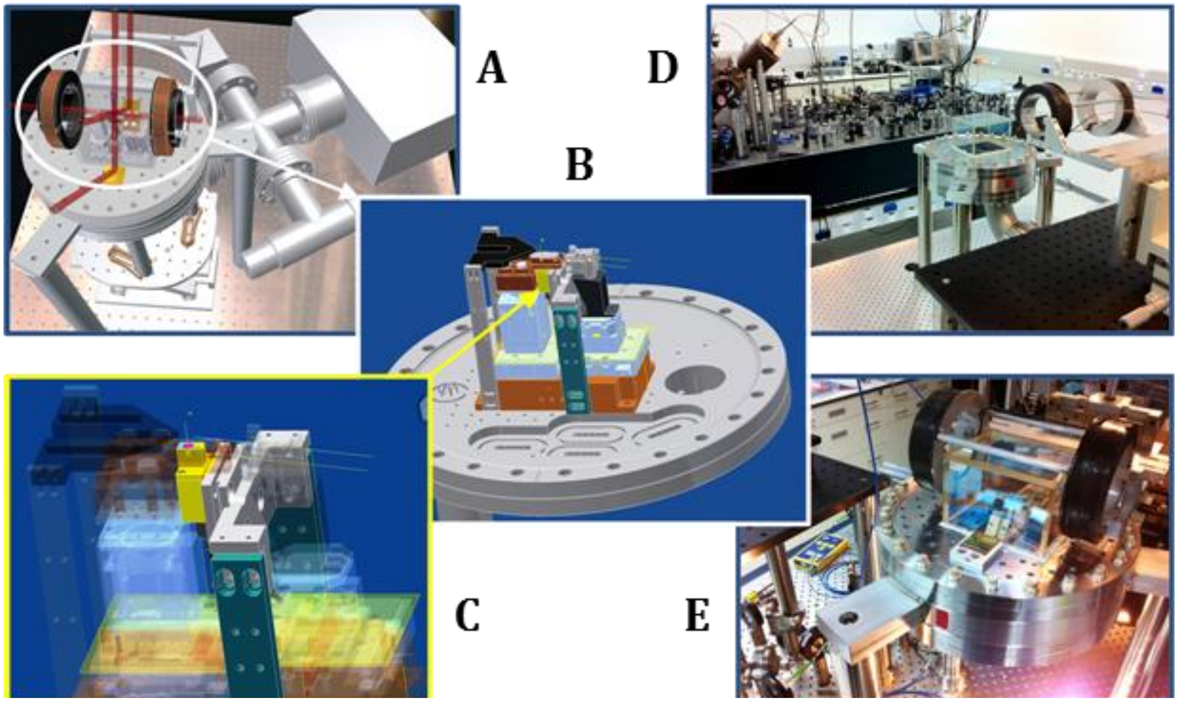

Fig. 2: A) an overlook on the design of the cavity-QED setup, showing the MOT coils around the glass vacuum chamber. B) the design of the chip assembly. C) a closer look at the chip assembly, showing the microwave dielectric resonator underneath the chip for fast ground state manipulation. D) The 'old' cold-atoms setup, on the far optical table, and the early stages of the cavity QED chamber on the closer table. E) the cavity-QED chamber after initial assembly.

and a repelling force to prevent the atoms from hitting the surface and to counter the attractive Van der Waals forces that start dominate at distances of < 100nm from the surface. Instead, we have built the ability to detect, probe and manipulate the atoms using pulses as short as 1ns, using fiber-based electro-optic modulators (EOMs) and electronic equipment operating at rates > 5GHz. This ability enables us to run a complete experimental protocol that includes detection of the atom's presence in the mode, manipulating its internal state by resonant fields or optical Raman pulses, sending probe pulses at arbitrary detunings, detecting the emitted single photons at 6 channels with resolution of 100ps, and finally verifying that the atom is still in the mode - all this at ~2μs, which is less than a typical atom-transit duration.

The setup for blue-detuned guidance of the atoms was already put to good use in an experiment we performed on catastrophes in atom optics, and the ns pulses combined with 100ps single photon detection capabilities were harnessed to demonstrate a novel scheme for weak measurement based on spontaneous emission from a single atom in a superposition state.

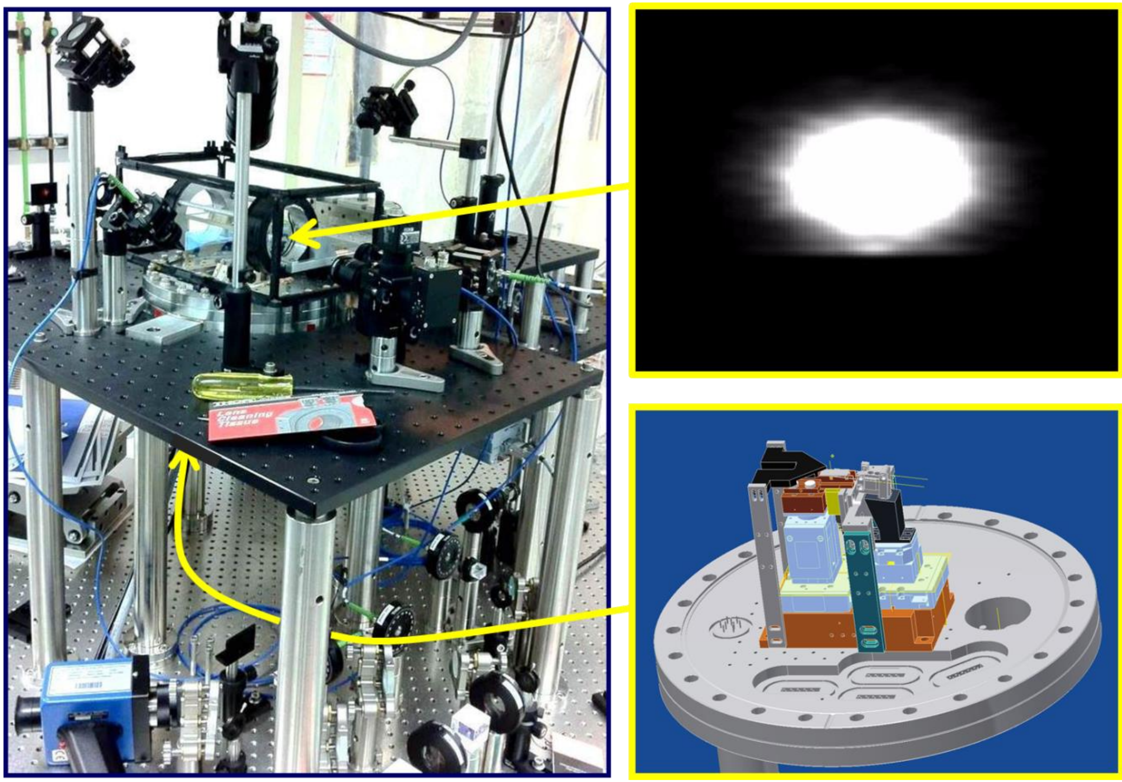

Fig. 3: The integrated, fully operational cavity-QED setup, together with an image of the MOT and a diagram showing how the entire chip assembly is built on the bottom flange, enabling replacement of the chip without disturbing the optical setup which is located around the glass chamber attached to the top flange.

To summarize, in these 4 years we have mastered the fabrication high-Q microresonators, taper pulling and coupling, constructed an advanced setup for fast manipulation and control of ultracold atoms, and have constructed the integrated cavity-QED setup which we now implement for demonstrating photon-photon interactions. We have performed and published (PRA) a comprehensive theoretical study, which forms the basis for our current experiments. Using these capabilities we have also performed two experiments, one in which we demonstrate catastrophes in atom optics, and one in which we demonstrate a novel method for weak measurement based on spontaneous emission from a single atom in a superposition state (published in PRL).