iWave: A New Scheme for Matter Wave Interferometry

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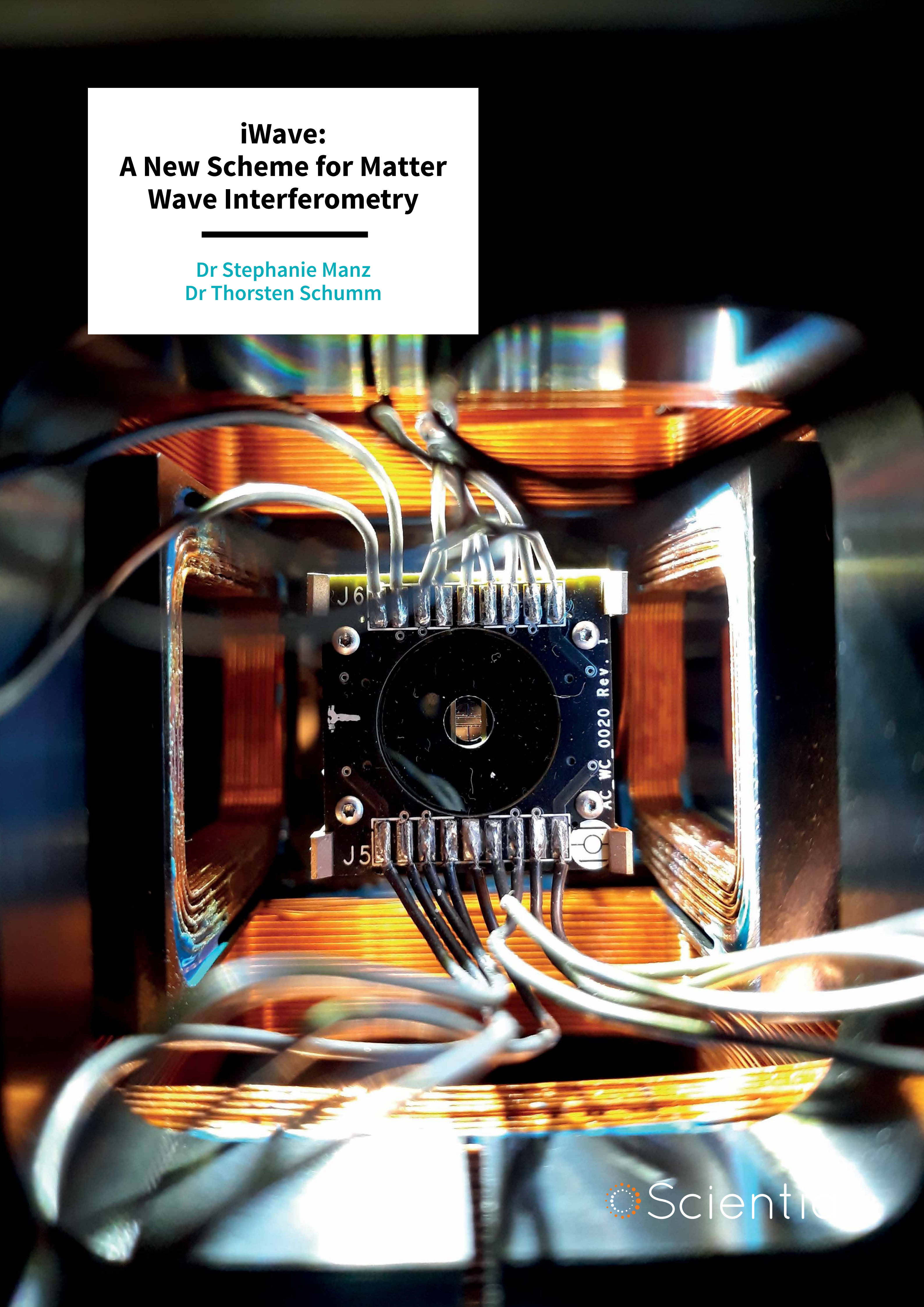


iWave: A NEW SCHEME FOR MATTER WAVE INTERFEROMETRY

By precisely measuring path differences in light waves as they are split apart and recombined, interferometers have allowed physicists to make some of their most profound discoveries: from disproving the ether theory in the late 19th century, to the first detections of gravitational waves in 2016. Now, **Dr Stephanie Manz** and **Dr Thorsten Schumm** at TU Vienna aim to push the capabilities of interferometers further with iWave: an instrument that exploits particle-wave-duality, one of the fundamental principles of quantum mechanics. By replacing light waves with matter waves, the duo and their team believe that their new interferometer could bring about exciting experimental opportunities.

Interferometry

Interferometers are incredibly powerful tools in physics. They operate by first splitting a coherent beam of light along two paths, and then recombining them. If the conditions along the two paths are identical, then the peaks and troughs of these light waves will continue to line up, as they did the moment they were split. As they recombine, these waves are said to be 'in phase' or 'out of phase' with each other, and will constructively or destructively interfere depending on their relative phase, while the total intensity of the original wave is conserved.

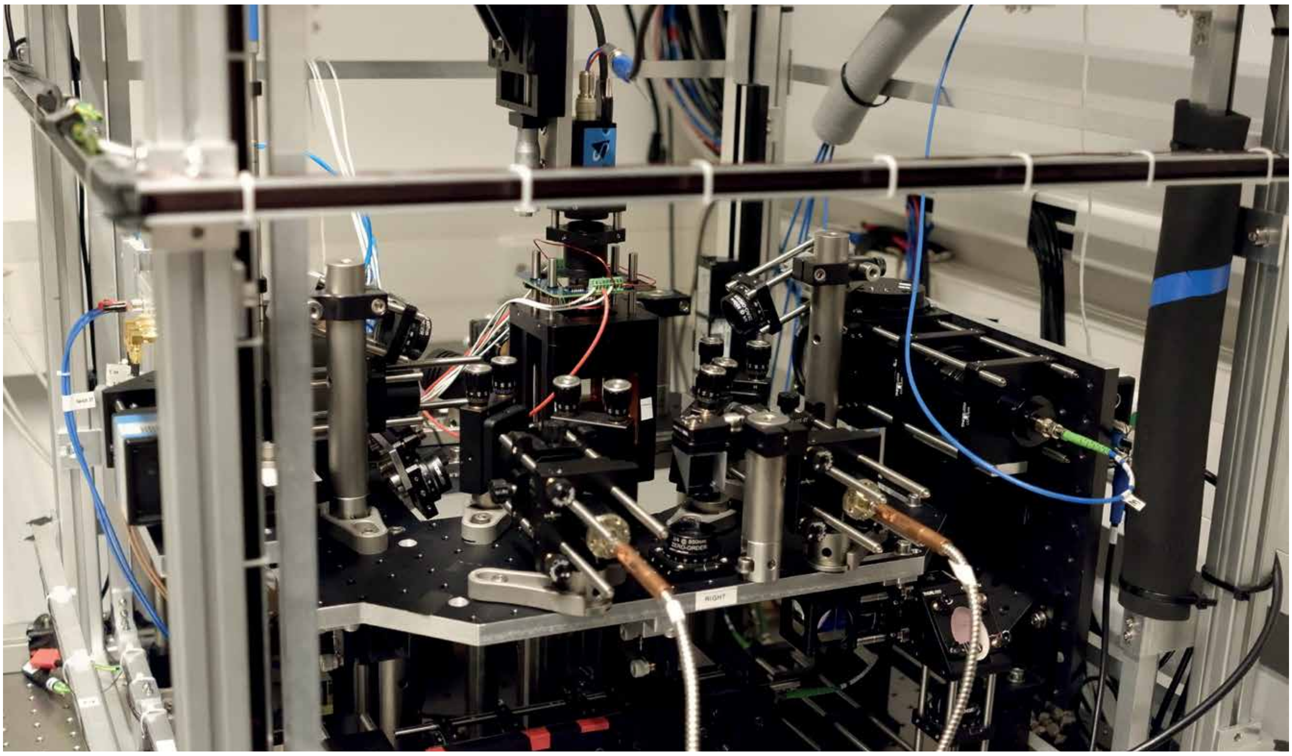
The relative phase depends on the variations of the conditions they may experience along each path – for reasons ranging from differences in the materials they travel through, to gravitational waves passing through them.

On recombination, therefore, they will interfere with each other to varying degrees, depending on how out of phase they are. By measuring the extent to which recombined waves are modified compared to the original wave, researchers can precisely measure the extent to which the phases of each beam have been shifted.

So far, this technique has been used for purposes ranging from measurements of optical components, to detections of gravitational waves originating from black hole mergers. However, Dr Stephanie Manz and Dr Thorsten Schumm at TU Vienna believe that interferometers are still a long way from fulfilling their potential.

Beyond Photonic Interferometry

As physicists began to discover around the turn of the 20th century, the description of light as a wave cannot explain all of its observed properties. In order to account for these phenomena, researchers including Einstein proposed that it must also exist in the form of massless particles, now known as 'photons'.



At the same time, this theory suggested that massive particles – and even composite particles such as atoms – must also have wave-like properties. In perhaps the most famous example, the electron double slit experiment gives clear evidence that the diffraction patterns produced by single electrons can interfere with each other: a strictly wave-like trait. Such properties are characterised by particle 'wavefunctions', which describe the probability of a particle being found in a particular position when observed.

In their earlier research, published in 2005 and 2013, Dr Schumm and colleagues created the key elements of an interferometer in which light beams could be replaced with matter waves. Just like light waves, they demonstrated, particle wavefunctions should also be able to split and recombine. In this case, a phase difference in the recombining wavefunctions could be converted into a number difference in the 'double-well' potentials trapping the atoms – essentially moveable W-shaped containers with magnetic field walls. Ultimately, this meant that phase differences could be easily read out.

Since massive particles are extremely sensitive to forces acting on them on atomic scales, the researchers concluded that this technique would make matter wave interferometers an order of magnitude more sensitive than their traditional optical counterparts.

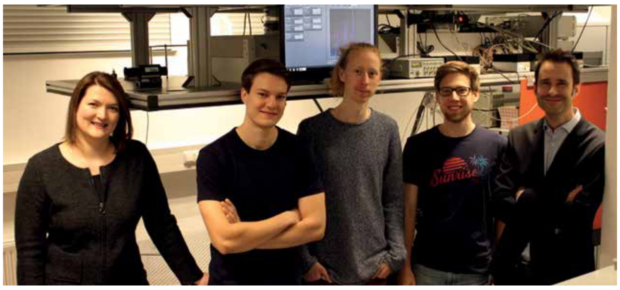
As Dr Manz describes, there is a key further distinction, relating to the controllability of matter wave interferometers. 'There is a fundamental difference between photon and atom optics,' she says. 'While photons do not interact, atom-atom interactions lead to an intrinsic non-linearity in the matter-wave dynamics. As these interactions can in principle be controlled, this adds a powerful degree of freedom to explore new physics regimes, fundamentally inaccessible to photon optics.'

Enlisting Bose-Einstein Condensate Sources

The first hurdle that Drs Manz and Schumm would need to overcome in realising matter wave interferometry would be the fact that compared to photons, massive particles are affected by gravity – just as a bullet speeding across a field must eventually hit the ground. While 'ballistic' interferometers, in which the motions of massive atoms have a vertical component, have been very successful over the last 20 years, their operation time is severely limited by factors including the size of the device, and the thermal expansion of the atomic clouds.

As an alternative approach, the duo proposes the use of trapped 'Bose-Einstein condensates' (BECs), which are ultracold gases of atoms that mostly have the same quantum properties, in close analogy to a photon laser.

BECs are remarkably useful in physics, since the wavefunctions of individual atoms can be trapped or confined in free space using optical or magnetic fields, making them measurable on macroscopic scales. For Drs Manz and Schumm, this means that keeping the atoms trapped as compared to experiments in free fall, allows for far longer operation times. Furthermore, by deforming the potentials used to confine the atoms, the researchers could split and recombine their wavefunctions with high degrees of control, finally realising a matter wave interferometer.



Studies of this technique have dominated the team's latest research. 'Our group and others are working towards understanding how the physical properties of ultracold quantum gases have to be prepared and controlled in order to enhance their metrological gain,' Dr Schumm explains. 'The aim of this project is to establish matter-wave optics with tuneable atom interactions to realise a new class of experiments that go beyond the photon analogy.'

Problems with Phase Diffusion

Despite the numerous advantages, Dr Schumm and his colleagues identified a problem with the use of BECs in their earlier research, which arises from the interactions of the atoms among themselves. Although the initial conditions of the gases could be precisely tuned, the researchers had very little control over how its individual atoms behaved during experiments, most importantly during splitting and recombining. 'The overarching problem with current BEC interferometers is that they are built from atoms with fixed, usually repulsive interactions,' describes Dr Manz. 'This leads to fundamental phase diffusion, severely limiting the operation time of the interferometer.'

If this issue can't be solved, the entire approach would offer no improvement over previous devices, entirely defeating the point of using BECs in the first place. To overcome this next roadblock, Dr Manz and Dr Schumm aim to implement new techniques to control the interactions of individual atoms during the interferometer sequence. This will involve changing the composition of the BEC itself – from the rubidium atoms used in their previous experiments, with another, better-suited element.

Conceiving the iWave

Unlike the case for rubidium, interactions between atoms of caesium can be tuned using relatively weak magnetic fields. By trapping caesium BECs within optical double-well potentials, the researchers could ensure that the gases became trapped for seconds, avoiding the diffusion that had hindered their previous efforts. 'We will aim at the realisation of matter-wave optics using caesium atoms, where atom interactions can be dynamically adjusted,' Dr Manz continues. 'This should allow us to extend the interferometer operation time beyond what is accessible in other approaches and reach new regimes of sensitivity.'

The researchers would require a reliable new platform to implement this upgrade. They now intend for this to take the form of a highly compact, easily tuneable micro-fabricated chip – dubbed the 'iWave'. 'Our trusted workhorse for this endeavour is a so-called atomchip,' says Dr Schumm. 'Such chips provide tight magnetic trapping configurations and allow for near field manipulation with radiofrequency and microwave fields, and allow for close optical access for trapping and imaging with laser techniques.'

Although this setup has yet to be realised, Drs Manz and Schumm are already envisaging the new experiments that iWave will enable, through the ongoing control of caesium BECs during interferometry.

Measuring Gravity's Variation

One particular application the researchers envisage for iWave is a fundamental test of the Earth's gravitational field. Although we perceive the force of gravity as being uniform no matter where we stand on Earth's surface, this isn't strictly true. In reality, a wide variety of structures and mechanisms will vary the force in ways too subtle for our bodies to perceive, including mountains, ocean tides, and a slightly bulging equator. Drs Manz and Schumm hope that their device will one day allow researchers to probe these variations in unprecedented levels of detail, once it has been implemented onto their proposed 'tiltmeter'.

'The setup we propose is designed to measure feeble tilts of the direction of gravitational acceleration,' Dr Schumm explains. 'The plumb line of gravity exhibits interesting dynamics on daily timescales due to tides, celestial mechanics, processes of the Earth's interior and several others. We are working towards a local probe of gravitational gradients and forces, which implies keeping the setup as compact as possible, and at the same time being ridged enough to be tilted and rotated during a measurement campaign.'

Once completed, Drs Manz and Schumm predict that iWave will be so accurate that it will enable them to detect tidal deformations of the Earth's crust from the comfort of their lab in Vienna.

New Possibilities

The influence of quantum mechanics is now becoming spread across an increasingly diverse range of fields in physics. Now, thanks to the research of Dr Manz and Dr Schumm, this could soon extend to interferometry. If fully realised, the iWave will be able to pick up phase differences between split beams 10 times more precisely than conventional, light-based devices. The team will now continue working towards this goal in earnest, and could soon enable the most intricate ever analyses of the Earth's gravitational field to take place in the coming years.

Meet the researchers

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Dr Stephanie Manz achieved her PhD in Physics at Vienna University of Technology in 2010. She then went on to work as a postdoctoral fellow at institutions including the Max Planck Institute for the Structure and Dynamics of Matter in Hamburg, where she became a group leader in 2016. She returned to TU Vienna in 2017 as an assistant postdoc. Dr Manz's main research interests include quantum and matter wave optics, ultracold atom physics, electron diffraction, and the imaging of biological samples.

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Dr Thorsten Schumm completed his PhD in Physics at Paris-Sud University in 2006. He then worked as an Assistant Professor at Vienna University of Technology's Institute of Atomic and Subatomic Physics, before becoming the leader of the Quantum Metrology group in 2011. His broader research interests involve using the effects of quantum mechanics to construct high precision measurement devices and sensors. Through his research, Dr Schumm aims to realise devices including atomic clocks, matter-wave interferometers, and precision lasers.

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FURTHER READING

T Schumm, S Hofferberth, LM Andersson, S Wildermuth, S Groth, I Bar-Joseph, J Schmiedmayer, and P Krüger, Matter-wave interferometry in a double well on an atom chip, Nature Physics, 2005, 1, 57.

T Berrada, S van Frank, R. Bücker, T Schumm, JF Schaff, and J Schmiedmayer, Integrated Mach–Zehnder interferometer for Bose–Einstein condensates, Nature Communications, 2013, 4, 2077.

K Bongs, M Holynski, J Vovrosh, P Bouyer, G Condon, E Rasel, C Schubert, WP Schleich, and A Roura, Taking atom interferometric quantum sensors from the laboratory to real-world applications, Nature Reviews Physics, 2019, 1, 731.

T Berrada, S van Frank, R Bücker, T Schumm, J-F Schaff, J Schmiedmayer, B Julía-Díaz, and A Polls, Matter-wave recombiners for trapped Bose-Einstein condensates, Physical Review A, 2016, 93, 063620.