Macroscopic quantum mechanics in gravitational-wave observatories and beyond

Roman Schnabel\textsuperscript{1} and Mikhail Korobko\textsuperscript{1}
Institut für Laserphysik & Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
(*Electronic mail: roman.schnabel@uni-hamburg.de)
(Dated: 7 September 2022)

The existence of quantum correlations affects both microscopic and macroscopic systems. On macroscopic systems they are difficult to observe and usually irrelevant for the system’s evolution due to the frequent energy exchange with the environment. The world-wide network of gravitational-wave (GW) observatories exploits optical as well as mechanical systems that are highly macroscopic and largely decoupled from the environment. The quasi-monochromatic light fields in the kilometre-scale arm resonators have photon excitation numbers larger than $10^{19}$, and the mirrors that are quasi-free falling in propagation direction of the light fields have masses of around 40 kg. Recent observations on the GW observatories LIGO and Virgo clearly showed that the quantum uncertainty of one system affected the uncertainty of the other. Here, we review these observations and provide links to research goals targeted with mesoscopic optomechanical systems in other fields of fundamental physical research. These may have Gaussian quantum uncertainties as the ones in GW observatories or even non-Gaussian ones, such as Schrödinger cat states.

I. INTRODUCTION

Quantum physical experiments regarding the motion of macroscopic or even heavy bodies require low-noise and highly efficient sensing. An ideal system is a highly reflecting mirror whose motion is sensed by monochromatic light which is photo-electrically detected with high quantum efficiency. The motion of the mirror needs to be isolated from any forces of the environment over the duration of the experiment. A feasible approach is a mirror suspension with a high quality factor (Q-factor). The suspension turns the mirror motion into that of a (quantum) mechanical oscillator. The higher the Q-factor the lower the coupling rate to the environment. A quantum optomechanical experiment is achieved if the quantum uncertainties of light and mirror motion influence each other, ultimately leading to the observation of entanglement between optical and motional degrees of freedom.

The existence of quantum uncertainties reveals itself by so-called ensemble measurements. These are large numbers of identical and precise measurements of the same observable performed on identical physical systems being in identical quantum states. One might assume that the preparation of an ensemble of truly identical ensemble members is impossible because of some remaining distinguishability, potentially given with respect to ‘hidden variables’. But this assumption was proven wrong through experimental violations of Bell inequalities, see for instance Ref\textsuperscript{[1]}. The term ‘quantum uncertainty’ describes the fact that provably identical measurement settings provide nevertheless different measurement outcomes. As a direct consequence of the initial indistinguishability, the individual outcomes have a truly random character, and just the outcomes’ probability distribution is determined.

As given by the shape of the probability distributions, continuous-variable quantum uncertainties, such as those of position and momentum, can be either Gaussian or non-Gaussian. The most important example of a (pure) Gaussian quantum state is the ground state. The most famous (pure) non-Gaussian quantum state with macroscopic excitation energy is the Schrödinger cat state\textsuperscript{[2]}. It is a superposition of two macroscopically distinct states. The measurement results on an ensemble of such states are discrete and two-valued (‘dead’ and ‘alive’). Nevertheless, non-Gaussian states can also be represented by continuous spectra. Generally, the terms ‘quantum uncertainty’ and ‘superposition’ refer to the same physical phenomenon. In contrast to non-Gaussian measurement spectra, Gaussian measurement spectra can generally not be used for violating a Bell inequality. Nevertheless, some of them are as distinct as the pure non-Gaussian states. These are the squeezed states\textsuperscript{[3]} and other related ones\textsuperscript{[4]}. The state is called ‘nonclassical’ if its Glauber-Sudarshan P-function does not correspond to a positive-valued (classical) probability distribution in the phase space spanned by two non-commuting observables. The Gaussian or non-Gaussian shape of a quantum uncertainty is not relevant.

Squeezed states for improving interferometric GW observatories were proposed in 1986\textsuperscript{[5]}, two years after they were...
FIG. 2. Gravitational waves (GWs) are transverse quadrupole waves that propagate at the speed of light and expand and stretch space-time \((\pm \Delta L/L)\). Sources are for instance compact binary systems of black holes and neutron stars. The LIGO and Virgo observatories are Michelson laser interferometer with an ultra-stable single mode input laser beam of about 100 W, km-scale arm resonators, power- and signal recycling resonators, a squeeze laser for the targeted signal spectrum from 10 Hz to 10 kHz, and a high-quantum-efficiency PIN photo diode in the output port. The time-frequency spectrum of the photo-electric voltage resembles the GW signal plus observatory noise. \(2f_{\text{gw}}\): Frequency of the GW; PRM: power-recycling mirror; SRM: signal-recycling mirror; PBS: polarising beam splitter; \(U(t)\): photo-electric voltage with AC-signal.

The spectrum of observables of GW observatories – GW observatories are Michelson-type laser interferometers with Fabry-Perot arm resonators, see Fig. 2. The latter are established by two pendulum-suspended laser mirrors each, separated by three kilometres in Virgo and four kilometres in LIGO, respectively. During observation runs, GW observatories are in continuous operation with steady state Gaussian quantum uncertainties. During the detection of a GW or in case of disturbances, the quantum observables of related frequencies \(f\) show uncertainties that are displaced over some finite time period.

Gravitational waves modulate the arm length of the interferometric GW observatory, and the signal appears at the output as the amplitude modulation of the light field, with targeted signal frequencies \(f\) range from about 10 Hz to a few kHz. Fig. 1 shows the famous signal of the first ever measured signal (GW150914). The signal was produced by two merging black holes and shows a frequency chirp (exponential increase with time). The signal looks fuzzy, because a single frequency at a single point of time is unphysical. The relevant quantum observable in the detector is the amplitude of the amplitude quadrature of the output laser beam, \(\tilde{X}_{f,\Delta f}(t \pm \Delta t)\), defined in some frequency band \(\Delta f\) around the Fourier frequency \(f\) and time span \(\Delta t\) at time \(t\).

Observables are always defined with respect to a physical system. Here, these systems are light fields as well as oscillations of the mirror motion. A suitable name for any of these physical systems is the word ‘mode’. A ‘mode’ should be defined as being Fourier limited. An ensemble of identical such modes might be in a pure quantum state or in a rather mixed thermal state. The observable \(\tilde{X}_{f,\Delta f}(t \pm \Delta t)\), however, addresses a specific, single Fourier-limited mode of modulation of the monochromatic carrier output light of the GW observatory, see Fig. 1. The mode has the eigenfrequency \(f \pm \Delta f\), when its energy is absorbed over the time period...
the optomechanical coupling factor $K$ the input light’s modulation mode with frequency $f = \text{f}_{\text{SQL}}$, at which the optomechanical coupling factor $\mathcal{X}(\text{f}_{\text{SQL}}) = 1$. The two vertical dashed (magenta) lines represent two example values (1) and (2) of the light’s amplitude quadrature $\hat{X}$. The positive value (1) produces a larger radiation pressure than the average one, and the resulting mirror movement lengthens the optical path length. Consequently, and because of $\mathcal{X}(\text{f}_{\text{SQL}}) = 1$, the phase quadrature $\hat{Y}$ is delayed by the same value (1). This coupling is illustrated by the large curved dashed arrow. Any negative value (2) advances the phase quadrature. The quantum uncertainty of the reflected light in $\hat{Y}$ thus corresponds to that of two uncorrelated units of ground state uncertainty. The displacement due to a gravitational wave (arrow pointing along $\hat{Y}$), which is a classical modulation at $\text{f}_{\text{SQL}}$, is unchanged but measured with a halved signal to noise ratio.

$\Delta t \pm \Delta t$. This is mathematically described by the Fourier transform according to which the smallest phase space area for an energy distribution is $\Delta f \cdot \Delta t = 1/(4\pi)$, also providing the well-known energy-time uncertainty relation, see e.g. Ref. [29]

An ensemble of this mode with the same excitation is not available since the GW does not repeat itself. An example of the excitation of single modulation modes due to a GW is shown in Fig. [1]. The important fact is that the displayed ‘modes’ are defined by the data post-processing. At first instance, the photo-electric voltage is sampled at a rate that is significantly higher than the highest expected frequency component of the GW signal. Only after the content of frequency components has been analysed the modes of half widths $\Delta f$ and $\Delta t$ are defined. The much higher eigenfrequency of the optical carrier field is not relevant.

The relevant mechanical system in LIGO and Virgo is composed of four mirrors, the ‘test masses of space-time’. They are suspended as pendulums with even (resonance) frequencies slightly below 1 Hz. This frequency is below the targeted signal spectrum. In order to understand how the motions of the mirrors affect the sensitivity of the GW observatory, we need to define Fourier limited ‘overtone’ modes of the pendulum. The relevant modes of motion have the position excitation $\hat{x}_{f,\Delta f}(t \pm \Delta t)$ and the momentum excitation $\hat{p}_{f,\Delta f}(t \pm \Delta t)$. In GW observatories, these operators are one-dimensional along the laser beams’ optical axes, and the position and momentum observables that actually couple to $\hat{x}_{f,\Delta f}(t \pm \Delta t)$ describe the difference of the two arms and are the corresponding combination of the four mirrors’ individual quantities.

Quantum optomechanics in mesoscopic systems – Quantum effects have also been observed in small-scale devices, where the mechanical oscillators have typical masses in the nanogram and microgram regime. The optomechanical coupling strength is stronger for smaller masses, and for the same optical power the uncertainty of the reflected light’s radiation pressure has a much stronger effect in small-scale systems. In case of continuous steady state measurements, the quantum uncertainties in such systems are also Gaussian. In the past years, motional ground state across all scales was achieved (see[36] for overview), quantum radiation pressure was observed[41–43] and evaded[44,45] in various systems, and Gaussian entanglement was observed[27,46]. Other systems were observed in non-Gaussian quantum states[41,44]. There, however, the relevant observable was not the quadrature, but the photon number and correlations between the photons. So-far, no non-Gaussian state tomography on the optomechanical system has been demonstrated. A more complete overview of recent advances in quantum optomechanics can be found in Ref. [41] and of the progress in a rising field of levitated optomechanics in
II. COUPLING MECHANICAL AND OPTICAL UNCERTAINTIES

Macroscopic mechanical oscillators promise to enable tests of quantum physics on a macroscopic scale. Furthermore, solid bodies couple to the gravitational force, which enables tests of quantum gravity theories in the weak field regime. The idealised model of such a mechanical system is a movable rigid mirror that is suspended as a pendulum and probed by a monochromatic laser beam. The light propagates over some distance, reflects off the mirror, and propagates further where it is photoelectrically detected. The total optical path length depends on the precise position of the mirror surface. The phase of the light when detected thus carries information about even tiniest position changes of the mirror. A laser interferometer measures this phase change in comparison to the optical length of a reference path, see Fig. 2. There are two quantum systems involved, both defined by their own uncertainty: the continuously measured optical modes and the mechanical modes of the mirror that interacted with the optical modes. Usually, the optical modes are in rather pure states, i.e. in ground state or in displaced ground states when a GW signal is observed or disturbances present. The mechanical modes are in thermal states because they are in thermal equilibrium with the environment. The high Q-factor of the suspension leads to a characteristic time during which the thermal decoherence (thermalisation) takes place. The higher the Q-factor, the slower the decoherence.

An optical field with fluctuations over a broad spectrum of frequencies is traditionally described in terms of spectral Fourier components of amplitude (X) and phase quadrature fluctuations (Y) at frequency f: \( \Delta X(f) \) and \( \Delta Y(f) \) respectively. The actual observables \( \tilde{X}_{f,\Delta f}(t,\Delta t) \) and \( \tilde{Y}_{f,\Delta f}(t,\Delta t) \), however, are the Fourier transformed averages over the resolution bandwidth \( \pm \Delta f \) of these quantities. When the mode is in a pure quantum state, the uncertainties of its phase and amplitude quadratures obey Heisenberg uncertainty relation: \( \Delta X_{f,\Delta f}(t,\Delta t) \cdot \Delta Y_{f,\Delta f}(t,\Delta t) \geq 1/4 \), where the actual number on the right depends on the normalisation. For a coherent state, the uncertainties are equal, i.e. \( \Delta X_{f,\Delta f}(t,\Delta t) = \Delta Y_{f,\Delta f}(t,\Delta t) = 1/2 \). It is possible to create a state, in which one of the uncertainties is decreased at the expense of the other, i.e. \( \Delta X_{f,\Delta f}(t,\Delta t) = e^{-r}/2 \) and \( \Delta Y_{f,\Delta f}(t,\Delta t) = e^{r}/2 \), while also obeys the uncertainty relation. Such state is called ‘squeezed’ with r the squeeze factor. In general, a state can also be squeezed for any linear combination of the amplitude and phase quadratures. The ‘squeeze angle’ is usually defined with respect to the amplitude quadrature.

Whenever light is reflected off a mirror, it exerts radiation pressure on it. The corresponding force accelerates the mirror, i.e. transfers momentum. This radiation-pressure force depends on the amplitude of the input light field \( \tilde{X}_{f,\Delta f}(t,\Delta t) \). Since this amplitude has some uncertainty, it is transferred onto the mirror’s momentum \( p_{f,\Delta f}(t,\Delta t) \), which influences at

FIG. 5. Back action evasion in \( \hat{Y} \) – The fuzzy ellipse with squeeze angle \( \theta = 45^\circ \) represents the injected state at \( f_{\text{SQL}} \), where \( \kappa(f_{\text{SQL}}) = 1 \). Shown is that the radiation pressure that drives \( \hat{X} \) has a dominating correlated component in the uncertainty of \( \hat{Y} \). The correlation is the stronger the larger the squeeze parameter is. The radiation pressure back action produces an anti-correlated component in the uncertainty of \( \hat{Y} \) (curved dashed arrow). The two components cancel in the conventional readout quadrature angle, which is aligned to the GW signal.

FIG. 6. Remaining uncertainty in \( \hat{Y} \) – This figure completes the illustration in Fig. 5 by its remaining uncertainty in \( \hat{Y} \). Shown here is that the same radiation pressure as in the figure above has also a subordinate anti-correlated component in the uncertainty of \( \hat{Y} \). The radiation pressure back action produces another anti-correlated component in the uncertainty of \( \hat{Y} \) of the same magnitude (curved dashed arrow). The two anti-correlated components constructively interfere to a magnitude that is \( \sqrt{2} \) larger than the squeezed standard deviation. Since at \( f_{\text{SQL}} \) the standard deviation of the quantum uncertainty in \( \hat{Y} \) is \( \sqrt{2} \) larger than the ground state standard deviation, the full squeeze factor is retained. Note that at higher (lower) frequencies the injected squeeze angle needs to be lower (higher) to retain the full squeeze factor. In the recent experiment at LIGO, the injected squeeze angle was 24°, 35°, and 46° for which the inferred quantum noise in the observation of gravitational waves surpassed the SQL, see Figs. 2 and 3 in Ref. [34].
later times its position \( \hat{x}_{t,\Delta t}(t, \Delta t) \). This phenomenon is called quantum back-action (QBA) when sensing the mechanical motion with light. When continuously sensing (monitoring) the mirror position, QBA increases the position uncertainty, which results in additional quantum noise in the measurement record. This quantum radiation-pressure noise (QRPN)\textsuperscript{[28]} may hinder the sensitivity of various detectors operating in quantum domain, such as gravitational-wave detectors. QRPN was first observed in microscopic systems \textsuperscript{[49,50]} and only recently in GW observatories, see the next section.

In the following, we describe quantum radiation pressure formally in a quasi-stationary case. The Fourier components of the quantum radiation pressure force are given by the amplitude quadrature of the incident light \( F_{\text{rp}}(f) = h\alpha \hat{a}_{\chi}(f) \propto \sqrt{P_0} \hat{a}_{\chi}(f) \), where \( \alpha \) is the normalized average amplitude, which depends on the average optical power \( P_0 \) of the monochromatic carrier light at the mirror. The force leads to a mechanical displacement \( \hat{x}_{\text{q}}(f) = \chi(f) F_{\text{rp}}(f) \), where \( \chi(f) \) is the complex valued mechanical response function. The phase quadrature of the light field reflected of a movable mirror \( \hat{b}_{\chi}(f) \) picks up the displacement of the mechanical oscillator, which in turn is driven by the radiation-pressure force. Fluctuations of the quadratures in the linear approximation, i.e. when the displacement is small relative to the wavelength, and the fluctuations are small relative to average field amplitude, can be expressed by two equations (ignoring irrelevant phase factors):

\[
\hat{b}_{\chi}(f) = \hat{a}_{\chi}(f); \quad (1)
\]

\[
\hat{b}_{\chi}(f) = \hat{a}_{\chi}(f) - \alpha (\chi_{\text{q}}(f) + \chi_{\text{sig}}(f)) = \hat{a}_{\chi}(f) - \chi_{\text{f}}(f) \hat{a}_{\chi}(f) - \alpha \chi(f) F_{\text{sig}}(f), \quad (2)
\]

where \( F_{\text{sig}}(f) \) is the signal force and \( \chi_{\text{f}}(f) = h\alpha^2 \chi(f) \) is the optomechanical coupling factor (also called Kimble factor\textsuperscript{[25]})

In a more general case, \( \chi_{\text{f}}(f) \) also includes the effects of the optical cavities in the arms (see for details e.g.\textsuperscript{[51]}).

Eq. (2) describes the emergence of quantum back action, which is illustrated in Fig. 3. The first term corresponds to the measurement (shot) noise (QMN), and the second term – to quantum back action noise (QBN). An important property of quantum back action can be seen in this equation: radiation-pressure force quantum-correlates phase quadrature of the output field with amplitude quadrature of the incoming field. The output state becomes \textit{ponderomotively squeezed}\textsuperscript{[25]}. This quantum correlation can be seen from the fact that for some linear combinations of \( \hat{b}_{\chi}(f) \) and \( \hat{b}_{\chi}(f) \) the radiation pressure back action cancels, see the illustration in Fig. 4.

Unfortunately, a GW observatory with just a single photo diode cannot benefit from ponderomotive squeezing alone\textsuperscript{[25]}. In contrast, the ponderomotive anti-squeezing results in the quantum radiation pressure noise.

The standard quantum limit – The total quantum noise of a measurement device is given by the sum of quantum back-action noise and quantum measurement noise, where both are normalised to the signal strength\textsuperscript{[28]}.

\[
S_{x}(f) = \frac{x^2_{\text{SQL}}}{2} \left( \frac{1}{\chi_{\text{f}}(f)} + \chi_{\text{f}}(f) \right); \quad (3)
\]

\[
x_{\text{SQL}}(f) = \frac{1}{2\pi} \sqrt{\frac{8h}{M f^2}}, \quad (4)
\]

where \( x_{\text{SQL}}(f) \) is the SQL for the free mirror with a mass of \( M \). The SQL is achieved at the frequency, where \( \chi_{\text{f}}(f) = 1 \). Eq. (3) also holds if squeezed light is injected for squeezing the output light’s amplitude quadrature spectrum. In this case \( \chi_{\text{f}}(f) \) needs to be multiplied by \( e^{2\theta} \), and the SQL cannot be overcome. The SQL can be overcome, however, by employing quantum correlations or quantum non-demolition measurements\textsuperscript{[28,29,51]}. The simplest approach is the injection of a squeezed light with a frequency independent squeeze angle \( \theta \neq 0^\circ \) in this case, Eq. (3) is not valid. This was recently demonstrated in LIGO, as we summarise in the next section.
III. OBSERVATION OF OPTOMECHANICAL COUPLING IN GW OBSERVATORIES

Recent experiments with LIGO and Virgo revealed coupling of the quantum uncertainties of the light with the differential motion of the four 40 kg-sized mirrors of the two arm resonators. In Virgo, the squeezed vacuum state was injected with a squeezing angle $\theta = 0^\circ$ as it was done previously in GEO 600 [17], LIGO [22], and Virgo [23]. With a slightly increased laser power, the noise of the output light showed a significant contribution of quantum back-action at frequencies between 30 Hz and 40 Hz. The back-action in terms of quantum radiation pressure noise was due to the anti-squeezed quadrature of the injected squeezed vacuum states. The illustration of the setting is given in Fig. [7]. It is similar to Fig. [3] but due to the injected squeezed vacuum states the quantum uncertainty in the radiation pressure is anti-squeezed and visible even in the presence of non-quantum noise sources. Fig. [8] shows measurements of the square root of the Virgo noise spectral density calibrated to differential arm length in m/√Hz. The effect of quantum radiation pressure noise (QRPN) was directly observed through the elevation of the upper trace between 30 Hz and 40 Hz with respect to the other traces. Notably, the QRPN effect was not masked by non-quantum noise sources. (The same effect can also be seen to a small extent in Fig. 1 of Ref. [22] and in Fig. 2 of Ref. [23].)

The spectral density of the squeezed noise generated in Virgo was 13.8 dB below that of the ground state noise (vacuum noise). The total quantum efficiency was about 54%, i.e. 46% of the energy in the squeezed vacuum states were lost and the pure squeezed states got mixed with the corresponding contribution of the ground state. The loss reduced the anti-squeezing from 13.8 dB (a factor of about 24 above the variance of the ground state) to 11.3 dB (13.4). The square root of this factor ($\sim 3$) corresponds to the factor between the black and the blue trace at the high frequencies in Fig. [8]. The same loss reduced the squeezing from $-13.8$ dB to about $-3$ dB ($\sim 0.5$), and a phase squeezed trace (red) a factor of about 0.7 below the vacuum noise (black) at the high frequencies in Fig. [8]. In reality both values were closer to unity because of the underlying non-quantum noise (grey). The observed QRPN was thus produced by a mixed state with a product of the uncertainty standard deviations that was a factor of $0.7 \times 3.7 = 2.6$ above minimum uncertainty. The lower the factor is, the more ‘pure’ is the optomechanical coupling and the ‘more quantum’ is the observed QRPN.

A more solid criterion for ‘quantumness’ of optomechanical coupling is given by the standard quantum limit. If the measured total spectral density shows with statistical significance (over some finite frequency band $f \pm \Delta f$) that the overall quantum noise is below the SQL, optomechanical quantum correlations (OMQC), i.e. quantum correlations between the uncertainties of the light field and the mirror motion are proven. Therefore, the SQL serves as a useful benchmark for quantifying the possibility to measure quantum-mechanical effects for the specific optomechanical Fourier mode with eigenfrequency $f \pm \Delta f$. This mode could then be used to study the foundations of quantum theory or gravity, as we discuss in the next section.

With the input squeeze angle set to $\theta = 0^\circ$, today’s GW observatories cannot observe a quantum noise below the SQL at any frequency. The reason is that surpassing the SQL requires the actual exploitation of quantum correlations, but this is impossible with just a single photo diode in the output port and a zero squeeze angle in the input. The quantum noise can surpass the SQL over a broad frequency range if the input squeeze angle is set to an optimal (non-zero) value and the output optics supplemented by filter cavities, which provide a frequency dependent quadrature rotation, and a balanced homodyne detector, which is able to detect an arbitrary fixed quadrature angle. The simplest approach to surpass the SQL is the optimisation of the input squeeze angle without any further changes to the optics at the output port of a today’s GW observatory. This approach allows for suppressing the quantum noise below the SQL over a finite but not too narrow frequency band around a well-defined frequency ($f_{\text{OMQC}}$). This experiment was done in LIGO [23]. The total spectral density was considerably above the SQL, but its reduction over the characteristic frequency band when optimising the squeeze...
angle allowed the inference of the overall quantum noise below the SQL. The results are shown in Figs.7 and 8. The quantum noise was demonstrated to be below the SQL for three different squeeze angles.

The overall displacement-normalised quantum noise spectral density for injected squeezed light with squeeze angle \( \theta \) can be calculated by the following expression

\[
S_x(f) = \frac{x^2_{\text{SQL}}}{2} \left( \frac{1}{K \mathcal{K}(f)} + \mathcal{K}(f) \right) \times \left[ e^{-2r} \cos^2(\theta - \vartheta(f)) + e^{2r} \sin^2(\theta - \vartheta(f)) \right];
\]

(5)

where \( \gamma \) is the detector bandwidth, \( L \) is the arm length, \( P_{\text{arm}} \) is the optical power in the arm cavities, \( v_0 \) is the frequency of laser, \( c \) is the speed of light, \( M \) is the mass of an end mirror. For example, at the frequency, where the noise touches the SQL, \( \mathcal{K}(f_{\text{SQL}}) = 1, \vartheta(f_{\text{SQL}}) = 45^\circ \). Then, choosing the injected squeeze angle of \( \theta = \vartheta(f_{\text{SQL}}) \) allows to dip below the SQL exactly by the amount of available squeezing:

\[
S_x(f_{\text{SQL}}) = x^2_{\text{SQL}} e^{-2r}.
\]

(8)

This can be seen in Fig.10 right.

A direct observation of the total noise spectral density below the SQL was not possible in LIGO because there are multiple sources of technical noise, which contribute at a level above the SQL. Most notable sources of noise are: thermal motion of suspensions\(^{53,54} \) and surfaces\(^{55} \) of test masses, seismic vibrations coupling to the motion of the mirror\(^{56,57} \) as well as control noises.

These observations of quantum effects in the detectors are just the first steps towards application of advanced quantum technology for gravitational-wave observatories, which are reviewed in detail in Refs.\(^{21,22} \). Nonetheless, even this progress opens the path towards the tests of fundamental quantum mechanics and gravity, as we discuss in the next section.

IV. QUANTUM CORRELATIONS AND TESTS OF SPONTANEOUS DECOHERENCE

A. Non-Gaussian optomechanical states for probing decoherence

Macroscopic systems are generally not observed in pure quantum states, such as superposition states. The question of why the world appears “classical” to us, is understood as the consequence of decoherence mechanisms, which quickly destroy macroscopic superpositions\(^{58} \). These mechanisms usually considered obey the rules of standard quantum mechanics. Therefore, they neither allow to resolve the measurement problem of quantum mechanics, nor shine light on the connection between quantum mechanics and gravity. Spontaneous decoherence models attempt to resolve either problem, or both, by modifying quantum mechanics and introducing additional terms in the Schrödinger equation. This manifests itself as a source of spontaneous decoherence, which for large objects is stronger than other typical sources of environmental decoherence. Two most prominent examples of these spontaneous decoherence models are continuous spontaneous localisation (CSL)\(^{59,60,61} \) and Diósi-Penrose (DP) models\(^{62,63} \). In the CSL models, the decoherence occurs due to an additional stochastic force, which acts on all objects, with its strength being stronger for larger objects. In the DP model, the decoherence is caused by the gravitational self-interaction of different parts of a wave-function. Both mechanisms, although different in nature, are related to the mass of objects. The potential relevance of gravity in the emergence of a ‘classical’ everyday world was pointed out by Frigyes Karolyhazy already in the 1960s\(^{64} \), and a recent review is given in Ref.\(^{65} \).

In 2003, Marshall, Simon, Penrose, and Bouwmeester proposed an experiment\(^{66} \) that was intended to realise a mechanical system having a position uncertainty with two probability maxima that were separated by the width of the ground state uncertainty. The envisioned mechanical system was a mirror with a volume of 10\( \mu \)m cubed and a mass of \( m \approx 5 \text{ng} \) that constituted one end of a 5 cm long cavity in one arm of a Michelson interferometer, see Fig.10. The second cavity mirror was much heavier and not movable. The mesoscopic mirror was mechanically suspended with a resonance frequency of \( f_{\text{m}} = 500 \text{ Hz} \) which resulted in a ground state half-width position uncertainty of \( \Delta x_{\text{m}} = \sqrt{\hbar/(4\pi mf_{\text{m}})} \approx 6 \cdot 10^{-15} \text{ m} \).

The excitation of the cavity mode to a single photon Fock state\(^{1} \) was calculated to be sufficient to produce a radiation pressure induced displacement of the tiny mirror by about the same size. The second arm of the interferometer contained another cavity of identical optical parameters but with two immovable macroscopic mirrors. Coupling a single photon to a decoherence-free interferometer entangles the quantum uncertainty of the mirror position with the optical fields in the two arm cavities. If the position of the mirror shows some spontaneous decoherence, the mirror either experiences the full radiation pressure, is displaced, and the photon is in cavity A, or the mirror does not experiences any radiation pressure, is not displaced, and the photon is in cavity B. Ensemble measurements without decoherence would result in self-interference of the photon into one of the output ports. Ensemble measurements with decoherence of the mirror position would always result in a photon that is localised to one of the arm cavities. Interference would not possible any more. An ensemble measurement would find the out-coupled single photons always randomly distributed in the output ports, regardless what the precise differential arm length of the interferometer was. Note, that the entire ensemble measurement is conditioned on a single ‘click’ of either detector D1 or D2.

The non-Gaussian position uncertainty of a mesoscopic mirror proposed in Ref.\(^{27} \) has two local maxima with a separation of the order of the motional ground state. The dimension of the mirror, however, is many orders of magnitudes larger. Preparing mesoscopic objects in superpositions of two positions that are separated by more than the objects diameter is
Macroscopic quantum mechanics in gravitational-wave observatories and beyond

FIG. 9. Experimental inference of mirror/light quantum correlation in LIGO – Squeezed vacuum states with a squeeze angle of $\theta = 35^\circ$ were injected. The noise spectral density around 40 Hz was below the one without squeezing injection. A total quantum noise below the SQL was inferred by subtracting non-quantum noise, which was determined by reference measurements. The smooth solid lines represent quantum noise models. Reproduced with permission from H. Yu et al., Nature 583, 43 - 47 (2020). Copyright 2020 Springer Nature.

FIG. 10. Inferred mirror/light quantum correlation for different squeeze angles – Squeezed vacuum states with squeeze angles of $\theta = 7^\circ, 24^\circ, 46^\circ$ were injected. For the two larger angles, a total quantum noise below the SQL was inferred by subtracting non-quantum noise, which was determined by reference measurements. The inference for $\theta = 46^\circ$ at a frequency of $f_{SQL, LIGO} \approx 30$ Hz almost resembles the illustration in Figs. 5 and 6. Reproduced with permission from H. Yu et al., Nature 583, 43 - 47 (2020). Copyright 2020 Springer Nature.

far beyond current technology. (Such a state could rightly be called a Schrödinger cat state.) Theoretical work showed that reasonable assumptions on gravitational decoherence mechanisms might involve rather large decoherence time scales. Experiments with state of the art technology will be rather limited by environmental decoherence mechanisms and thus not sensitive to most of the gravitational decoherence mechanisms discussed so far \([68-71]\). Due to this, recent works focused on more microscopic systems, involving matter-wave interferometry \([72, 73]\) or Bose-Einstein condensates \([74]\).

Ensemble of non-Gaussian states of light have been usually produced from spontaneously produced photon pairs. Conditioned on the successful detection of one of the photons, a Fock-1-states can be created and phase space tomography performed \([75]\). Recently, also phononic Fock-1-states were produced \([42, 43, 76]\). A theoretical analysis suggested to prepare the mirror motion in GW observatories in non-Gaussian states by injecting optical Fock-1-states into the signal output port following previous theoretical work \([77]\). The quantum uncertainty of the single photon is optically amplified by the intense light in the arms and produces a significant non-Gaussian quantum radiation pressure force on the mirrors and thus a non-Gaussian quantum state of the joint mirror motion. It was pointed out that some experiments on testing stochastic gravitational wave-function collapse large masses are not always preferable, despite stronger coupling to gravity \([79]\). However, bringing massive mechanical oscillators into quantum regime allows to test the limits of quantum theory as well as gravity.

B. Gaussian optomechanical states for probing decoherence

Both, nonclassical Gaussian and non-Gaussian states are viable probes for testing spontaneous decoherence. On both nonclassical states, any decoherence is noticeable through a redistribution of the uncertainty.

Gaussian squeezed states were recently used as probe systems to quantify an environmental decoherence process \([80]\).
The decoherence of interest was the escape of photons in the course of their detection by photodiodes. The measurement utilised the fact that photon escape deteriorates the measured state's purity. The product of the standard deviations of the squeezed and anti-squeezed uncertainties increased successively. By the direct observation of a 15 dB squeezed state and independent reference measurements of other loss sources, it was possible to quantify the photon escape during measurement to about 0.5% with an error bar of the same size. The photo diodes’ quantum efficiency was thus measured to (99.5 ± 0.5)%.

One could argue that a non-Gaussian state is more sensitive to decoherence and is therefore better suited as a probe system. However, in this case the same state is also more sensitive to decoherence due to disturbances from the environment, which offsets such an advantage. Nevertheless, non-Gaussian states might be more sensitive to some models of gravitational decoherence, owing to distinct spatial maxima in a wavefunction. Gaussian states, on the other hand, offer a possibility to evolve freely, without interaction with the probe light. Subsequent research found that stationary entanglement between vibrational modes of two cavity mirrors, with an effective mass of the order of micrograms, can be generated between the motion of the four mirrors in a LIGO-type GW observatory. Here, the generated entanglement is with respect to position and momentum of the entire pendulum suspended mirrors, however, not for the resonance mode of the pendula but for overtone modes of the frequency band f ± Δf, for which the sum of all classical noise contributions was below the spectral density of the SQL. The continuous monitoring of the mechanical mode allowed for the measurement of the thermally driven random walk and for the conditioning (referencing) of the quantum uncertainties with respect to this random walk.

Using an optomechanical system in a nonclassical Gaussian states for probing decoherence processes is done via continuous monitoring of the states uncertainty under the continuous influences of optomechanical coupling and decoherence. Crucial is the reconstruction of the thermally driven random walk and subtracting it from the measurement data. The quantum uncertainty is then revealed conditioned on the knowledge of this classical trajectory. Unlike the conditioning on the click of a photon detector in non-Gaussian state preparation, here a full measurement record is taken into account to estimate the current state. The classical random walk requires optimal processing of the information with the use of Wiener (or Kalman) filtering, which includes the complete model of the system. This allows to trace the random evolution of the state, as well as its uncertainty, as it was theoretically proposed, further theoretically investigated, and recently demonstrated experimentally.

Continuous monitoring and conditioning on the knowledge of the mean random walk provide the key feature that allows to check for the changes in the evolution of the quantum state, and not only for stationary effects. This can allow to directly probe for modifications to the Schrödinger equation, which governs the evolution of the system, and potentially see the dynamical effects of decoherence, possible non-linearities in the equation or signatures of classical gravity. Usually, in order to observe these changes, the system should be allowed to evolve freely, without interaction with the probe light.

The state after the free evolution is then verified and compared to the predicted dynamics, as was demonstrated experimentally. At this stage any deviation from the predicted dynamics becomes visible. The verification stage is required, since the state obtained during the preparation stage depends on the validity of the model for the system. The main difficulty of this process is in the need for sub-SQL sensitivity for revealing non-classical features. The verification step is crucial, but also the most difficult, since it requires a back-action evasion protocol in order to reveal non-classical features in the state.

Continuous monitoring of a nonclassical Gaussian optomechanical quantum state can allow for detecting decoherence effects, which might be not visible with the use of non-
Gaussian states. For example, if the entanglement is prepared for the mirrors of LIGO for the 50 Hz Fourier mode, and then let to evolve freely, it would decohere due to thermalization over the timescale of $\approx 3\,\text{ms}$. One of the gravitational decoherence models suggest the characteristic timescale of $\tau_{\text{gd}} \approx 1\,\mu\text{s}$ (based on the consideration in Ref. 23). Therefore, if we verify the state after $\sim 100\,\mu\text{s}$, and find no entanglement between the test masses, we can be confident that this decoherence occurred due to the unknown mechanism, possibly gravitational. The timescales of the experiment are easily adjustable, since it is done in continuous regime. Similar experiment with non-Gaussian states would be difficult, since the preparation of the state is single-shot.

Although the dynamics of the entangled state would allow for testing for a wide parameter range of decoherence models, conditional state preparation is experimentally challenging. We suggest that even the direct observation of ponderomotively squeezed states in optomechanical experiments can act as a probe of spontaneous decoherence processes on the mechanical motion. If the mirror motion spontaneously decoheres during the interaction time of light and mirror, the ponderomotively squeezed state becomes a mixture of several states and its purity degrades. The quantum correlation between the reflected light and the mirror motion is always affected by several decoherence mechanisms from the local environment. If a spontaneous decoherence mechanism exists on top, it might be observable and quantified if reference measurements can be used to quantify all environmental decoherence mechanisms. This way, the LIGO experiment can in principle be used to search for unknown spontaneous (gravitational) decoherence mechanisms. Whether the conventional decoherence mechanisms can be quantified with a precision high enough to actually challenge well-motivated spontaneous decoherence mechanisms is not investigated here. However, in Ref. 25 it is argued that even with mixed states it might be possible to observe signatures of gravitational decoherence. In any case, the result in Ref. 25 can be used to set an upper bound for spontaneous decoherence mechanisms, simply because the quantum noise could be inferred to be below the SQL.

V. SUMMARY AND CONCLUSIONS

Gravitational-wave astronomy requires unprecedented sensitivities for measuring the tiny space-time oscillations at audio-band frequencies and below. 40 kg mirrors that are suspended as pendulums act as space-time test masses, and light fields of several 100 kW measure the changes in their distances. The high mass minimises the mirrors’ quantum uncertainties in position and momentum on absolute scales, the effect of the light’s radiation pressure uncertainty, as well as disturbances on the mirror motion due to the environment. Mechanical resonances have high quality factors and are designed to keep away thermally driven vibrations from the relevant spectrum. 27 The mirrors’ triple pendulum suspensions are complemented by a series of passive and active seismic isolations. 23,26 Mirror surfaces are super-polished to minimise light scattering and feedback of back-scattered light that carry modulations due to the movements of the environment. 25,29 The light power is high to maximise the optical GW signal on the output beam with respect to the latter’s quantum uncertainty. Despite the high power, neither the amplitude nor the frequency of the input light carry relevant disturbances from the environment, which is realised by a large number of passive and active laser stabilisation units. 29 Due to all these efforts, the light’s radiation pressure produces observable correlations of the optical and mechanical quantum uncertainties. A recent observation in Virgo showed that the quantum uncertainties of the light fields in the arms produce such a large differential quantum radiation pressure noise that it contributed significantly to the observatories sensitivity between 30 Hz and 70 Hz. 25 During this observation, Virgo used its squeeze laser to squeeze the shot noise on the output photo diode. Consequently, as described by Heisenberg’s uncertainty relation, the differential quantum radiation pressure in the arms had to increase.

LIGO used its squeeze laser to demonstrate the effect of ponderomotive squeezing, which is additional, superimposed squeezing due to the coupling of the light’s radiation pressure uncertainty and the momentum/position uncertainty of the mirror motion. 25 Ponderomotive squeezing is only produced if the quantum uncertainties of reflected light and mirror motion are quantum correlated. The injected squeezing plus the ponderomotive squeezing resulted in a quantum noise that was below the standard quantum limit (SQL) between 30 Hz and 50 Hz. This observation was possible after classical noise of about 1.5-times higher standard deviation was subtracted.

The quantum uncertainties of the test mass motion in LIGO and Virgo, as they were imprinted on the reflected light in 26 and 25, had magnitudes as expected. If they had been significantly weaker, potentially not visible at all, they would have pointed to an unknown decoherence process acting on the mirror motion. There are indeed hypothetical spontaneous decoherence mechanisms, which were proposed to explain why quantum coherent effects are not observed on macroscopic objects. Prominent examples are ‘gravitationally induced spontaneous localisation’ according to the Diósi-Penrose model. 25,29 Their typical rationals, however, lead to weak decoherence rates, which are not testable with state of the art technology. 25,29,74 Only a modified version of gravity decoherence as conjectured in 29 leads to sufficiently short decoherence times whose measurement is feasible. Other continuous spontaneous localisation (CSL) models that are independent of gravity were also proposed. 59,61 Some of them might result in measurable decoherence effects.

Historically, optomechanical non-Gaussian quantum states were first proposed for testing spontaneous decoherence/localisation models. In particular Schrödinger cat states, whose superimposed position states are macroscopically distinct and separated by more than the size of the gravitating body, seemed promising for testing gravitational decoherence models. 22,27,62,63 But these states are way beyond state of the art technology. 63 Feasible are only non-Gaussian states of mechanical oscillators, whose dimension is much larger than the size of the quantum uncertainty.
Taking this for granted, Gaussian nonclassical optomechanical states seem to us as suitable for testing spontaneous localisation models as the non-Gaussian ones. We suggest using the ponderomotively squeezed optical states. In the ideal case of zero decoherence on the light field and on the mirror motion, ponderomotively squeezed states are pure and have minimal quantum uncertainties. Spontaneous as well as environmental decoherence effects would be measured on a stationary system, in which continuous-wave light continuously places the optomechanical system of mirror motion and reflected light in a quantum correlated state. The various decoherence mechanisms continuously mix the state with uncorrelated thermal mechanical and optical states, and the continuous sampling on the steady-state light/mirror system would result mixed optical states with an above minimum uncertainty product. Quantum tomography on the output light in GW observatories is possible by replacing the traditional photo diode. Quantum tomography on the output light in GW observatories, however, is very low. The quantum correlations disturbances due to back-scattered light information but additionally allows for vetoing non-stationary two quadrature fields, which also provides the full quantum two such photo diodes in balanced homodyne detector arrangement, which needs to subsequently measure the field variance at some sideband frequency near the SQL in the most squeezed quadrature and in the one 90° off. Alternatively, two balanced homodyne detectors simultaneously measure the two quadrature fields, which also provides the full quantum information but additionally allows for vetoing non-stationary disturbances due to back-scattered light[100]. The sensitivity of searches for such unknown decoherence processes in GW observatories, however, is very low. The quantum correlations between the optical field and mirror movement are observable but obscured by thermal energy and other noise sources.

ACKNOWLEDGMENTS

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) under Germany’s Excellence Strategy EXC 2121 ‘Quantum Universe’ – 390833306.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors have no conflicts to disclose.

REFERENCES

1. A. Aspect, P. Grangier, and G. Roger, “Experimental Tests of Realistic Local Theories via Bell’s Theorem,” Physical Review Letters 47, 460 (1981).
2. E. Schrödinger, “Die gegenwärtige Situation in der Quantenmechanik,” Die Naturwissenschaften 23, 807–812 (1935).
3. D. F. Walls, “Squeezed states of light,” Nature 306, 141–146 (1983).
4. R. Schnabl, “Squeezed states of light and their applications in laser interferometers,” Physics Reports 684, 1–51 (2017).
5. Y. Ou, S. F. Pereira, H. J. Kimble, and K. C. Peng, “Realization of the Einstein-Podolsky-Rosen paradox for continuous variables,” Physical Review Letters 68, 3663–3666 (1992).
6. W. P. Bowen, R. Schnabl, H.-A. Bachor, and P. K. Lam, “Polarization Squeezing of Continuous Variable Stokes Parameters,” Physical Review Letters 88, 4 (2002).
7. B. P. Abbott et al., “Observation of Gravitational Waves from a Binary Black Hole Merger,” Physical Review Letters 116, 061102 (2016), CC BY: https://creativecommons.org/licenses/by/3.0/.
8. C. Caves, “Quantum-mechanical noise in an interferometer,” Physical Review D 23, 1693–1708 (1981).
9. J. Hollenhorst, “Quantum limits on resonant-mass gravitational-radiation detectors,” Physical Review D 19, 1669–1679 (1979).
10. R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley, “Observation of Squeezed States Generated by Four-Wave Mixing in an Optical Cavity,” Physical Review Letters 55, 2409–2412 (1985).
11. H. J. Kimble, J. L. Hall, and W. H. Wu, “Generation of Squeezed States by Parametric Down Conversion,” Physical Review Letters 57, 2520–2523 (1986).
12. K. McKenzie, N. Grosse, W. P. Bowen, S. E. Whitcomb, M. B. Gray, McCelland, and Lam, “Squeezing in the Audio Gravitational-Wave Detection Band,” Physical Review Letters 93, 161105 (2004).
13. H. Vahlbruch, S. Chelkowski, B. Hage, A. Franzen, K. Danzmann, and R. Schnabl, “Demonstration of a Squeezed-Light-Enhanced Power- and Signal-Recycled Michelson Interferometer,” Physical Review Letters 95, 211102 (2005).
14. H. Vahlbruch, S. Chelkowski, B. Hage, A. Franzen, K. Danzmann, and R. Schnabl, “Coherent Control of Vacuum Squeezing in the Gravitational-Wave Detection Band,” Physical Review Letters 97, 011101 (2006).
15. H. Vahlbruch, S. Chelkowski, K. Danzmann, and R. Schnabl, “Quantum engineering of squeezed states for quantum communication and metrology,” New Journal of Physics 9, 371–371 (2007).
16. H. Vahlbruch, M. Mehmet, S. Chelkowski, B. Hage, A. Franzen, N. Lastzka, S. Gölter, K. Danzmann, and R. Schnabl, “Observation of Squeezed Light with 10-dB Quantum-Noise Reduction,” Physical Review Letters 100, 033602 (2008).
17. H. Vahlbruch, A. Khalaidovski, N. Lastzka, C. Gräf, K. Danzmann, and R. Schnabl, “The GEO 600 squeezed light source,” Classical and Quantum Gravity 27, 084027 (2010).
18. R. Schnabl, N. Mavalvala, D. E. McClelland, and P. K. Lam, “Quantum metrology for gravitational wave astronomy,” Nature communications 1, 121 (2010).
19. J. Abadie et al., “A gravitational wave observatory operating beyond the quantum shot-noise limit,” Nature Physics 7, 962–965 (2011).
20. H. Grote, K. Danzmann, K. L. Dooley, R. Schnabl, J. Slutsky, and H. Vahlbruch, “First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observer,” Physical Review Letters 110, 181101 (2013).
21. J. Lough, E. Schreiber, F. Bergamin, H. Grote, M. Mehmet, H. Vahlbruch, C. Affeldt, M. Brinkmann, A. Bisht, V. Kringle, H. Lück, N. Mukund, S. Nadji, B. Sorazu, K. Strain, M. Weinert, and K. Danzmann, “First Demonstration of 6 dB Quantum Noise Reduction in a Kilometer Scale Gravitational Wave Observer,” Physical Review Letters 126, 041102 (2021).
22. M. Tse et al., “Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy,” Physical Review Letters 123, 231107 (2019).
23. F. Acernese et al., “Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light,” Physical Review Letters 123, 231108 (2019).
24. R. Abbott et al., “GWTEO-2 Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run,” Physical Review X 11, 021053 (2021).
Macroscopic quantum mechanics in gravitational-wave observatories and beyond

25. H. Yu et al., “Quantum correlations between light and the kilogram-mass mirrors of LIGO,” Nature 583, 43–47 (2020).

26. F. Acernese et al. (The Virgo Collaboration), “Quantum backaction on kg-scale mirrors: Observation of radiation pressure noise in the advanced virgo detector,” Phys. Rev. Lett. 125, 131101 (2020), CC BY https://creativecommons.org/licenses/by/4.0/.

27. W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester, “Towards Quantum Supereposition of a Mirror,” Physical Review Letters 91, 130401 (2003), https://doi.org/10.1103/PhysRevLett.91.130401.

28. H. J. Kimble, Y. Levin, A. B. Matsko, K. S. Thorne, and S. P. Vyatchanin, “Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics,” Physical Review D 65, 022002 (2001).

29. R. Schuller, “Quantum Weirdness in Exploitation by the International Gravitational-Wave Observatory Network,” Annalen der Physik 532, 1900508 (2020).

30. C. Whittle et al., “Approaching the motional ground state of a 10-kg object,” Science 372, 1333–1336 (2021).

31. M. Rossi, D. Mason, J. Chen, and A. Schliesser, “Observing and Verifying the Quantum Trajectory of a Mechanical Resonator,” Physical Review Letters 125, 163601 (2020).

32. N. Aggarwal, T. J. Cullen, J. Cripe, G. D. Cole, R. Lanza, A. Libson, D. Follman, P. Heu, T. Corbitt, and N. Mavalvala, “Room-temperature multistage vibration isolation system for Advanced Virgo suspended optics,” Nature Photonics 14, 19–23 (2020).

33. J. Cripe, T. Cullen, Y. Chen, P. Heu, D. Follman, G. D. Cole, and T. Corbitt, “Quantum Backaction Cancellation in the Audio Band,” Physical Review X 10, 031065 (2020).

34. D. Mason, J. Chen, M. Rossi, Y. Tsaturyan, and A. Schliesser, “Continuous force and displacement measurement below the standard quantum limit,” Nature Physics 15, 745–749 (2019).

35. F. Ockeloen-Korppi, E. Damskägg, J. M. Pirkkalainen, M. Asjad, A. A. Clerk, F. Massel, J. M. Woolley, and M. A. Sillanpää, “Stabilized entanglement of massive mechanical oscillators,” Nature 556, 478–482 (2018).

36. J. Chen, M. Rossi, D. Mason, and A. Schliesser, “Entanglement of propagating optical modes via a mechanical interface,” Nature Communications 11, 943 (2020).

37. R. A. Thomas, M. Parniak, C. Østfeldt, C. B. Møller, C. Berrentsen, Y. Tsaturyan, A. Schliesser, J. Appel, E. Zeuthen, and E. S. Polzik, “Entanglement between distant macroscopic mechanical and spin systems,” Nature Physics 17, 228–233 (2021).

38. S. Kotler, G. A. Peterson, E. Štoupae, F. Lecocq, K. Cicak, 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 mono-lithic fused silica suspension,” Classical and Quantum Gravity 32, 035005 (2015).

39. M. Granata, A. Amato, G. Cagnoli, M. Coulon, J. Degallaix, D. Forrest, L. Mereni, C. Michel, L. Pinard, B. Sassolas, et al., “Progress in the measurement and reduction of thermal noise in optical coatings for gravitational-wave detectors,” Applied optics 59, A229–A235 (2020).

40. V. Van Heijningen, A. Bertolini, E. Hennes, M. G. Beker, M. Doets, H. J. Bulten, K. Agatsuma, T. Sekiguchi, and J. F. Van Den Brand, “A multistage vibration isolation system for Advanced Virgo suspended optical benches,” Classical and Quantum Gravity 36, 2–16 (2019).

41. S. L. Danilishin, F. Y. Khalili, and H. Miao, “Advanced quantum techniques for future gravitational-wave detectors,” (2019), arXiv:1903.05222.

42. W.H.Zurek, “Decoherence, einselection, and the quantum origins of the classical,” Reviews of Modern Physics 75, 715 (2003).

43. G. C. Ghirardi, P. Pearle, and A. Rimini, “Markov processes in Hilbert space and continuous spontaneous localization of systems of identical particles,” Physical Review A 42, 78–89 (1990).

44. A. Bassi and G. Ghirardi, “Dynamical reduction models,” Physics Reports 379, 257–426 (2003).

45. A. Bassi, L. Occhialini, S. Satin, S. Singh, and H. Ulbricht, “Models of wave-function collapse, underlying theories, and experimental tests,” Reviews of Modern Physics 85, 471–527 (2013).

46. L. Diósi, “A universal master equation for the gravitational violation of quantum mechanics,” Physics Letters A 120, 377–381 (1987).

47. L. Diósi, “Models for universal reduction of macroscopic quantum fluctuations,” Physical Review A 40, 1165–1174 (1989).

48. R. Penrose, “On Gravity’s Role in Quantum State Reduction,” General Relativity and Gravitation 28, 581–600 (1996).

49. R. Penrose, “Quantum computation, entanglement and state reduction,” Phil. Trans. R. Soc. Lond. A 356, 1927 (1998).

50. F. Karolyhazy, “Gravitation and quantum mechanics of macroscopic objects,” Il Nuovo Cimento A 42, 390–402 (1966).

51. A. Bassi, A. Grolaard, and H. Ulbricht, “Gravitational decoherence,” Classical and Quantum Gravity 34, 193002 (2017).

52. S. Bose, K. Jacobs, and P. Knight, “Scheme to probe the decoherence of a macroscopic object,” Physical Review A 59, 3204–3210 (1999).

53. J. Z. Bernád, L. Diósi, and T. Geszt, “Quest for quantum superpositions of a mirror: High and moderately low temperatures,” Physical Review Letters 97, 8–11 (2006).
Macroscopic quantum mechanics in gravitational-wave observatories and beyond

70S. L. Adler, “Comments on proposed gravitational modifications of Schrödinger dynamics and their experimental implications,” Journal of Physics A: Mathematical and Theoretical 40, 755–763 (2007).

71D. Kleckner, I. Pikovsky, E. Jeffrey, L. Amin, E. Elieil, J. Van Den Brink, and D. Bouwmeester, “Creating and verifying a quantum superposition in a micro-optomechanical system,” New Journal of Physics 10, 081005 (2008).

72S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Torsi, M. Paternostro, A. A. Geraci, P. F. Barker, M. S. Kim, and G. Milburn, “Spin Entanglement Witness for Quantum Gravity,” Physical Review Letters 119, 0126 (2017).

73S. Nimmrichter, K. Hornberger, P. Haslinger, and M. Arndt, “Testing spontaneous localization theories with matter-wave interferometry,” Physical Review A 83, 043621 (2011).

74J. Howl, R. Penrose, and I. Fuentes, “Exploring the unification of quantum theory and general relativity with a Bose-Einstein condensate,” New Journal of Physics 21 (2019), 10.1088/1367-2630/ab104a.

75A. I. Lvovsky, H. Hansen, T. Aichele, O. Benson, and J. Mlynek, “Quantum State Reconstruction of the Single-Photon Fock State,” Physical Review Letters 87, 50402 (2001).

76R. Riedinger, A. Wallucks, I. Marinković, C. Löschnauer, M. Aspelmeyer, S. Hong, and S. Gröblacher, “Remote quantum entanglement between two micromechanical oscillators,” Nature 556, 473–477 (2018).

77F. Khalili, S. Danilishin, H. Miao, H. Müller-Ebhardt, H. Yang, and Y. Chen, “Preparing a Mechanical Oscillator in Non-Gaussian Quantum States,” Physical Review Letters 105, 070403 (2010).

78J. Zhang, K. Peng, and S. Braunstein, “Quantum-state transfer from light to macroscopic oscillators,” Physical Review A 68, 031808 (2003).

79S. Nimmrichter, K. Hornberger, and K. Hammerer, “Optomechanical sensing of spontaneous wave-function collapse,” Physical Review Letters 113, 020405 (2014).

80H. Vahlbruch, M. Mehmet, K. Danzmann, and R. Schnabel, “Detection of 15 dB Squeezed States of Light and their Application for the Absolute Calibration of Photoelectric Quantum Efficiency,” Physical Review Letters 117, 110801 (2016).

81S. Bose, K. Jacobs, and P. Knight, “Preparation of nonclassical states in cavities with a moving mirror,” Physical Review A 56, 4175–4186 (1997).

82D. Vitali, S. Mancini, and P. Tombesi, “Stationary entanglement between two movable mirrors in a classically driven Fabry-Perot cavity,” Journal of Physics A: Mathematical and Theoretical 40, 8055–8068 (2007).

83H. Müller-Ebhardt, H. Rehbein, R. Schnabel, K. Danzmann, and Y. Chen, “Entanglement of Macroscopic Test Masses and the Standard Quantum Limit in Laser Interferometry,” Physical Review Letters 100, 013601 (2008).

84H. Müller-Ebhardt, H. Rehbein, C. Li, Y. Mino, K. Somiya, R. Schnabel, K. Danzmann, and Y. Chen, “Quantum-state preparation and macroscopic entanglement in gravitational-wave detectors,” Physical Review A 80, 043802 (2009).

85R. Schnabel, “Einstein-Podolsky-Rosen-entangled motion of two massive objects,” Physical Review A 92, 012126 (2015).

86H. Müller-Ebhardt, On quantum effects in the dynamics of macroscopic test masses, Ph.D. thesis, Leibniz Universität Hannover (2009).

87U. B. Hoff, J. Kollath-Bönig, J. S. Neergaard-Nielsen, and U. L. Andersen, “Measurement-Induced Macroscopic Superposition States in Cavity Optomechanics,” Physical Review Letters 117, 143601 (2016).

88S. G. Hofer and K. Hammerer, “Entanglement-enhanced time-continuous quantum control in optomechanics,” Physical Review A - Atomic, Molecular, and Optical Physics 91, 1–19 (2015).

89W. Wieczorek, S. G. Hofer, J. Hoelscher-Obermaier, R. Riedinger, K. Hammerer, and M. Aspelmeyer, “Optimal State Estimation for Cavity Optomechanical Systems,” Physical Review Letters 114, 1–6 (2015).

90K. W. Murch, S. J. Weber, C. Macklin, and I. Siddiqi, “Observing single quantum trajectories of a superconducting quantum bit,” Nature 502, 211–214 (2013).

91C. Gut, K. Winkler, J. Hoelscher-Obermaier, S. G. Hofer, R. M. Nia, N. Walk, A. Steffens, J. Eisert, W. Wieczorek, J. A. Slater, M. Aspelmeyer, and K. Hammerer, “Stationary optomechanical entanglement between a mechanical oscillator and its measurement apparatus,” Physical Review Research 2, 1–15 (2020).

92L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. G. Hofer, S. Hong, N. Kiesel, A. Kugi, and M. Aspelmeyer, “Real-time optimal quantum control of mechanical motion at room temperature,” Nature 595, 373–377 (2021).

93B. Helou, J. Luo, H.-C. Yeh, C.-g. Shao, B. J. J. Slagmolen, D. E. McClelland, and Y. Chen, “Measurable signatures of quantum mechanics in a classical spacetime,” Physical Review D 96, 044008 (2017).

94H. Miao, S. Danilishin, H. Müller-Ebhardt, H. Rehbein, K. Somiya, and Y. Chen, “Probing macroscopic quantum states with a sub-Heisenberg accuracy,” Physical Review A 81, 012114 (2010).

95S. Danilishin, H. Miao, H. Müller-Ebhardt, and Y. Chen, “Optomechanical entanglement: How to prepare, verify and steer a macroscopic mechanical quantum state?” Tech. Rep. (2013).

96L. Diósi, “Testing spontaneous wave-function collapse models on classical mechanical oscillators,” Physical Review Letters 114, 1–5 (2015).

97S. Rowan, J. Hough, and D. Crooks, “Thermal noise and material issues for gravitational wave detectors,” Physics Letters A 347, 25–32 (2005).

98J. D. Ottaway, P. Fritschel, and S. J. Waldman, “Impact of upconverted scattered light on advanced interferometric gravitational wave detectors,” Optics Express 20, 8329 (2012).

99P. Kwee, C. Bogan, K. Danzmann, M. Frede, H. Kim, P. King, O. Puncken, R. L. Savage, F. Seifert, P. Wessels, L. Winkelmann, and B. Willke, “Stabilized high-power laser system for LIGO,” Optics Express 20, 459–465 (2012).

100S. Steinlechner, J. Bauchwrotz, M. Meinders, H. Müller-Ebhardt, K. Danzmann, and R. Schnabel, “Quantum-dense metrology,” Nature Photonics 7, 626–630 (2013).