Scientific contributions of Tobias J. Kippenberg to:

Cavity Optomechanics and Microresonator based Optical Frequency Combs

- **Quantum Manipulation of Mechanical Oscillators with Laser Light**

Mechanical oscillators are ubiquitous in science and technology alike; mechanical oscillators are used in time-keeping, as filters in cell-phones, MEMS accelerometers in phones, atomic force microscopes that probe the nanoscale, or large-scale pendulum suspended mirror masses used in gravitational wave detectors. Yet, the ability to achieve *quantum control over mechanical system* – which had sparked imagination[1,2] - had been a longstanding challenge of condensed matter Physics[1] and quantum optics[2] alike. In contrast to atoms or trapped ions[3] , that can now be routinely manipulated in the quantum regime due to the methods of atomic laser cooling, no such manipulation techniques were available or known. This has changed in the last 15 years: Following quantum control of individual isolated quantum systems, the latter has now been extended to macroscopic, engineered mechanical oscillators, starting with the advances in the field of **cavity optomechanics**[4–6], and continuing with advances made in quantum acoustics[7]. Today, mechanical systems can routinely manipulated in the quantum regime, cooled to the quantum ground state, allow preparation of mechanical squeezed states of motion, Fock states and can even be entangled, with light, microwaves or other mechanical oscillators. Mechanical oscillators have become firmly controlled at the quantum level, with repercussion from fundamental Physics of testing quantum mechanics and gravity, to entirely novel sensing principles that can interconvert radio frequency optical and microwave signals. The quantum effects of mechanical systems can even be probed today at ambient temperature. Cavity optomechanics has enabled such quantum control to be achieved.

Several discoveries let to these development. The field of 'optomechanics' started with pioneering studies on observing radiation pressure on macroscopic mirrors, and the pioneering and seminal theoretical studies of Braginsky on the role of radiation pressure in interferometric positions measurements[8,9]. Braginsky laid the foundations to quantum measurement theory and considered optical and microwave cavities coupled to mechanical test masses to detect gravitational waves. His studies even detected the faint radiation pressure force. Caves[10] understood that radiation pressure eventually limits interferometric measurements and described what is now commonly knowns as the "standard quantum limit". In the decades that followed, expect pioneering studies of Dorsel[11] at MPQ and feedback cooling of a macroscopic mirror by Heidman[12].

An unexpected and breakthrough discovery, and a catalyzer to *cavity optomechanics*, has been the observation of radiation pressure *dynamical backaction.* In pioneering work Braginsky predicted in 1969[13] that radiation pressure dynamical backaction, can be used to cool mechanical oscillators, even pre-dating the first proposals on atomic laser cooling[14,15] from 1975. Yet, this effect remained experimentally out of reach many decades, due to the faint nature of the radiation pressure force, the fact that radiation pressure is easily masked by the more common thermal effects, that are already known since Crook's famous light mill experiments, and the requirement on optical cavity finesse. A key and surprising discovery was made in 2005, when Kippenberg and Vahala, observed for the first time the effect of *dynamical backaction* amplification[16] experimentally. This work demonstrated that radiation pressure can exert not only forces, but also lead to amplification of mechanical motion. Moreover, this work revealed that optical micro-resonators can simultaneously act as mechanical oscillators coupled to light via radiation pressure.

Importantly, and breaking with the prevailing dogma of thermal laser heating, in these systems the radiation pressure response dominates. In the year 2006 three research groups demonstrated for the first time the converse effect, radiation pressure dynamical backaction cooling, for the first time simultaneously, Heidman[1], Kippenberg at MPQ and Markus Aspelmeyer[2] in Vienna, as originally predicted by Braginsky in 1969[3]. This work established a new 'backaction' cooling method for mechanical oscillators, with which unprecedentedly low temperatures could be reached, and which was ascribed purely to radiation pressure [4,5] overcoming thermal heating. This cooling can moreover enable to reach the quantum ground state, under conditions which were first derived by Kippenberg and Zwerger in a quantum theory[6,7] of dynamical backaction cooling (simultaneously to work of S. Girvin and F. Marquardt[17]). In 2008, optomechanical resolved sideband cooling was first demonstrated[5] by Kippenberg. Optomechanical sideband cooling has been a workhorse technique since then[18], and proven critical to enable to access the quantum regime of mechanical oscillators[8-10].

The immense attention that the optomechanical cooling experiment garnered in the years following 2006, let numerous groups to explore this new interaction in various micro- and nanoscale optomechanical[19–22]. The series of papers[17,23–27] developing the framework of backaction sideband cooling, garnered immense attention, led numerous groups to explore micro- and nanoscale optomechanical[19–22] cooling experiments and led to the development of a new research field of "*cavity optomechanics*"[4,5] . Cavity optomechanics led to major scientific advances and breakthroughs by many research groups, which include cooling close to the quantum ground state[28–30], phonon lasing[16], entanglement[31] of mechanical motion and microwaves, observation of radiation pressure shot noise[32,33], optomechanical squeezing[34,35], quantum coherent coupling[28,30], measurement rates at the thermal decoherence rate[36], coherent state transfer[11], backaction evading techniques[3738] and preparation of mechanical squeezed states[394041], among many others. It has also led to new technological developments, such as interfaces that convert via mechanical systems radio waves to optical signals[42], quantum limited measurements of radio waves[43], optomechanical accelerometers, or amplification of microwaves[44]. Indeed, these experiments signal that after quantum control of atoms, ions and superconducting circuits, quantum control of engineered mechanical oscillators has become a reality. It has also has led to new technological developments, such as interfaces that convert via mechanical systems radio waves to optical signals[42], quantum limited measurements of radio waves[43], optomechanical accelerometers, or amplification of microwaves[44,45]. Theoretically a myriad of advances have been made and theoretical protocols emerged, for instance new schemes for optomechanical reservoir engineering[46] to generate optical and mechanical squeezing[4748], and entirely new interactions of light and sound conceived[49] to create topological phases of light and sound[50]. Cavity optomechanics, beyond enabling to reach and explore the quantum regime of mechanical systems, has the potential to allow testing quantum mechanics on unprecedented scales[51], and impact sensing technologies, via some of the most sensitive measurements of mechanical motion to date[36,52], and by offering new ways in which light and mechanical motion can be interconverted, stored or processed[53].

Optomechanics is until today an extremely rich and active research field, with recent demonstrations of on demand entanglement of mechanical oscillators the use of mechanical oscillators for reading out a superconducting qubit[54], quantum mechanical free subspaces[55], remote entanglement between mechanical oscillators[56], sideband cooling beyond the quantum limit[57], stabilization of macroscopic entanglement of mechanical oscillators[58], direct observation and deterministic entanglement of mechanical oscillators[59]. In addition the SQL has been overcome[45,60] – a limit thought purely of textbook character.

Fundamentally, all these experiments share the same principles and techniques: notably radiation pressure sideband cooling, amplification and enhancing optomechanical coupling in engineered micro-resonators and – first observed in 2005 and 2006 by Kippenberg. Beyond this, the group of Kippenberg contributed in numerous ways to this field over the past decade, that shaped the field in many regards, in addition to the ground-laying pioneering experiments, on amplification and sideband cooling, contributing experiments that demonstrated quantum coherent coupling of light and mechanical motion[30], room temperature optomechanical quantum correlations, quantum feedback[61], and demonstrating the highest mechanical Q oscillator of any kind at room temperature[62]. Moreover this group's work demonstrated optomechanically induced transparency[63,64], widely used in optomechanical experiments as it is a required protocol in storage of phonons[65], wavelength conversion[42,66,67]. Their work developed calibration techniques for the vacuum coupling rate, that are widely employed in the field[68], extended optomechanics to near fields[69], proposingschemes for Fock state generation[70] and analyzing multi-mode optomechanical interactions[71]. Their work observed quantum sideband asymmetry[72], along with many other groups[73]. In addition their work elucidated sideband cooling theory for describing the oscillator in the strong coupling regime[74], which was key to understand the regime of ground state cooling[28] in the presence of quantum coherent coupling. Moreover their work led to the most precise measurements of mechanical motion to date, with an imprecision below that at the standard quantum limit (SQL)[69,75] (simultaneous to work from JILA[76]), culminating in real time quantum feedback[36] and quantum coherent coupling[12]. Moreover his group laid the foundation to the most coherent mechanical oscillators to date, quantum coherent even at ambient temperature[62], and led to ground state cooling of trapped particles in cavities[77].

The discovery dynamical backaction, and in particular optomechanical sideband cooling and amplification as well as intrinsic optomechanical coupling in microcavities - along with other advances on optomechanical systems - has now, 15 years after the discovery, led to methods and techniques by *which quantum control of mechanical systems can be achieved* and by which mechanical oscillators can be manipulated and measured with unprecedented sensitivity. Moreover, optomechanical coupling has been extended to other forms of mechanical systems such as superfluid modes, trapped particles[78], plasmonic systems, or even molecules. It moreover has led to entirely new ways in which electromagnetic or optical fields can be manipulated, measured or interconverted, with evident application potential. The discovery of optomechanical dynamical that Vahala and Kippenberg discovered are today textbook knowledge, and firmly established in Quantum Physics. Owing to these developments the *enigmatic zero point fluctuation* has a physical meaning; and cavity optomechanics made it possible to measure the quantum mechanical vacuum fluctuations of macroscopic mechanical oscillators, that one can witness with the bare eye. Even more remarkably triggered by the discovery of optomechanical coupling on microresonators, it is today possible to measure with a imprecision that is more than 7 orders of magnitude below the standard quantum limit[79], and thereby enabling to realize experimentally the Heisenberg microscope. Looking to the future it is fascinating to see that cavity optomechanics is moreover enabling a route to test quantum mechanics on a macroscopic scale, and make steps towards experiments that could test quantum mechanics and gravity[51].

- **Discovery of Microresonator based Optical Frequency Combs "Microcombs"**

The development of optical frequency combs[80], and notably self-referencing[81], has revolutionized precision measurements over the past decade, and enabled counting of the cycles of light. Frequency combs, for which Hall and Hänsch shared the Physics Nobel Prize in 2005 has enabled dramatic advances in timekeeping, metrology and spectroscopy. In 2007, research on microresonators by the Kippenberg group resulted in the discovery of a novel method[13,14] to generate optical frequency combs using parametric frequency conversion in optical microresonators[82,83]. **This unexpected observation broke with the conventional dogma that optical combs can only be generated with mode locked pulsed laser sources.** Instead this work showed that a CW laser can be converted into a broadband frequency comb, using parametric frequency conversion[1583], overcoming passive cavity dispersion. Kippenberg's research group demonstrated with his group the accuracy of the mode spacing to be better than 1 part in 10(17) – hence unambiguously proving the comb nature[13]. The discovery of microresonator frequency combs[84,85] in 2007 have made it possible to synthesize optical combs in compact devices that can be microfabricated on chip, with unprecedented high repetition rates in the technologically relevant gigahertz regime, and with optical bandwidths that are far beyond what can be achieved with conventional mode locked lasers. The original report, published in *Nature* in 2007 (**>cited more than 2000 times** in GoS to date), has **opened a new field of research at the intersection of optical metrology and nano- and micro-photonics and nonlinear optics**, and has exploded in the recent years in terms of research activities. Microresonator Kerr combs have been demonstrated now in virtually all material platforms[86–89] ranging from Silicon, SiC, Lithium Niobate to compound III-V semiconductors - including the all important fully CMOS compatible platforms[90,91]. Their spectral coverage extended to the visible[87] and mid infrared[92,93], repetition rates in the microwave regimes have been achieved[94]. In addition, microresonator combs have been successfully applied to the field of coherent communication[95], demonstrated for use in waveform synthesis[96] and low noise microwave generation[87] as well as the realization of compact atomic clocks[97]. The Kippenberg group also revealed their universal dynamics[98], which culminated in the observation of low phase noise integrated silicon nitride frequency combs. A key second discovery, that has propelled "microcombs", has been that of *dissipative Kerr solitons* in 2014. His research group discovered for the first time dissipative cavity solitons in optical microresonators[99]; short bursts of optical pulses formed by the balance and interplay of nonlinearity and dispersion as well as parametric gain and loss. This work, first published in 2014 and cited > 1000 times in GoS, has in particular in the last years led to major theoretical activities[100,101] as it connected Kerr combs to dissipative temporal soliton Physics[101], as described by the Lugiato Lefever equation[102]. Such soliton microcombs have now been shown in a wide variety of platforms, ranging from crystalline resonators, chipscale silica disks to integrated devices to materials that are electro-optic in nature. Such soliton Kerr combs have in recent years led and enabled dramatic advances including many system level applications: ranging from coherent communications[103], dual comb spectroscopy[104], chipscale integrated frequency synthesizers[105] to turnkey to integrated battery operated devices[106] and even astrophysical spectrometer calibration[107108]. Soliton microcombs enabled the Kippenberg group to demonstrate the counting of cycles of light using a microresonator[109], and demonstrating the first observation of soliton induced Cherenkov radiation[110], enabling coherent and broadband combs. Moreover in joint work with Prof. Koos at KIT the team demonstrated the use of soliton microresonator comb for coherent communication[103] at terabit per second, at both the receiver and transmitted side, and ultrafast dual comb distance measurements[111] and in most recent work demonstrated the use of microcombs for massively parallel LiDAR[112].

The discovery of dissipative solitons in micro-resonators has enabled many other advances – as recently reviewed[113] - notably dual comb spectroscopy[104], counter-clockwise solitons[114], dual soliton comb based distance measurements[115,116], or synthesizing frequencies on chip[117]. Micorcombs have the potential to revolutionize data center interconnects, with demonstrations of compact transceivers[118], to counteract the growing demand in energy consumption, and application potential in numerous other areas including neuromorphic computing[119,120] enabling Teraflops per second computation. Microcombs can also be applied to FCMW LIDAR and allow novel parallelization[112]. The integration of microcombs have also advanced significantly: triggered with the observation of self-injection locked soliton microcombs[121] with hybrid III-V integration, **it is possible today to create microcombs on a 4-inch wafer with pump lasers integrated – a single wafer can contain several 1000's of laser soliton microcombs**[122]: more than conventional fiber based femto-second laser combs exist on the planet. They have been integrated moreover with other functionality, piezo-electrical[123] or soliton photonics[124] based technology.

The discovery of dissipative solitons in micro-resonators has enabled many other advances in numerous fields that span across a remarkably wide range of disciplines– as recently reviewed[113]: microcombs can be used for astrophysical spectrometer calibration to seek exo-planets[107,108]. Microcombs have been used for neuromorphic computing[120,125], and can also serve as source of 'quantum frequency combs'[126,127] generating correlated photon pairs. Microcombs have also been used to create low noise microwave, implement microwave photonic filters, allow optical communication with peta-bit per second, and are host a plethora of nonlinear dynamical states, and soliton interactions. In addition to theoretically predicted dissipative soliton behavior such as breather soliton dynamics[128–130], also new and theoretically not previously predicted dynamics has been observed ranging from formation of soliton crystals[131], soliton switching[132], and new type of breather solitons[133] and complex dynamics[134,135]. Microcombs are therefore an new experimental setting to explore the Physics of driven dissipative nonlinear systems, and more general spatio-temporal pattern formation. Today it is widely understood that driven nonlinear resonators host many more 'dissipative structures' from platicons[136] to zero dispersion solitons, to compound waveforms[137].

The disruptive potential of this discovery and the potential to advance technologies from metrology, sensing, timekeeping and spectroscopy has led to intense interest in this field – and major national funding initiatives such as in the US by DARPA (SCOUT, DODOS, PULSE) as well as in Australia. It has become widely recognized that microcombs are an area in which optical micro resonator research can actually lead to actual application outside the academic laboratory. It is even possible to obtain commercial samples from LIGENTEC – a company Kippenberg co-founded that has democratized access to photonic chipscale microcombs. The ability to create chipscale combs could contribute to making frequency metrology ubiquitous, and enable new applications that require large mode spacing. Today more than **1000's of paper have been published on the topic of 'microcombs'**, including dozens of papers in Nature and Science.

Moreover, microcombs have enabled numerous fascinating studies of nonlinear dynamics: in addition to theoretically predicted dissipative soliton behavior such as breather soliton dynamics[128–130], also new and theoretically not previously predicted dynamics has been observed ranging from formation of soliton crystals[131], soliton switching[132], and new type of breather solitons[133]. The soliton Kerr frequency combs thereby provided a highly fruitful new playground for fundamental nonlinear science and applications alike.

The disruptive potential of this discovery and the potential to advance technologies from metrology, sensing, timekeeping and spectroscopy has led to intense interest in this field. It has become clear that optical combs are an area in which optical micro resonator research can actually lead to actual application outside the academic laboratory, but also can be equally useful in other areas of science. For instance, the large mode spacing achieved in these micro-combs (>10 GHz) makes these devices ideal for Astronomy to calibrate spectrometer[138] in the quest to search explants[138]. The ability to create chipscale combs could contribute to making frequency metrology ubiquitous, and enable new applications that require large mode spacing.

Summary

In summary, the research by the Kippenberg group on optomechanical effects and optical frequency comb generation in high Q micro-resonators, catalyzed the new research field of *cavity quantum optomechanics*, that enabled a new frontier in quantum and classical control of mechanical systems, and has opened a new field of *micro-resonators frequency combs*, providing a highly fruitful playground for science and technology alike. In addition his has been transitioned to the real world with the foundation of LIGENTEC SA, a foundry for ultra-low loss silicon nitride photonics circuits, that is shipping globally chips for numerous applications, including quantum computing, frequency combs and many other applications.

Quotes from Literature:

"A major achievement of the past decade has been the realization of macroscopic quantum systems by exploiting the interactions between optical cavities and mechanical resonators"[139]

"Since this first demonstration, resolved-sideband cooling has been the workhorse of most experiments aimed at observing quantum effects in macroscopic mechanical resonators"[18]

"Such microcombs offer revolutionary advantages over existing comb technology, including chip-based photonic integration, uniquely large comb-mode spacings in the tens of gigahertz range, and monolithic construction with small size and power consumption. "[97]

Key publications of the Kippenberg lab on: Cavity Quantum optomechanics

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Key publications on: Microresonator frequency combs

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10. J Riemensberger, J. *et al.* Massively parallel coherent laser ranging using soliton microcombs. *Nature* (2020)

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