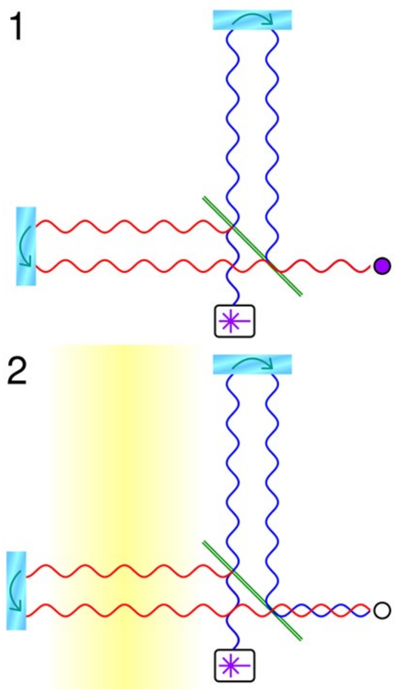
Removing thermal noise from optical interferometry

Thermal noise presents a significant challenge for many cutting-edge physics experiments, often preventing researchers from gaining accurate measurements of sub-atomic features. Through a new, statistics-based approach, Dr Johannes Dickmann at the Technical University of Braunschweig, Germany, shows how the fluctuations introduced by thermal noise could be predicted and removed. In a series of studies, he has applied his method to a variety of experimental scenarios involving optical interferometry. The approach could soon aid these experiments in detecting and studying a variety of key physical phenomena: including the gravitational waves which permeate our universe.

Using optical interferometry, researchers can now measure changes to physical systems which occur on scales smaller than the widths of single atoms. The technique works by first splitting a beam of light into two identical beams, which are each sent down separate paths, and reflected back to the beam splitter. Here, both parts are recombined back into a single beam.



Simplified diagram showing a gravitational wave observatory.

If the two beams experience different conditions on their separate journeys: whether they are temperature-induced changes to the media they are travelling through, or ripples in the very fabric of spacetime, their phases will become shifted relative to each other. This means that when they are recombined, the effects of optical interference will cause the beams to cancel each other out to varying degrees, depending on the size of the phase difference between them.

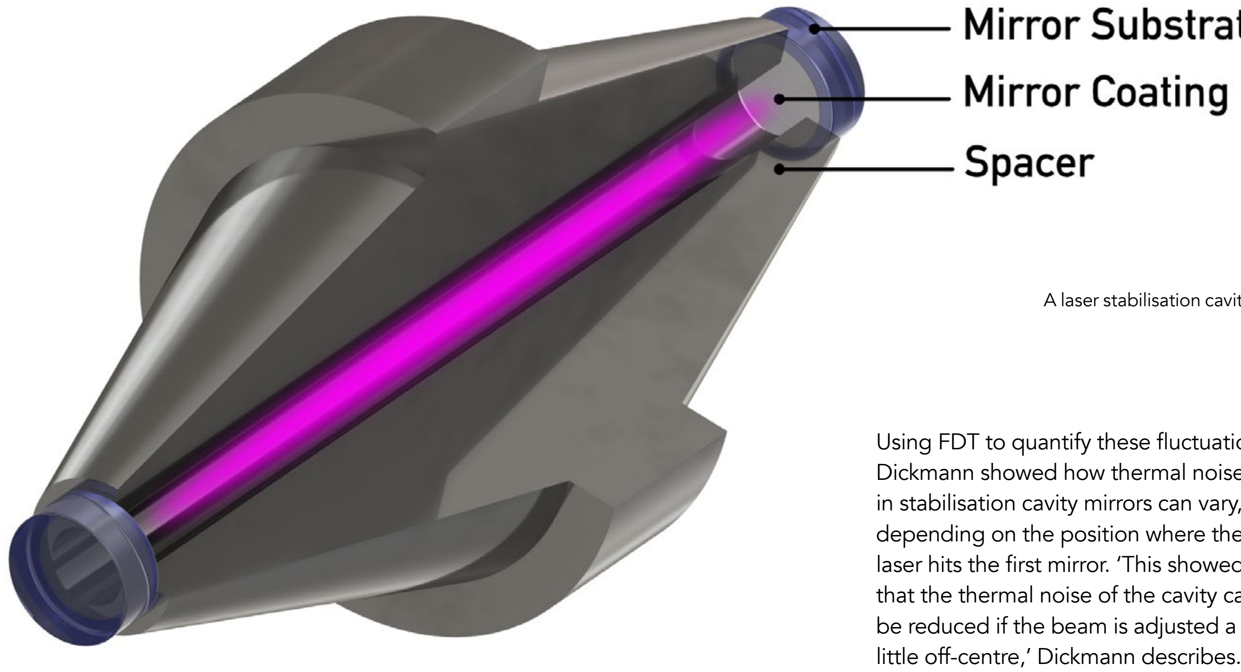
By measuring this interference, researchers can now determine any differences between the lengths of their paths, down to sub-nanometre accuracy. As Dr Johannes Dickmann at the Technical University of Braunschweig, Germany, describes, 'the most precise measuring instruments of mankind are based on optical interferometry, with prominent examples including gravitational wave detectors and ultra-stable lasers.'

However, such extreme levels of precision present their own challenge. On such minuscule scales, the motions of atoms and molecules are measurably affected by random fluctuations in heat: an effect named 'thermal noise'. So far, this effect has placed a limit on the accuracy achievable with the optical elements used in modern experiments, as they interact with incoming light beams.

CALCULATING THERMAL NOISE

To address this challenge, Dickmann has developed a new technique based on the principles of the 'fluctuation-dissipation theorem' (FDT). This powerful statistical tool is applicable to physical systems whose motions can be broken down into elementary steps – namely, collisions between single atoms. If such a system is in equilibrium with its surrounding environment, any change in momentum experienced by one atom during a collision must be accompanied by an equal and opposite change in momentum by the other particle.

Given this condition, FDT allows researchers to predict the responses of a material on a molecular level, when subjected to external effects like an applied voltage, or a temperature difference. In this case, the approach enabled Dickmann to calculate the thermal noise which arises in the optical elements of an interferometer, when illuminated by a laser beam. 'This is achieved by introducing virtual force fields, which compensate for any kind of resistance to momentum changes within the optical element,' he explains.



A laser stabilisation cavity.

By recombining these beams, the device produces an interference pattern with extremely high resolution.

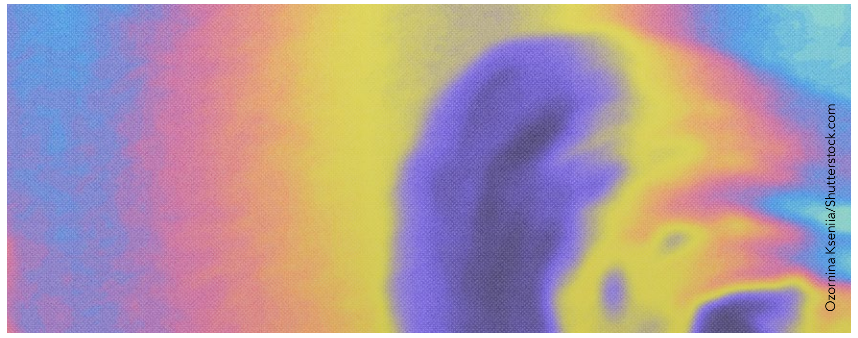
Calculated precisely using a set of differential equations, these force fields have enabled Dickmann to quantify the influence of thermal noise in a variety of optical interferometry scenarios, and remove it from experimental measurements. In his recent research, Dickmann has explored three applications for his method which could have particularly important implications in modern experimental physics.

IMPROVING STABILISATION CAVITIES

To ensure stability in the frequencies of their laser beams, researchers often use a type of interferometer named a 'laser stabilisation cavity'. This device features a pair of parallel, partially reflective mirrors, placed a small distance apart. This distance will exactly match the wavelength of light at one specific frequency – which is exclusively allowed to pass through the cavity.

As this light interacts with one of the mirrors while inside the cavity, part of it will be allowed to pass through. The rest will be reflected back to the other mirror, and subsequently back to the first – and the process repeats. This produces a series of beams passing through the first mirror with identical wavelengths, but with shifted phases.

By recombining these beams, the device produces an interference pattern with extremely high resolution, which can be used as a highly stable reference for the frequency of a laser. Through a feedback loop, this laser can adjust its frequency in real time to match that of the stabilisation cavity – allowing researchers to prevent any unwanted fluctuations. The problem with this approach is that the resolution of the cavity's interference pattern will itself be limited by thermal noise in its mirrors.



By adjusting the beam in the stabilisation cavity, thermal noise could be successfully reduced.

Using FDT to quantify these fluctuations, Dickmann showed how thermal noise in stabilisation cavity mirrors can vary, depending on the position where the laser hits the first mirror. 'This showed that the thermal noise of the cavity can be reduced if the beam is adjusted a little off-centre,' Dickmann describes. 'The efficiency of the reduction depends largely on the mirror thickness.'

NANOSTRUCTURED MIRRORS

In a further study, Dickmann investigated how noise could be reduced in sophisticated mirror designs, featuring nanostructured layers of reflective coatings. Here, any beam which passes through one structure will be mostly reflected by the structures next to it. As the incoming light is reflected, the parts of the beam reflected by each separate structure will interfere – reconstructing the original beam almost entirely.

Again using FDT, Dickmann showed that the amount of thermal noise associated with this setup doesn't necessarily depend on the thickness of the mirror's coatings, as some previous studies had suggested. A more important factor is the choice of material used in the coatings – which vary the degree to which light is refracted as it passes through. 'This study shows

A nanostructured mirror.

that mirror noise can be reduced by several orders of magnitude when silicon or diamond is used as the material,' Dickmann summarises.

GRAVITATIONAL WAVE DETECTORS

In his final study, Dickmann explored the potential for reducing thermal noise in one of the newest, most exciting branches of observational physics: the search for gravitational waves. First detected in 2015, the phenomena are created as pairs of black holes spiral into each other, and eventually merge together. These dramatic events generate ripples which stretch and squeeze the very structure of spacetime and go on to travel across cosmic distances.

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To detect these ripples, physicists have built a global network of giant optical interferometers, in which both parts of a split laser beam travel down perpendicular paths with identical, kilometre-scale lengths. If a gravitational wave passes through the interferometer, it will alter the length of one of these paths relative to the other – generating a phase shift between the two beams, which will show up in the resulting interference pattern.

Despite the immense size of this set-up, its optical elements are required to detect changes in length just fractions of the width of a single atom – making it particularly crucial to eliminate any thermal noise as thoroughly as possible. For the first time, Dickmann has used FDT to assess the influence of thermal noise on one particularly crucial element of these interferometers.

'In gravitational wave detectors, the beam splitter is the heart of the gravitational wave interferometer,' he describes. 'This is the first calculation of how much the beam splitter affects the sensitivity of the detector. It turns out that it must be considered from a sensitivity of 10^{-26}.' This level of sensitivity is so extreme, it would be comparable with the ability to detect a single water molecule being added to a full bucket.

By drawing from this important insight, Dickmann hopes that physicists will be able to improve the sensitivity of existing gravitational wave experiments. If achieved, this could allow them to pick up more subtle ripples – produced by smaller black holes, and potentially cosmological events that took place directly after the Big Bang.

ANSWERING FUNDAMENTAL QUESTIONS

More broadly, Dickmann is hopeful that his approach to identifying and eliminating thermal noise will present new opportunities in a wide array of cutting-edge physics experiments. 'It will open up new applications and possibly allow questions of fundamental research to be investigated experimentally, such as quantum relativity or dark matter.' With such a powerful tool, researchers could soon be better placed than ever to answer some of the most pressing questions to date about the nature of our universe.

Behind the Research

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Research Objectives

Dr Johannes Dickmann is working to predict and remove thermal noise from the process of optical interferometry.

Detail

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Bio

Dr Johannes Dickmann is currently scientist at the Laboratory for Emerging Nanometrology, a joint institution of the TU Braunschweig and the PTB (National Metrology Institute). He is investigating novel nanostructured surfaces for use in ultra-stable lasers and next-generation gravitational wave detectors from both theoretical and experimental perspectives.

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Personal Response

What are some of the main implications of your work for gravitational wave research?

" With the help of the new calculation method, it has become possible to optimise all components of the gravitational wave detectors. This allows the optics of the new detectors to be perfectly matched, further increasing the sensitivity of the systems. The hope is to measure the most primordial existing gravitational waves with these new detectors. Perhaps we will then understand how our universe was born and how it continues to evolve on cosmic scales. "