Towards the Standard Quantum Limit in a Table-Top Interferometer

Jiří Smetana,[1] Denis Martynov[1]

[1] School of Physics and Astronomy and Institute for Gravitational Wave Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

March 30, 2020

Abstract

We discuss the development and expected performance of a table-top experiment for measuring quantum fluctuations in a suspended-test-mass interferometer. The ultimate goal of this experiment is to perform measurements of the quantum noise-limited displacement sensitivity of the interferometer at the level of the standard quantum limit (5×10^{-19} m/$\sqrt{\text{Hz}}$ at 100 Hz). The case is made for an experiment that will show the feasibility of preparing a macroscopic quantum-limited system within a regular laboratory environment. This will be achieved by suspending a cryogenically cooled, high-finesse, optical cavity via a multi-stage suspension. We motivate the utility of our experiment in providing an increased understanding of the nature of quantum fluctuations in current and future gravitational wave detectors, as well as opening an avenue for research into aspects of macroscopic quantum mechanics and quantum gravity. We explain how these requirements drove our design specification. Given the extremely small displacements in question, particular attention is devoted to discussing noise mitigation, with a focus on the suppression of seismic and thermal noise.

DOI: 10.5281/zenodo.3561043

Introduction

The standard quantum limit (SQL) is an elusive target in the field of fundamental quantum mechanics and a soon-to-be formidable obstacle in fields of precision measurement such as gravitational wave (GW) detection. It is our goal to make the first measurements of the SQL in a 'table-top' experiment and enhance our understanding of the behaviour of macroscopic quantum systems. This paper describes the motivation and design of this experiment, with a particular focus on the mitigation of noise sources, including the novel use of silicon test-masses.

Precision measurements are concerned with the detection of very weak signals. In these applications, the primary concern is often the reduction of noise sources, which can very easily overpower the signal. Many state-of-the-art instruments used in the precise measurement of displacements use interferometric read-out, which utilises the interference of laser beams to obtain a very sharp response on scales smaller than the size of an atom. Continued improvements in noise reduction mean that the field of precision measurement has reached the quantum frontier. It is not often that we observe the effects of quantum uncertainty in a macroscopic system. However, at the level of precision attainable with current instruments, the quantum fluctuations on the microscopic scale begin to compete with the measured signals.

Our ability to suppress many noise sources, such as thermal noise and seismic noise, is quite extensive. However, the effects of quantum uncertainty upon measurements (collectively termed quantum noise) provide an imposing limit to the sensitivity of instruments. The theory surrounding the origins of quantum noise in interferometric devices has been extensively studied [1, 2, 3], leading to the development of the so-called standard quantum limit (SQL): a strong limitation on precision enforced by the quantum nature of light.

The current pinnacle of precision measurement has been attained by gravitational wave (GW) detectors. The *Advanced LIGO* detectors [4]—amongst the current leaders in GW detection—have reached a strain sensitivity of 4×10^{-24} $\mathrm{Hz}^{-1/2}$ at their most sensitive frequency of around 100 Hz [5]. These detectors are already limited by quantum noise in the high-frequency region of their detection band [6] and it is likely that future generations of GW detectors will be able to surpass current performance to the point of reaching the SQL [7]. Techniques for exploiting quantum correlations to improve the sensitivity below the current quantum limit have already been explored by e.g. [8]. The use of squeezed vacuum states of light to reduce so-called shot noise has been experimentally verified and applied to great effect in increasing the detection rate of GW sources by the *Advanced Virgo* detector [9]. Furthermore, Südbeck et al. have recently demonstrated the use of Einstein-Podolsky-Rosen entanglement to tackle the low-frequency component of quantum noise [10]. Recent developments at the *Advanced LIGO* detectors have shown evidence of existing quantum correlations surpassing the SQL [11]. However, the quantum noise spectrum was inferred from a subtraction of the classical noise dominant over the frequency range of sub-SQL quantum noise. Despite these successes in the suppression of quantum noise, to date, a macroscopic, quantum-noise dominated system at the level of the SQL has not been realised.

In light of this focus on the GW community, much of the discussion below will be in relation to GW detectors and the measurement and noise suppression techniques they employ. Of particular interest to us will be the developments taking place at the *AEI* 10 m prototype facility [12]: the first large-scale facility designed to operate at the SQL in the future.

To appreciate the utility of our experiment, it is important to ask whether improvements beyond the SQL are of interest. In the context of GW detectors, the answer is a resounding 'yes'. Improving the sensitivity of the existing detectors will allow for the detection of merger events earlier, which will, in turn, allow for simultaneous observation of these events with telescopes detecting in the electromagnetic spectrum [13]. Furthermore, sensitivity gains at higher frequencies may enable measurements of the neutron star equation of state [14]—a result which could lead to profound advancements in many fields of physics. On a fundamental level, simply measuring the SQL will lead to tests of theories of macroscopic quantum mechanics, such as those explored by Chen [15]. A small-scale experiment operating at the SQL would provide a better platform than the few kilometre scale facilities, which already serve the purpose of GW detection.

Reaching the Standard Quantum Limit

In a broad sense, the quantum fluctuations that limit the precision of interferometers as tools of displacement measurement can be understood as the consequences of the Heisenberg uncertainty principle, applied to the laser light and its interaction with the test masses (mirrors). The quantum fluctuations (often referred to as quantum noise in reference to their undesirable presence in GW detectors), can be separated into two principle sources. These are the so-called shot noise and radiation pressure noise. A rigorous derivation can be found in the work by Kimble et al. [16]. However, a thorough discussion of the origin of these two phenomena will be omitted in the interests of brevity, as the final result of the full treatment should suffice for our purposes.

The quantum noise power spectral density (PSD) for a Fabry-Perot interferometer topology is given by [3]:

$$S_x(\Omega) = \left[\frac{1}{\kappa} + \kappa\right] \frac{S_{SQL}(\Omega)}{2}, \tag{1}$$

where κ is:

$$\kappa = \frac{\omega_0 T_1 P_c}{mL^2\Omega^2\left(\Omega^2 + \left(\frac{T_1 c}{4L}\right)^2\right)} \tag{2}$$

and

$$S_{SQL}(\Omega) = \frac{8\hbar}{m\Omega^2} \tag{3}$$

is the so-called standard quantum limit. For these equations, we have adopted the convention used in the derivation by Miao & Chen. [3]. Most of the quantities above retain their usual definitions and T_1 and P_c are the power transmissivity of the input test mass and circulating (intra-cavity) power respectively.

From Equations 1 and 2, it can be shown that the minimum quantum noise achievable is given by S_{SQL}, which occurs when $\kappa = 1$. This is the point where the radiation pressure noise, given by the term linear in κ, balances out with the inversely scaling shot noise. Due to the frequency dependence of κ, this minimum-uncertainty condition cannot be met for all frequencies simultaneously and thus we arrive at the common understanding of the SQL as a surface of minimum uncertainty, which places a lower bound on the quantum noise in the interferometer read-out. For a given detector configuration, the SQL will only be reached at one particular frequency. Figure 1 illustrates a representative quantum noise spectrum in amplitude (ASD), with the SQL frequency placed at 100 Hz. Through consideration of Equation 1 and Figure 1, we can see there are three qualitatively distinct regions of interest. The region below the SQL frequency, where the radiation pressure noise dominates, the region above the SQL frequency, where the shot noise dominates and the region at and around the SQL frequency, where both noise sources contribute significantly. A similar result was derived by Enomoto et al. for the quantum noise in the angular degree of freedom [17].

These quantum fluctuations cannot be easily revealed due to the usually dominant presence of other noise sources. The presence of coating thermal noise is a particular concern due to its significant contribution around the peak sensitivity of existing GW detectors [18, 19]. In light of this, our experiment will consist of a suspended optical cavity in the Fabry-Perot configuration, cryogenically cooled inside an evacuated cryostat chamber. The silicon test masses will be coated to a high reflectivity resulting in high cavity finesse. This should ensure the necessary low-noise operation required to reach the SQL but comes with many design and control challenges. Each of these decisions will be justified in due course.

Many of our design features will be familiar to those acquainted with current generation GW detector technology. However, a noteworthy departure is our choice of a Fabry-Perot topology as opposed to the Michelson topology ubiquitous in terrestrial GW detector designs. The quantum noise in a Michelson configuration has an almost identical form to Equation 1 and, in fact, the SQL surface is given precisely by Equation 3. Hence we can concern ourselves with the simpler and more compact Fabry-Perot topology without loss of insight into the nature of quantum noise in GW detectors.

The control of a suspended, high-finesse optical cavity is challenging and thus our first goal will be to **lock and control the cavity** for a substantial period of time. Whilst it may seem that this would be just one of the many necessary steps along the road to achieving the greater goals of the experiment, we anticipate that the difficulty of this task will deserve its special place as the first of three milestones along this road.

The remaining milestones will both be measurements of the quantum noise spectrum. Reaching a shot-noise dominated state would not constitute a particularly novel result given the current generation of GW detectors such as *Advanced LIGO* already operate at a shot-noise limited sensitivity [4]. The two remaining regions, however, provide a good illustration for our primary goals. Upon locking the cavity, we aim to **perform measurements of the radiation pressure noise** using a prototype suspension design. This would constitute the first measurement of the so-called quantum back-action effect in a suspended-test-mass interferometer (a recent measurement of quantum back-action has been performed in the kilohertz range using a cantilever experiment [20]). Ultimately, we aim to **measure the SQL sensitivity**, the far more challenging region, which will require the final, low-noise iteration of the suspension design. In this case we will be considering the use of a silicon substrate, which should further aid us in the reduction of the limiting thermal noise.

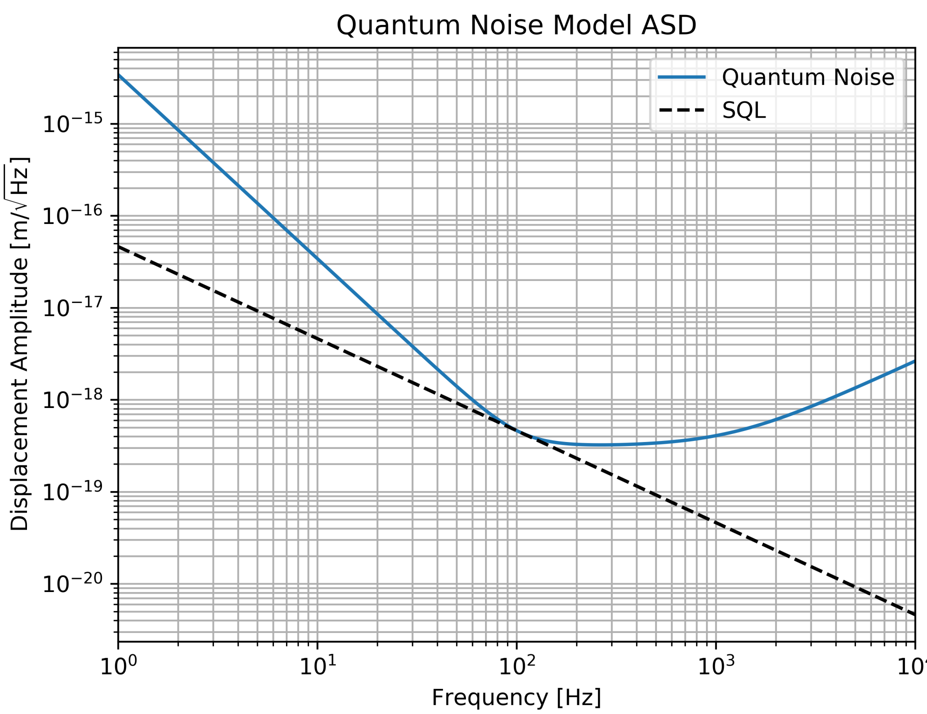

Figure 1: Model of quantum noise for a 10 cm Fabry-Perot cavity with 10 g mirrors of 10 ppm transmissivity. The SQL noise level is shown with the quantum noise curve intersecting at a frequency of 100 Hz.

Overview of Design and Initial Constraints

Unlike in the case of GW detectors and similar measurement devices, we are not trying to minimise the effects of quantum noise, which leads to a somewhat different set of requirements. However, much of the inspiration for our design comes directly from the decades of theoretical and experimental expertise that have culminated in the success of detectors such as *Advanced LIGO* [4] and *Advanced Virgo* [21]. Much inspiration has also been drawn from the designs of the *AEI* 10 m [12] prototype, which aims to operate at a quantum limited sensitivity much like our experiment and *KAGRA* [22], from which we can understand the challenges of cryogenic operation.

In order to reach the desired level of sensitivity and measure the behaviour of a quantum limited system at its SQL frequency, the optimised solution will have to take into account the constraints of space, practicality, material availability and cost. Furthermore, many of the aspects driving our design are intimately linked, such that we cannot simply consider the design decisions as leading from one to the other in a linear fashion.

Some considerations are, however, more limiting than others and are effectively immutable aspects of our design. This is best exemplified by the geometric constraints placed upon the experiment by our choice of cryostat. The maximum volume available for our suspension and cavity is constrained by the innermost cylindrical shield of the cryostat with dimensions of approximately 75 cm in height and 30 cm in diameter. It is clear from current GW detectors that thermal noise poses a substantial barrier to measurements of the SQL (see for example the *Advanced LIGO* noise spectrum [4]). As such, one of the first design requirements was to be able to cool the test masses down to cryogenic temperatures. The choice of available cryostats for this task is rather limited and thus this places a hard constraint on the space available for our experiment.

The need for some form of suspension is clear when we consider the seismic noise spectrum in comparison to the quantum noise level. Figure 2 shows the on-site seismic noise ASD in comparison to the expected quantum noise level. One existing solution would be to attach the mirrors to some rigid base plate, effectively making the transferred ground vibrations common to both mirrors. However, this defeats one of the primary aspects of our design, which is to measure the quantum fluctuations between 'free' masses. This is achievable for masses that have been suspended with resonances well below the frequencies of interest. Nonetheless, the loss of a rigid connection between the mirrors means that a effective seismic noise suppression system has to be designed to ensure that ground vibrations do not significantly transfer into the differential motion of the cavity.

The exact shape of the quantum noise spectrum is largely driven by our choice of mirrors and is also a primary concern, which we can discuss with little reference to the remainder of the design. The only variable within Equation 3 for the SQL curve is the mirror mass. This inverse scaling is favourable for our goals of a table-top experiment as a smaller mass both raises the level of the SQL and leads to a more compact experiment. We have chosen a mirror mass of approximately 10 g as a compromise between a desire for small mirrors and allowing for a feasible suspension design. The SQL frequency was chosen to be 100 Hz in reference to the frequency of peak sensitivity of *Advanced LIGO* [4]. This decision is motivated by the fact that we are constrained to approximately the same frequency range due to relatively similar limitations (e.g. suspension resonances at similar frequencies). In a more direct sense, we also wish to provide an analogous system to modern GW detectors as we expect these to be the primary beneficiaries of our results.

For the goal of measuring radiation pressure noise, we have chosen to use a high-finesse cavity. This will consist of mirrors with a power transmissivity of around 10 ppm, or a cavity finesse of approximately 10^5. High finesse leads to a higher build-up of circulating power inside the optical cavity for a given input power. A higher circulating power raises the level of the radiation pressure noise (see Equation 2), which is beneficial for our quantum back-action measurement. However, the high-finesse cavity will pose a substantial challenge in terms of control and locking and thus aspects of our design are significantly affected by this constraint. The cavity length is variable and will be chosen to achieve the highest level of stability. The cavity length can be tuned within a range of 5–15 cm.

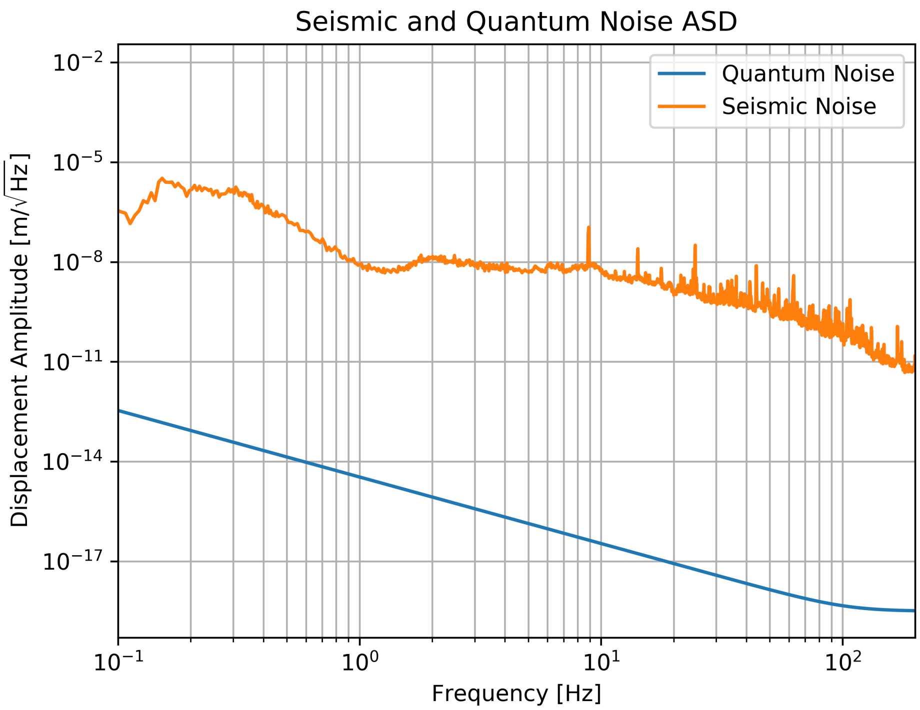

Figure 2: On-site seismic noise shown together with the expected quantum noise in the system. A suspension will be necessary to suppress the seismic noise by over 10 orders of magnitude in order to reveal the quantum noise.

Design Choices and Noise Suppression

The remaining design decisions were driven by a need to suppress the numerous noise sources that would otherwise obscure the weak quantum noise. The noise sources that have most shaped the design are seismic noise and thermal noise and thus deserve the most focus. The design will be discussed below one aspect or 'component' at a time. The low-noise suspension necessary for the SQL measurement will be an evolution of the prototype design that will serve at least as an initial proof of concept and we hope will be able to achieve the goal of measuring quantum back-action. In light of this, some components of the design will be discussed in terms of the prototype and the anticipated changes that will be made in the ultimate, low-noise design. A simplified diagram of the suspension inside the cryostat can be found in Figure 3.

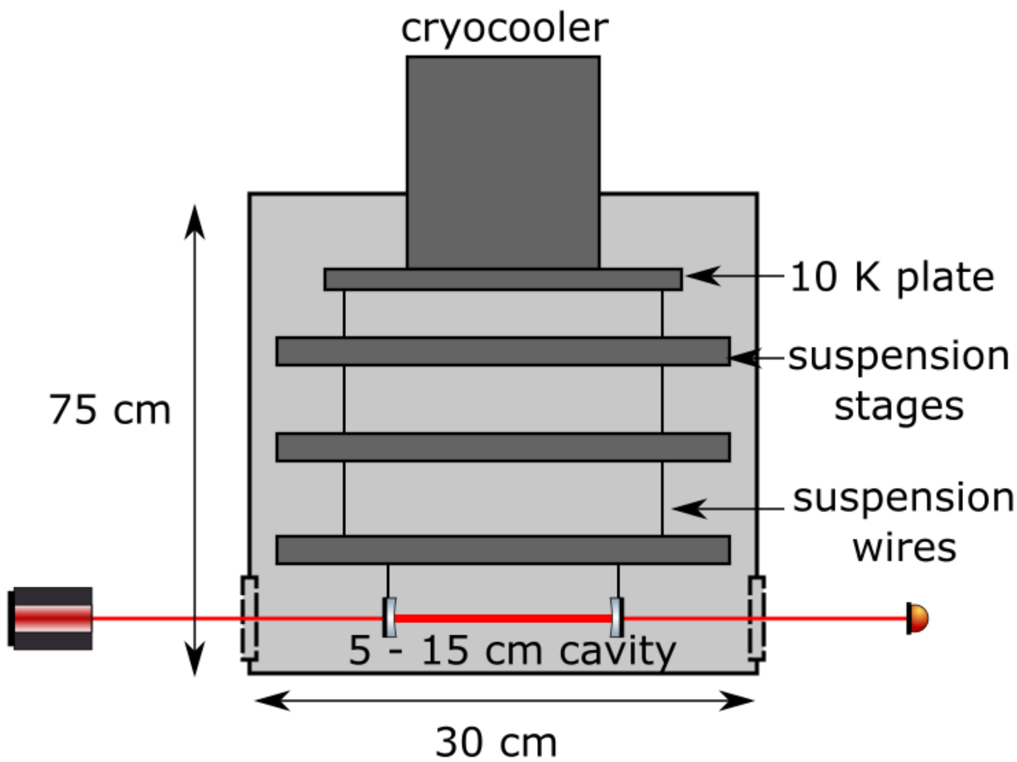

Figure 3: Diagram showing the simplified set-up of the suspended cavity inside the cryostat. The cryocooler at the top will cool the cold plate down to 10 K. The suspension will hang from this plate, providing cooling for the mirrors. Windows on the sides of the cryostat sleeve will provide entry and exit for the laser beam after treatment by out-of-vacuum optics (not pictured).

Active vs Passive Isolation

As has been shown in Figure 2, some form of seismic noise suppression is necessary. Broadly, the two possible avenues are through passive isolation in the form of a suspension or through active control. Contemporary large-scale interferometers use a mixture of the two. Examples of active isolation include the ISIs [23] at *Advanced LIGO* and the inertial control of the *Superattenuator* [24] at *Advanced Virgo*. Passive isolation is almost universally achieved by multi-stage pendulums, such as the quadruple suspension [25] of the *Advanced LIGO* test masses.

In our case, we considered passive isolation only and the added difficulty of introducing active control of the suspension was determined unnecessary. Furthermore, the current design avoids the need for in-vacuum sensors, actuators or any other form of electronics that would need to operate at cryogenic temperatures. Although out-of-vacuum seismometers for active isolation have been considered, this would require significant alternations to the stock cryostat design and thus will be avoided if possible.

Isolation Stages

The number of suspension stages was determined by considering the required level of seismic noise suppression at 100 Hz together with the feasible range of resonant frequencies (between 0.5 Hz and 5 Hz for the upper and lower limit of pendulum lengths reasonably achievable within the lab space available). IT is well-known that each stage of isolation adds an extra $1/\omega^2$ level of suppression above its resonance. Using straight-forward analysis of multiple pendulums, We can use the equation:

$$T_n(\omega) \approx \frac{G}{\omega^{2n}}, \tag{4}$$

where G is the product of the system's resonant frequencies, to determine the approximate number of stages necessary to achieve the desired level of suppression at 100 Hz. We find that 4 stages of isolation should be sufficient to reduce the seismic noise from the approximately 10^{-10} m/$\sqrt{\text{Hz}}$ at 100 Hz, as suggested by Figure 2, to below the 10^{-19} m/$\sqrt{\text{Hz}}$ required. An even larger number of stages is, in theory, beneficial as long as the resonances remain below the detection band. However, the design should be constrained to the smallest number of stages necessary as more stages will be more difficult to align and handle from a practical standpoint, as well as potentially leading to higher cross-couplings from other degrees of freedom. Figure 4 shows a model of the expected (damping-free) performance of the suspension.

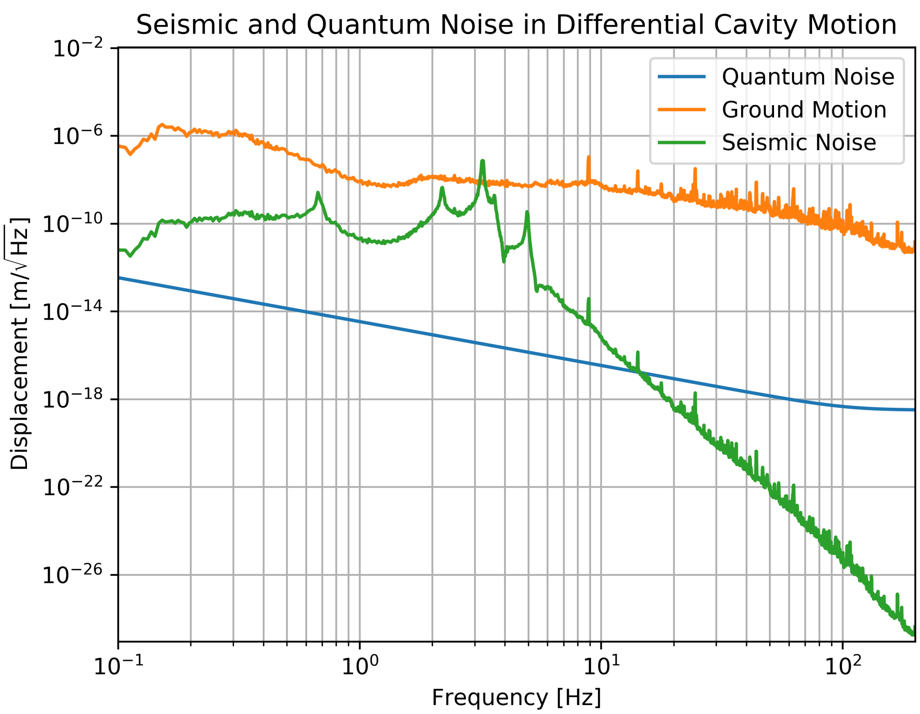

Figure 4: On-site ground motion and the expected seismic noise transferred to the cavity length measurement compared to the quantum noise model. The multi-stage suspension is shown to suppress the seismic noise sufficiently to reveal quantum fluctuations around the SQL frequency.

The masses at the ends of the pendulum suspension stages will be constructed from high-purity aluminium, which has two primary purposes. Aluminium exhibits very high conductivity of around 10^4 W m^{-1} K^{-1} for temperatures close to the expected 18 K operating point [26]. This high thermal conductivity will increase the efficiency of conductive cooling and thus lowering the cooling time. Furthermore, the low density of aluminium means we can ensure a lightweight construction. This is important for the efficiency of the damping of the mirror resonance, the significance of which is discussed below. The suspension stages will inevitably be substantially heavier than the 10 g mirrors, which reduces the efficiency of damping applied higher up in the suspension stack and any weight-reduction measures are beneficial.

Suspension Wires

The masses and mirrors will be suspended by wires. The prototype suspension will consist of tungsten wires as a compromise between high thermal conductivity and high strength. In the interests of low thermal noise and better seismic suppression (see references [27, 28] for discussion of suspension thermal noise), the wires should be as thin as possible. The range of diameters under consideration for tungsten is from 40 μm to 400 μm. However, this is in opposition to the requirements for a large cross-sectional area in order to cool the suspension efficiently. This is an important consideration as the cooling rate through the wires will be the bottleneck in the conductive cooling process. Aluminium was considered for this role due to its high thermal conductivity. However, the low yield stress of aluminium makes it unsuitable.

A later consideration will be a monolithic fused silica/silicon suspension for the final mirror stage. The excellent, low-noise performance of a silica fibre suspension is readily apparent in the final stage of the *Advanced LIGO* test mass suspension [29]. However, such an advanced design will not be considered for the prototype suspension, particularly because a monolithic suspension does not allow for easily changeable mirrors.

Differential Mode Suppression

The cavity mirrors will be suspended from a single penultimate stage. This allows us to retain some of the benefits of attaching the mirrors to a rigid base plate. In this sense, the idea is that all of the motion transferred to the penultimate stage will then be common to both mirrors and thus, in theory, there will be no coupling of seismic noise into differential cavity motion. In reality, however, the imperfect balancing of the two final mirror suspensions will lead to some residual coupling of noise into differential motion. The expected performance, shown in Figure 4 has been calculated for a target discrepancy of 1% between the properties of note such as the final wire lengths and mirror masses. The feasibility of this target will largely depend on manufacturing tolerances and homogeneity of materials.

Suspension Blades

Much of the design concerns the suppression of the direct horizontal-to-horizontal coupling of seismic motion. However, it is also necessary for us to also consider the suppression of vertical motion, due to its cross-coupling to horizontal motion. The vertical resonances of the suspension wires are mostly above the detection band and, therefore, very little vertical motion is filtered out from the lower suspension stages. To this end, we have designed suspension blades in much the same vein as those found in the upper stages of the *Advanced LIGO* quadruple suspension [25] and in general amongst most passive isolation systems for large-scale optics. The prototype blades may be machined from stainless steel due to its relatively low cost and familiarity in current GW detectors. However, stainless steel is a poor conductor of heat at cryogenic temperatures. Therefore, it is unlikely that this material will be used in the final, low-noise suspension design.

Mirror Substrate

The mirror substrates considered are silicon and silica. It is expected that both of these substrates will be used in the different iterations of our design and hence we require a laser that is appropriate for both materials. The choice of 1550 nm was quite natural given both substrates' good optical properties at this wavelength. The discussion of substrate can then be isolated to a discussion of thermal noise contributions at room temperature and at the desired cryogenic operation. A detailed description of substrate thermal noise can be found in references [30, 31, 32]. The key component of thermal noise that we are interested in is the so-called loss angle of the material—a measure of fraction of stored energy that is dissipated by the material due to thermal losses.

The loss angle of silica (predicted to be as little as 4×10^{-10} [33]) is promising for room temperature operation. However, this beneficial property does not persist at low temperatures, where a large peak in loss angle (rising to 10^{-3}) makes it unsuitable for use as a mirror substrate [34, 26]. Due to its availability and good room temperature properties, it remains the preferred candidate for the room temperature prototype suspension.

For cryogenic operation, silicon shows greater promise. The linear expansion coefficient of silicon passes through a zero at approximately 18 K [26]. The loss angle is predicted to scale with the square of this coefficient [35, 36], therefore the loss angle is likely to be very low. This special property of silicon is the primary motivating factor behind our choice of this exact temperature. The later, low-noise design will most likely incorporate silicon mirrors.

Passive Damping

The high level of seismic isolation at frequencies within and above the detection range comes at a price. The resulting seismic noise is amplified at and around the suspension resonances as seen in Figure 4. Whilst the location of these peaks is not a problem, their presence does raise the RMS cavity motion. Due to the high finesse of the cavity, the resulting error signal for control and locking will be very narrow and the cavity build-up time will be relatively long (0.2 ms). This has two major implications. Firstly, we must invest in a high bandwidth actuator. Secondly, it takes a long time to build up a clean error signal, which places a constraint on how quickly the cavity can swing through resonance such that the actuator can still acquire lock. For our configuration, we suspect that the maximum tolerable RMS velocity will be 40 nm s^{-1}. This relatively challenging constraint means that we will have to significantly damp the resonances of our suspension.

Continuing with our desire for no in-vacuum electronics, we have elected to implement passive, eddy current damping. This will inevitably lead to a $1/\omega$ loss of suppression, raising the seismic noise above resonances. This is the reason for the seemingly larger-than-necessary suppression shown in the damping-free model in Figure 4. The exact location of the eddy current damping is still under investigation there exists a compromise between more effective damping closer to the final mirror suspensions and the resulting increase in thermal noise.

Laser Actuation

As stressed above, a key aspect of the design is the avoidance of in-vacuum electronics. The lack of any active control or in-vacuum actuators means that the cavity will be left in a 'free-swinging' state. In order to lock the cavity, we will therefore actuate on the laser frequency rather than on the mirror positions. By controlling the carrier frequency of the laser to keep it on resonance with the constantly drifting cavity, we can achieve an analogous effect to actuating on the mirrors themselves but with all of the feedback sensors and actuators remaining at room temperature, out-of-vacuum and easily accessible.

Noise Budget and Conclusion

The prototype suspension is currently in the final stages of design with the aim of reaching the first two milestones of our experiment: locking the cavity and measuring quantum back-action. Figure 5 shows the noise budget for this initial design at room temperature. According to this noise budget, it is our expectation that these goals are within reach. However, it is clear that the quantum noise floor will be obscured by other noise sources in the prototype and thus measurements of quantum fluctuations around the SQL will be impossible.

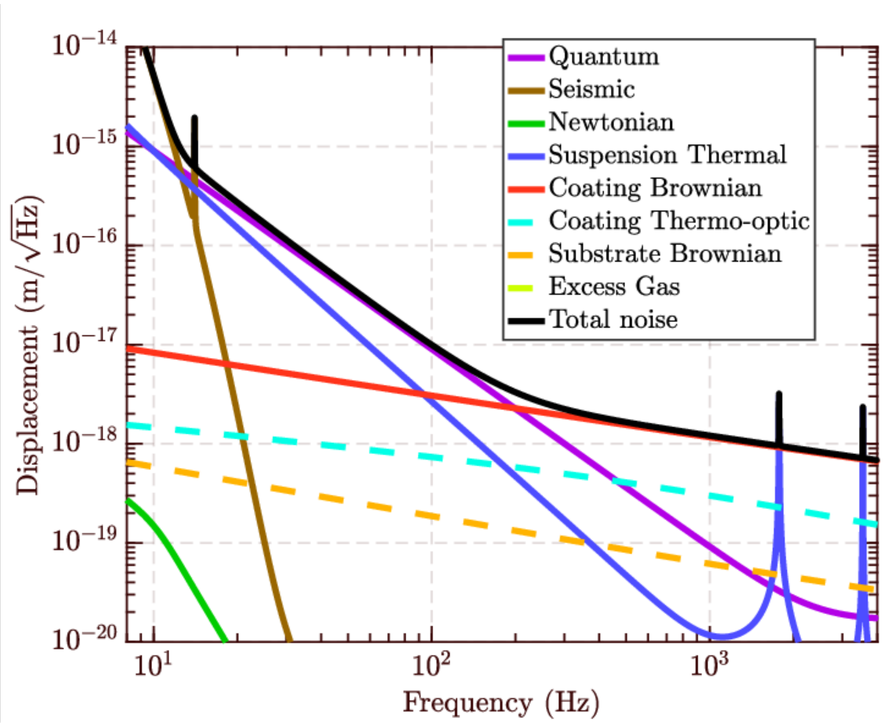

Figure 5: Noise budget for the room temperature prototype. It should be feasible to measure quantum back-action in the region around 100 Hz. In this case, the SQL frequency has been increased in order to boost the radiation pressure component of quantum noise at 100 Hz. The peak sensitivity (at SQL) will not be measurable at room temperature, however.

Currently, we have some planned improvements that will be implemented in the low-noise design, such as the use of silicon substrate. However, many of the design decisions are yet to be finalised. It is expected that the prototype run of the experiment will reveal many unforeseen challenges, both within the initial locking phase and when we attempt to cool the suspension down. Future reports will be able to give a more realistic estimate of the low-noise performance.

Conclusion

We have presented the motivation and development of a table-top experiment for measuring the quantum fluctuations in a suspended-test-mass interferometer. The two primary motivations are to provide enhanced understanding of the nature of quantum noise in terrestrial gravitational wave detectors and as a springboard for future experiments seeking to test theories of macroscopic quantum mechanics and quantum gravity.

The experiment consists of a cryogenically cooled, suspended Fabry-Perot interferometer with 10 g mirrors. The relatively compact nature of the experiment means that the design can be more easily reproduced and may lead to a greater availability of macroscopic quantum-limited systems for future fundamental research.

The experimental can be separated into three distinct milestones. The high finesse (10^5) of the cavity makes the locking and control of the cavity challenging and thus the first of these goals is to **achieve lock acquisition and control**. The next goal will be to **perform measurements of quantum back-action**, followed by the final goal of **measuring the peak sensitivity of the system at the so-called standard quantum limit (SQL)**.

The first two goals will be achieved with a prototype design, which has been the primary subject of discussion in this report. Upon successful implementation of the prototype, we will transition to a cryogenic, low-noise solution, operating at the required level of sensitivity to reach the SQL. Our principle concern with the future performance of this experiment is the presence of thermal noise, particularly that originating from the coating and the final stage of the suspension. This will therefore likely constitute the primary focus of future research and development.

References

[1] Kip S. Thorne. Gravitational radiation. In S. W. Hawking and W. Israel, editors, *Three hundred years of gravitation*, chapter 9, pages 330–458. Cambridge University Press, Cambridge, 1 edition, 1987.

[2] Alessandra Buonanno and Yanbei Chen. Quantum noise in second generation, signal-recycled laser interferometric gravitational-wave detectors. *Physical Review D*, 64(4):042006, 7 2001.

[3] H. Miao and Y. Chen. Quantum theory of laser interferometer gravitational wave detectors. In D. G. Blair, L. Ju, C. Zhao, and E. J. Howell, editors, *Advanced Gravitational Wave Detectors*, pages 277–297. Cambridge University Press, Cambridge, 2012.

[4] The LIGO Scientific Collaboration. Advanced LIGO. *Classical and Quantum Gravity*, 32(7):074001, 4 2015.

[5] M Tse, Haocun Yu, N Kijbunchoo, A Fernandez-Galiana, P Dupej, L Barsotti, C D Blair, D D Brown, S E Dwyer, A Effler, M Evans, P Fritschel, V V Frolov, A C Green, G L Mansell, F Matichard, N Mavalvala, D E McClelland, L McCuller, T McRae, J Miller, A Mullavey, E Oelker, I Y Phinney, D Sigg, B J J Slagmolen, T Vo, R L Ward, C Whittle, R Abbott, C Adams, R X Adhikari, A Ananyeva, S Appert, K Arai, J S Areeda, Y Asali, S M Aston, C Austin, A M Baer, M Ball, S W Ballmer, S Banagiri, D Barker, J Bartlett, B K Berger, J Betzwieser, D Bhattacharjee, G Billingsley, S Biscans, R M Blair, N Bode, P Booker, R Bork, A Bramley, A F Brooks, A Buikema, C Cahillane, K C Cannon, X Chen, A A Ciobanu, F Clara, S J Cooper, K R Corley, S T Countryman, P B Covas, D C Coyne, L E H Datrier, D Davis, C Di Fronzo, J C Driggers, T Etzel, T M Evans, J Feicht, P Fulda, M Fyffe, J A Giaime, K D Giardina, P Godwin, E Goetz, S Gras, C Gray, R Gray, Anchal Gupta, E K Gustafson, R Gustafson, J Hanks, J Hanson, T Hardwick, R K Hasskew, M C Heintze, A F Helmling-Cornell, N A Holland, J D Jones, S Kandhasamy, S Karki, M Kasprzack, K Kawabe, P J King, J S Kissel, Rahul Kumar, M Landry, B B Lane, B Lantz, M Laxen, Y K Lecoeuche, J Leviton, J Liu, M Lormand, A P

Lundgren, R Macas, M MacInnis, D M Macleod, S Márka, Z Márka, D V Martynov, K Mason, T J Massinger, R McCarthy, S McCormick, J McIver, G Mendell, K Merfeld, E L Merilh, F Meylahn, T Mistry, R Mittleman, G Moreno, C M Mow-Lowry, S Mozzon, T J N Nelson, P Nguyen, L K Nuttall, J Oberling, R J Oram, B O'Reilly, C Osthelder, D J Ottaway, H Overmier, J R Palamos, W Parker, E Payne, A Pele, C J Perez, M Pirello, H Radkins, K E Ramirez, J W Richardson, K Riles, N A Robertson, J G Rollins, C L Romel, J H Romie, M P Ross, K Ryan, T Sadecki, E J Sanchez, L E Sanchez, T R Saravanan, R L Savage, D Schaetzl, R Schnabel, R M S Schofield, E Schwartz, D Sellers, T J Shaffer, J R Smith, S Soni, B Sorazu, A P Spencer, K A Strain, L Sun, M J Szczepa\ifmmode \acuten\else ń\ficzyk, M Thomas, P Thomas, K A Thorne, K Toland, C I Torrie, G Traylor, A L Urban, G Vajente, G Valdes, D C Vander-Hyde, P J Veitch, K Venkateswara, G Venugopalan, A D Viets, C Vorvick, M Wade, J Warner, B Weaver, R Weiss, B Willke, C C Wipf, L Xiao, H Yamamoto, M J Yap, Hang Yu, L Zhang, M E Zucker, and J Zweizig. Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy. *Phys. Rev. Lett.*, 123(23):231107, 12 2019.

[6] D. V. Martynov, E. D. Hall, B. P. Abbott, R. Abbott, T. D. Abbott, C. Adams, R. X. Adhikari, R. A. Anderson, S. B. Anderson, K. Arai, M. A. Arain, S. M. Aston, L. Austin, S. W. Ballmer, M. Barbet, D. Barker, B. Barr, L. Barsotti, J. Bartlett, M. A. Barton, I. Bartos, J. C. Batch, A. S. Bell, I. Belopolski, J. Bergman, J. Betzwieser, G. Billingsley, J. Birch, S. Biscans, C. Biwer, E. Black, C. D. Blair, C. Bogan, R. Bork, D. O. Bridges, A. F. Brooks, C. Celerier, G. Ciani, F. Clara, D. Cook, S. T. Countryman, M. J. Cowart, D. C. Coyne, A. Cumming, L. Cunningham, M. Damjanic, R. Dannenberg, K. Danzmann, C. F.Da Silva Costa, E. J. Daw, D. Debra, R. T. Derosa, R. Desalvo, K. L. Dooley, S. Doravari, J. C. Driggers, S. E. Dwyer, A. Effler, T. Etzel, M. Evans, T. M. Evans, M. Factourovich, H. Fair, D. Feldbaum, R. P. Fisher, S. Foley, M. Frede, P. Fritschel, V. V. Frolov, P. Fulda, M. Fyffe, V. Galdi, J. A. Giaime, K. D. Giardina, J. R. Gleason, R. Goetz, S. Gras, C. Gray, R. J.S. Greenhalgh, H. Grote, C. J. Guido, K. E. Gushwa, E. K. Gustafson, R. Gustafson, G. Hammond, J. Hanks, J. Hanson, T. Hardwick, G. M. Harry, J. Heefner, M. C. Heintze, A. W. Heptonstall, D. Hoak, J. Hough, A. Ivanov, K. Izumi, M. Jacobson, E. James, R. Jones, S. Kandhasamy, S. Karki, M. Kasprzack, S. Kaufer, K. Kawabe, W. Kells, N. Kijbunchoo, E. J. King, P. J. King, D. L. Kinzel, J. S. Kissel, K. Kokeyama, W. Z. Korth, G. Kuehn, P. Kwee, M. Landry, B. Lantz, A. Le Roux, B. M. Levine, J. B. Lewis, V. Lhuillier, N. A. Lockerbie, M. Lormand, M. J. Lubinski, A. P. Lundgren, T. Macdonald, M. Macinnis, D. M. Macleod, M. Mageswaran, K. Mailand, S. Márka, Z. Márka, A. S. Markosyan, E. Maros, I. W. Martin, R. M. Martin, J. N. Marx, K. Mason, T. J. Massinger, F. Matichard, N. Mavalvala, R. McCarthy, D. E. McClelland, S. McCormick, G. McIntyre, J. McIver, E. L. Merilh, M. S. Meyer, P. M. Meyers, J. Miller, R. Mittleman, G. Moreno, C. L. Mueller, G. Mueller, A. Mullavey, J. Munch, L. K. Nuttall, J. Oberling, J. O'Dell, P. Oppermann, Richard J. Oram, B. O'Reilly, C. Osthelder, D. J. Ottaway, H. Overmier, J. R. Palamos, H. R. Paris, W. Parker, Z. Patrick, A. Pele, S. Penn, M. Phelps, M. Pickenpack, V. Pierro, I. Pinto, J. Poeld, M. Principe, L. Prokhorov, O. Puncken, V. Quetschke, E. A. Quintero, F. J. Raab, H. Radkins, P. Raffai, C. R. Ramet, C. M. Reed, S. Reid, D. H. Reitze, N. A. Robertson, J. G. Rollins, V. J. Roma, J. H. Romie, S. Rowan, K. Ryan, T. Sadecki, E. J. Sanchez, V. Sandberg, V. Sannibale, R. L. Savage, R. M.S. Schofield, B. Schultz, P. Schwinberg, D. Sellers, A. Sevigny, D. A. Shaddock, Z. Shao, B. Shapiro, P. Shawhan, D. H. Shoemaker, D. Sigg, B. J.J. Slagmolen, J. R. Smith, M. R. Smith, N. D. Smith-Lefebvre, B. Sorazu, A. Staley, A. J. Stein, A. Stochino, K. A. Strain, R. Taylor,

M. Thomas, P. Thomas, K. A. Thorne, E. Thrane, C. I. Torrie, G. Traylor, G. Vajente, G. Valdes, A. A. Van Veggel, M. Vargas, A. Vecchio, P. J. Veitch, K. Venkateswara, T. Vo, C. Vorvick, S. J. Waldman, M. Walker, R. L. Ward, J. Warner, B. Weaver, R. Weiss, T. Welborn, P. Weßels, C. Wilkinson, P. A. Willems, L. Williams, B. Willke, L. Winkelmann, C. C. Wipf, J. Worden, G. Wu, H. Yamamoto, C. C. Yancey, H. Yu, L. Zhang, M. E. Zucker, and J. Zweizig. Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy. *Physical Review D*, 2016.

[7] The LIGO Scientific Collaboration and J Harms. Exploring the sensitivity of next generation gravitational wave detectors. *Classical and Quantum Gravity*, 34(4):44001, 1 2017.

[8] Christopher Wipf. *Toward quantum opto-mechanics in a gram-scale suspended mirror interferometer*. PhD thesis, Massachusetts Institute of Technology, 2013.

[9] F Acernese, M Agathos, L Aiello, A Allocca, A Amato, S Ansoldi, S Antier, M Arène, N Arnaud, S Ascenzi, P Astone, F Aubin, S Babak, P Bacon, F Badaracco, M K M Bader, J Baird, F Baldaccini, G Ballardin, G Baltus, C Barbieri, P Barneo, F Barone, M Barsuglia, D Barta, A Basti, M Bawaj, M Bazzan, M Bejger, I Belahcene, S Bernuzzi, D Bersanetti, A Bertolini, M Bischi, M Bitossi, M A Bizouard, F Bobba, M Boer, G Bogaert, F Bondu, R Bonnand, B A Boom, V Boschi, Y Bouffanais, A Bozzi, C Bradaschia, M Branchesi, M Breschi, T Briant, F Brighenti, A Brillet, J Brooks, G Bruno, T Bulik, H J Bulten, D Buskulic, G Cagnoli, E Calloni, M Canepa, G Carapella, F Carbognani, G Carullo, J Casanueva Diaz, C Casentini, J Castañeda, S Caudill, F Cavalier, R Cavalieri, G Cella, P Cerdá-Durán, E Cesarini, O Chaibi, E Chassande-Mottin, F Chiadini, R Chierici, A Chincarini, A Chiummo, N Christensen, S Chua, G Ciani, P Ciecielag, M Cie\ifmmode \acutes\else ś\filar, R Ciolfi, F Cipriano, A Cirone, S Clesse, F Cleva, E Coccia, P.-F. Cohadon, D Cohen, M Colpi, L Conti, I Cordero-Carrión, S Corezzi, D Corre, S Cortese, J.-P. Coulon, M Croquette, J.-R. Cudell, E Cuoco, M Curylo, B D'Angelo, S D'Antonio, V Dattilo, M Davier, J Degallaix, M De Laurentis, S Deléglise, W Del Pozzo, R De Pietri, R De Rosa, C De Rossi, T Dietrich, L Di Fiore, C Di Giorgio, F Di Giovanni, M Di Giovanni, T Di Girolamo, A Di Lieto, S Di Pace, I Di Palma, F Di Renzo, M Drago, J.-G. Ducoin, O Durante, D D'Urso, M Eisenmann, L Errico, D Estevez, V Fafone, S Farinon, F Feng, E Fenyvesi, I Ferrante, F Fidecaro, I Fiori, D Fiorucci, R Fittipaldi, V Fiumara, R Flaminio, J A Font, J.-D. Fournier, S Frasca, F Frasconi, V Frey, G Fronzè, F Garufi, G Gemme, E Genin, A Gennai, Archisman Ghosh, B Giacomazzo, M Gosselin, R Gouaty, A Grado, M Granata, G Greco, G Grignani, A Grimaldi, S J Grimm, P Gruning, G M Guidi, G Guixé, Y Guo, P Gupta, O Halim, T Harder, J Harms, A Heidmann, H Heitmann, P Hello, G Hemming, E Hennes, T Hinderer, D Hofman, D Huet, V Hui, B Idzkowski, A Iess, G Intini, J.-M. Isac, T Jacqmin, P Jaranowski, R J G Jonker, S Katsanevas, F Kéfélian, I Khan, N Khetan, G Koekoek, S Koley, A Królak, A Kutynia, D Laghi, A Lamberts, I La Rosa, A Lartaux-Vollard, C Lazzaro, P Leaci, N Leroy, N Letendre, F Linde, M Llorens-Monteagudo, A Longo, M Lorenzini, V Loriette, G Losurdo, D Lumaca, A Macquet, E Majorana, I Maksimovic, N Man, V Mangano, M Mantovani, M Mapelli, F Marchesoni, F Marion, A Marquina, S Marsat, F Martelli, V Martinez, A Masserot, S Mastrogiovanni, E Mejuto Villa, L Mereni, M Merzougui, R Metzdorff, A Miani, C Michel, L Milano, A Miller, E Milotti, O Minazzoli, Y Minenkov, M Montani, F Morawski, B Mours, F Muciaccia, A Nagar, I Nardecchia, L Naticchioni, J Neilson, G Nelemans, C Nguyen, D Nichols, S Nissanke, F Nocera, G Oganesyan, C Olivetto, G Pagano, G Pagliaroli, C Palomba, P T H Pang, F Pannarale, F Paoletti, A Paoli, D Pascucci,

A Pasqualetti, R Passaquieti, D Passuello, B Patricelli, A Perego, M Pegoraro, C Périgois, A Perreca, S Perriès, K S Phukon, O J Piccinni, M Pichot, M Piendibene, F Piergiovanni, V Pierro, G Pillant, L Pinard, I M Pinto, K Piotrzkowski, W Plastino, R Poggiani, P Popolizio, E K Porter, M Prevedelli, M Principe, G A Prodi, M Punturo, P Puppo, G Raaijmakers, N Radulesco, P Rapagnani, M Razzano, T Regimbau, L Rei, P Rettegno, F Ricci, G Riemenschneider, F Robinet, A Rocchi, L Rolland, M Romanelli, R Romano, D Rosi\ifmmode \acuten\else ń\fiska, P Ruggi, O S Salafia, L Salconi, A Samajdar, N Sanchis-Gual, E Santos, B Sassolas, O Sauter, S Sayah, D Sentenac, V Sequino, A Sharma, M Sieniawska, N Singh, A Singhal, V Sipala, V Sordini, F Sorrentino, M Spera, C Stachie, D A Steer, G Stratta, A Sur, B L Swinkels, M Tacca, A J Tanasijczuk, E N Tapia San Martin, S Tiwari, M Tonelli, A Torres-Forné, I e Melo, F Travasso, M C Tringali, A Trovato, K W Tsang, M Turconi, M Valentini, N van Bakel, M van Beuzekom, J F J van den Brand, C Van Den Broeck, L van der Schaaf, M Vardaro, M Vasúth, G Vedovato, D Verkindt, F Vetrano, A Viceré, J.-Y. Vinet, H Vocca, R Walet, M Was, A Zadro\ifmmode \dotz\else ż\finy, T Zelenova, J.-P. Zendri, Henning Vahlbruch, Moritz Mehmet, Harald Lück, and Karsten Danzmann. Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light. *Phys. Rev. Lett.*, 123(23):231108, 12 2019.

[10] Jan Südbeck, Sebastian Steinlechner, Mikhail Korobko, and Roman Schnabel. Demonstration of interferometer enhancement through Einstein–Podolsky–Rosen entanglement. *Nature Photonics*, 14(4):240–244, 2020.

[11] Haocun Yu, L McCuller, M Tse, L Barsotti, N Mavalvala, J Betzwieser, C D Blair, S E Dwyer, A Effler, M Evans, A Fernandez-Galiana, P Fritschel, V V Frolov, N Kijbunchoo, F Matichard, D E McClelland, T McRae, A Mullavey, D Sigg, B J J Slagmolen, C Whittle, A Buikema, Y Chen, T R Corbitt, R Schnabel, R Abbott, C Adams, R X Adhikari, A Ananyeva, S Appert, K Arai, J S Areeda, Y Asali, S M Aston, C Austin, A M Baer, M Ball, S W Ballmer, S Banagiri, D Barker, J Bartlett, B K Berger, D Bhattacharjee, G Billingsley, S Biscans, R M Blair, N Bode, P Booker, R Bork, A Bramley, A F Brooks, D D Brown, C Cahillane, K C Cannon, X Chen, A A Ciobanu, F Clara, S J Cooper, K R Corley, S T Countryman, P B Covas, D C Coyne, L E H Datrier, D Davis, C Di Fronzo, K L Dooley, J C Driggers, P Dupej, T Etzel, T M Evans, J Feicht, P Fulda, M Fyffe, J A Giaime, K D Giardina, P Godwin, E Goetz, S Gras, C Gray, R Gray, A C Green, Anchal Gupta, E K Gustafson, R Gustafson, J Hanks, J Hanson, T Hardwick, R K Hasskew, M C Heintze, A F Helmling-Cornell, N A Holland, J D Jones, S Kandhasamy, S Karki, M Kasprzack, K Kawabe, P J King, J S Kissel, Rahul Kumar, M Landry, B B Lane, B Lantz, M Laxen, Y K Lecoeuche, J Leviton, J Liu, M Lormand, A P Lundgren, R Macas, M MacInnis, D M Macleod, G L Mansell, S Márka, Z Márka, D V Martynov, K Mason, T J Massinger, R McCarthy, S McCormick, J McIver, G Mendell, K Merfeld, E L Merilh, F Meylahn, T Mistry, R Mittleman, G Moreno, C M Mow-Lowry, S Mozzon, T J N Nelson, P Nguyen, L K Nuttall, J Oberling, Richard J Oram, C Osthelder, D J Ottaway, H Overmier, J R Palamos, W Parker, E Payne, A Pele, C J Perez, M Pirello, H Radkins, K E Ramirez, J W Richardson, K Riles, N A Robertson, J G Rollins, C L Romel, J H Romie, M P Ross, K Ryan, T Sadecki, E J Sanchez, L E Sanchez, T R Saravanan, R L Savage, D Schaetzl, R M S Schofield, E Schwartz, D Sellers, T Shaffer, J R Smith, S Soni, B Sorazu, A P Spencer, K A Strain, L Sun, M J Szczepańczyk, M Thomas, P Thomas, K A Thorne, K Toland, C I Torrie, G Traylor, A L Urban, G Vajente, G Valdes, D C Vander-Hyde, P J Veitch, K Venkateswara, G Venugopalan, A D Viets, T Vo,

C Vorvick, M Wade, R L Ward, J Warner, B Weaver, R Weiss, B Willke, C C Wipf, L Xiao, H Yamamoto, Hang Yu, L Zhang, M E Zucker, and J Zweizig. Quantum correlations between the light and kilogram-mass mirrors of LIGO, 2020.

[12] T. Westphal, G. Bergmann, A. Bertolini, M. Born, Y. Chen, A. V. Cumming, L. Cunningham, K. Dahl, C. Gräf, G. Hammond, G. Heinzel, S. Hild, S. Huttner, R. Jones, F. Kawazoe, S. Köhlenbeck, G. Kühn, H. Lück, K. Mossavi, J. H. Pöld, K. Somiya, A. M. van Veggel, A. Wanner, B. Willke, K. A. Strain, S. Goßler, and K. Danzmann. Design of the 10 m AEI prototype facility for interferometry studies. *Applied Physics B*, 106(3):551–557, 3 2012.

[13] Hang Yu, Denis Martynov, Salvatore Vitale, Matthew Evans, David Shoemaker, Bryan Barr, Giles Hammond, Stefan Hild, James Hough, Sabina Huttner, Sheila Rowan, Borja Sorazu, Ludovico Carbone, Andreas Freise, Conor Mow-Lowry, Katherine L. Dooley, Paul Fulda, Hartmut Grote, and Daniel Sigg. Prospects for Detecting Gravitational Waves at 5 Hz with Ground-Based Detectors. *Physical Review Letters*, 120(14):141102, 4 2018.

[14] Ian Harry and Tanja Hinderer. Observing and measuring the neutron-star equation-of-state in spinning binary neutron star systems. *Classical and Quantum Gravity*, 35(14):145010, 7 2018.

[15] Yanbei Chen. Macroscopic quantum mechanics: theory and experimental concepts of optomechanics. *Journal of Physics B: Atomic, Molecular and Optical Physics*, 46(10):104001, 5 2013.

[16] H. J. Kimble, Yuri Levin, Andrey B. Matsko, Kip S. Thorne, and Sergey P. Vyatchanin. Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics. *Physical Review D*, 65(2):022002, 12 2001.

[17] Yutaro Enomoto, Koji Nagano, and Seiji Kawamura. Standard quantum limit of angular motion of a suspended mirror and homodyne detection of a ponderomotively squeezed vacuum field. *Phys. Rev. A*, 94(1):12115, 7 2016.

[18] Gregory M Harry, Andri M Gretarsson, Peter R Saulson, Scott E Kittelberger, Steven D Penn, William J Startin, Sheila Rowan, Martin M Fejer, D R M Crooks, Gianpietro Cagnoli, Jim Hough, and Norio Nakagawa. Thermal noise in interferometric gravitational wave detectors due to dielectric optical coatings. *Classical and Quantum Gravity*, 19(5):897–917, 3 2002.

[19] Iain W. Martin and Stuart Reid. Coating thermal noise. In Gregory Harry, Timothy P. Bodiya, and Riccardo DeSalvo, editors, *Optical coatings and thermal noise in precision measurement*, chapter 4, pages 31–54. Cambridge University Press, Cambridge, 2012.

[20] Jonathan Cripe, Nancy Aggarwal, Robert Lanza, Adam Libson, Robinjeet Singh, Paula Heu, David Follman, Garrett D. Cole, Nergis Mavalvala, and Thomas Corbitt. Measurement of quantum back action in the audio band at room temperature. *Nature*, 568(7752):364–367, 4 2019.

[21] F Acernese, M Agathos, K Agatsuma, D Aisa, N Allemandou, A Allocca, J Amarni, P Astone, G Balestri, G Ballardin, F Barone, J-P Baronick, M Barsuglia, A Basti, F Basti, Th S Bauer, V Bavigadda, M Bejger, M G Beker, C Belczynski, D Bersanetti, A Bertolini, M Bitossi, M A Bizouard, S Bloemen, M Blom, M Boer, G Bogaert, D Bondi, F Bondu, L Bonelli, R Bonnand,

V Boschi, L Bosi, T Bouedo, C Bradaschia, M Branchesi, T Briant, A Brillet, V Brisson, T Bulik, H J Bulten, D Buskulic, C Buy, G Cagnoli, E Calloni, C Campeggi, B Canuel, F Carbognani, F Cavalier, R Cavalieri, G Cella, E Cesarini, E Chassande Mottin, A Chincarini, A Chiummo, S Chua, F Cleva, E Coccia, P-F Cohadon, A Colla, M Colombini, A Conte, J-P Coulon, E Cuoco, A Dalmaz, S D'Antonio, V Dattilo, M Davier, R Day, G Debreczeni, J Degallaix, S Deléglise, W Del Pozzo, H Dereli, R De Rosa, L Di Fiore, A Di Lieto, A Di Virgilio, M Doets, V Dolique, M Drago, M Ducrot, G Endrőczi, V Fafone, S Farinon, I Ferrante, F Ferrini, F Fidecaro, I Fiori, R Flaminio, J-D Fournier, S Franco, S Frasca, F Frasconi, L Gammaitoni, F Garufi, M Gaspard, A Gatto, G Gemme, B Gendre, E Genin, A Gennai, S Ghosh, L Giacobone, A Giazotto, R Gouaty, M Granata, G Greco, P Groot, G M Guidi, J Harms, A Heidmann, H Heitmann, P Hello, G Hemming, E Hennes, D Hofman, P Jaranowski, R J G Jonker, M Kasprzack, F Kéfélian, I Kowalska, M Kraan, A Królak, A Kutynia, C Lazzaro, M Leonardi, N Leroy, N Letendre, T G F Li, B Lieunard, M Lorenzini, V Loriette, G Losurdo, C Magazzù, E Majorana, I Maksimovic, V Malvezzi, N Man, V Mangano, M Mantovani, F Marchesoni, F Marion, J Marque, F Martelli, L Martellini, A Masserot, D Meacher, J Meidam, F Mezzani, C Michel, L Milano, Y Minenkov, A Moggi, M Mohan, M Montani, N Morgado, B Mours, F Mul, M F Nagy, I Nardecchia, L Naticchioni, G Nelemans, I Neri, M Neri, F Nocera, E Pacaud, C Palomba, F Paoletti, A Paoli, A Pasqualetti, R Passaquieti, D Passuello, M Perciballi, S Petit, M Pichot, F Piergiovanni, G Pillant, A Piluso, L Pinard, R Poggiani, M Prijatelj, G A Prodi, M Punturo, P Puppo, D S Rabeling, I Rácz, P Rapagnani, M Razzano, V Re, T Regimbau, F Ricci, F Robinet, A Rocchi, L Rolland, R Romano, D Rosińska, P Ruggi, E Saracco, B Sassolas, F Schimmel, D Sentenac, V Sequino, S Shah, K Siellez, N Straniero, B Swinkels, M Tacca, M Tonelli, F Travasso, M Turconi, G Vajente, N van Bakel, M van Beuzekom, J F J van den Brand, C Van Den Broeck, M V van der Sluys, J van Heijningen, M Vasúth, G Vedovato, J Veitch, D Verkindt, F Vetrano, A Viceré, J-Y Vinet, G Visser, H Vocca, R Ward, M Was, L-W Wei, M Yvert, A Zadro ży, and J-P Zendri. Advanced Virgo: a second-generation interferometric gravitational wave detector. *Classical and Quantum Gravity*, 32(2):024001, 1 2015.

[22] The LCGT Collaboration. Large-Scale Cryogenic Gravitational Wave Telescope (LCGT). *Progress of Theoretical Physics Supplement*, 151:221–225, 5 2003.

[23] F Matichard, B Lantz, R Mittleman, K Mason, J Kissel, B Abbott, S Biscans, J McIver, R Abbott, S Abbott, E Allwine, S Barnum, J Birch, C Celerier, D Clark, D Coyne, D DeBra, R DeRosa, M Evans, S Foley, P Fritschel, J A Giaime, C Gray, G Grabeel, J Hanson, C Hardham, M Hillard, W Hua, C Kucharczyk, M Landry, A Le Roux, V Lhuillier, D Macleod, M Macinnis, R Mitchell, B O'Reilly, D Ottaway, H Paris, A Pele, M Puma, H Radkins, C Ramet, M Robinson, L Ruet, P Sarin, D Shoemaker, A Stein, J Thomas, M Vargas, K Venkateswara, J Warner, and S Wen. Seismic isolation of Advanced LIGO: Review of strategy, instrumentation and performance. *Classical and Quantum Gravity*, 32(18):185003, 9 2015.

[24] G. Losurdo, G. Calamai, E. Cuoco, L. Fabbroni, G. Guidi, M. Mazzoni, R. Stanga, F. Vetrano, L. Holloway, D. Passuello, G. Ballardin, S. Braccini, C. Bradaschia, R. Cavalieri, R. Cecchi, G. Cella, V. Dattilo, A. Di Virgilio, F. Fidecaro, F. Frasconi, A. Gennai, A. Giazotto, I. Ferrante, P. La Penna, F. Lelli, T. Lomtadze, A. Marin, S. Mancini, F. Paoletti, A. Pasqualetti, R. Passaquieti, R. Poggiani, R. Taddei, A. Vicerè, and Z. Zhang. Inertial control of the mirror

suspensions of the VIRGO interferometer for gravitational wave detection. *Review of Scientific Instruments*, 72(9):3653–3661, 9 2001.

[25] N A Robertson, G Cagnoli, D R M Crooks, E Elliffe, J E Faller, P Fritschel, S Go$szlig$ler, A Grant, A Heptonstall, J Hough, H L$uuml$ck, R Mittleman, M Perreur-Lloyd, M V Plissi, S Rowan, D H Shoemaker, P H Sneddon, K A Strain, C I Torrie, H Ward, and P Willems. Quadruple suspension design for Advanced LIGO. *Classical and Quantum Gravity*, 19(15):311, 8 2002.

[26] Kenji Numata and Kazuhiro Yamamoto. Cryogenics. In Gregory Harry, Timothy P. Bodiya, and Riccardo DeSalvo, editors, *Optical coatings and thermal noise in precision measurement*, chapter 8, pages 108–128. Cambridge University Press, Cambridge, 2012.

[27] Peter R. Saulson. Thermal noise in mechanical experiments. *Physical Review D*, 42(8):2437–2445, 10 1990.

[28] Gabriela González. Suspensions thermal noise in the LIGO gravitational wave detector. *Classical and Quantum Gravity*, 17(21):4409–4435, 11 2000.

[29] A V Cumming, A S Bell, L Barsotti, M A Barton, G Cagnoli, D Cook, L Cunningham, M Evans, G D Hammond, G M Harry, A Heptonstall, J Hough, R Jones, R Kumar, R Mittleman, N A Robertson, S Rowan, B Shapiro, K A Strain, K Tokmakov, C Torrie, and A A van Veggel. Design and development of the advanced LIGO monolithic fused silica suspension. *Classical and Quantum Gravity*, 29(3):035003, 2 2012.

[30] A. Gillespie and F. Raab. Thermally excited vibrations of the mirrors of laser interferometer gravitational-wave detectors. *Physical Review D*, 52(2):577–585, 7 1995.

[31] François Bondu, Patrice Hello, and Jean-Yves Vinet. Thermal noise in mirrors of interferometric gravitational wave antennas. *Physics Letters A*, 246(3-4):227–236, 9 1998.

[32] Yuk Tung Liu and Kip S. Thorne. Thermoelastic noise and homogeneous thermal noise in finite sized gravitational-wave test masses. *Physical Review D*, 62(12):122002, 11 2000.

[33] Steven D. Penn, Alexander Ageev, Dan Busby, Gregory M. Harry, Andri M. Gretarsson, Kenji Numata, and Phil Willems. Frequency and surface dependence of the mechanical loss in fused silica. *Physics Letters A*, 352(1-2):3–6, 3 2006.

[34] O. L. Anderson and H. E. Bommel. Ultrasonic Absorption in Fused Silica at Low Temperatures and High Frequencies. *Journal of the American Ceramic Society*, 38(4):125–131, 4 1955.

[35] Clarence Zener. Internal Friction in Solids. I. Theory of Internal Friction in Reeds. *Physical Review*, 52(3):230–235, 8 1937.

[36] Clarence M. Zener and Sidney Siegel. Elasticity and Anelasticity of Metals. *The Journal of Physical and Colloid Chemistry*, 53(9):1468–1468, 9 1949.