Using quantum correlations to study black holes: squeezing techniques for quantum noise reduction in gravitational wave detectors

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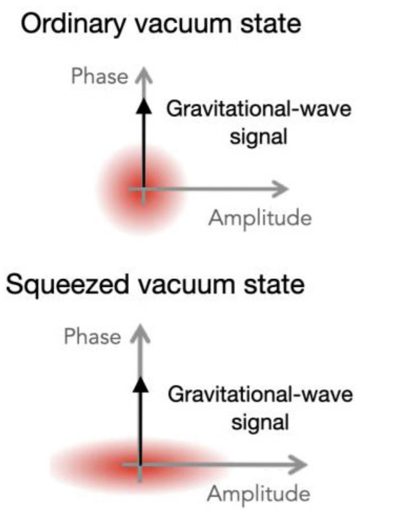

"Experimenters might then be forced to learn how to very gently squeeze the vacuum before it can contaminate the light in the interferometer."

Carlton Caves, 1981

Since 2015, the gravitational-wave detectors LIGO and Virgo have opened a new window on the universe, detecting hundreds of signals and launching a new era of astronomy with profound impact on relativity, astrophysics, and cosmology. To listen deeper into the cosmos, detectors must become increasingly sensitive. One of the main limitations is quantum noise, ultimately arising from vacuum fluctuations entering the instrument. By "squeezing" this vacuum, i.e. manipulating its noise properties, LIGO and Virgo have already extended their reach by up to 65%, revealing events that would otherwise remain hidden. This article provides an overview of squeezing techniques for gravitational-wave detectors, from their origins to the most recent advances.

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In April 2019, the gravitational-wave detectors LIGO and Virgo switched on for their 3rd observation run (O3) after a period of upgrade which allowed them to consistently increase their astrophysical reach. Among the many actions taken during the break, the most remarkable was the injection of a specially prepared quantum state, known as squeezed vacuum. Thanks to this technique, quantum noise, which is the primary factor limiting the instrument's sensitivity, was significantly reduced, allowing the detectors to observe over 50% more black hole mergers. In other words, out of every 10 black holes detected, 3 are observable specifically because of vacuum injection. Although counterintuitive, squeezing injection is arguably the most impactful application of quantum vacuum fluctuations developed to date. An unconventional economist might even venture to quantify, in millions of euros, the value of the vacuum itself.

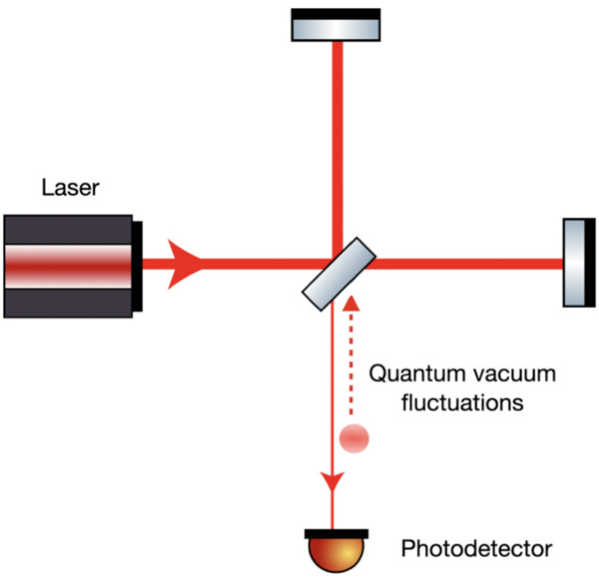
The technique relies on manipulating quantum fluctuations to redistribute uncertainty between the quadratures of the optical field. To understand how vacuum allows us to observe more distant gravitational wave sources, we need to take a step back and address the two theories that revolutionized physics in the 20th century: general relativity and quantum mechanics. Let's begin with the first.
In 1915, Albert Einstein, predicted that spacetime is curved, revolutionizing our

understanding of physics' most fundamental concepts. Einstein showed that Newton's theory of universal gravitation, in which gravity is an instantaneous force between masses, is actually an approximation of a more general theory.

The new theory of general relativity became the framework through which we study the universe at large scale, stars, and new, exotic objects discovered in the 20th century, such as pulsars, black holes, and neutron stars. Soon after publishing his famous equations relating energy and matter to spacetime curvature (the field equations of general relativity), Einstein discovered that a specific solution to these equations involved waves. In other words, the curvature of spacetime, produced by violent phenomena in the universe, can propagate through space, just as electromagnetic waves do. When an extremely energetic phenomenon shakes spacetime, it vibrates, such ripples of the spacetime, called gravitational waves spread throughout the universe.

However, spacetime is extremely rigid and the distortion produced by gravitational waves is incredibly small. We now know that the most powerful sources observed by LIGO and Virgo produced a change in the detector baseline (which is a few km) smaller than the size of an atomic nucleus. Such extremely precise measurement has been done for the first time by LIGO in 2015 [1], and then jointly by LIGO and Virgo in 2017 and it was possible after more than 50 years of experimental development of interferometric detectors. These instruments, known as Michelson interferometers, operate on a simple principle: a laser beam is split into two by a beam splitter and the two paths travel along two perpendicular arms, each several kilometers long. At the

Figure 1. Simplified schematic of a gravitational-wave detector showing the entry points of vacuum fluctuations that give rise to shot noise.

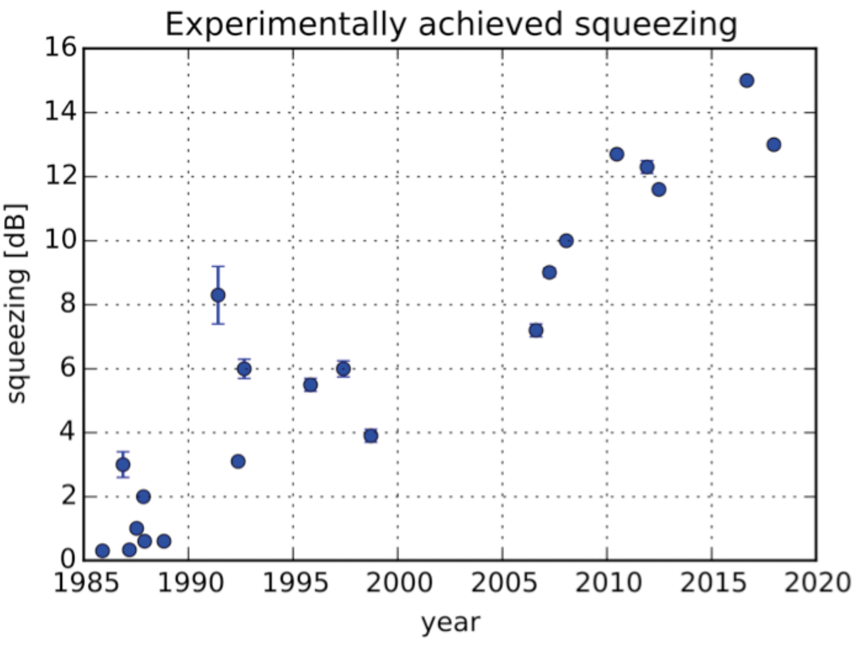


ends of the arms, mirrors reflect the beams back toward the beam splitter. The returning beams recombine at the interferometer output, producing interference. The output power depends on the difference in the arms' lengths. A passing gravitational wave induces a differential change in the arm lengths, altering the interference condition and causing a measurable power variation at the detector output.

The challenge in these measurements lies in reducing every possible source of noise that could mask the tiny variations caused by gravitational waves (of the order of 10^{-19} m over 3 km). Over the past 10 years since the first detection, more than 300 gravitational wave events have been measured from merging compact objects, especially binary black hole systems. This new form of astronomy has already unveiled a new cosmos: previously unobserved binary black hole systems and a new population of more massive black holes. They have also enabled new measurements of the universe's expansion rate, contributing to a major scientific debate that may lead to a crisis in modern cosmology. Over the next decade, gravitational waves will provide even more insight into cosmology, nuclear physics, and astrophysics—and may even offer clues to a quantum theory of gravity, *the holy grail* of theoretical physics.

To push this scientific program forward, detectors must increase their sensitivity more and more. This is a challenging task, as lowering the noise level becomes increasingly difficult when approaching the fundamental limits of the instruments. The main limiting factor is quantum noise, which constrains the detector sensitivity across much of its frequency band (10 Hz to a few kHz). In a semi-classical view, quantum noise arises because light consists of photons. The photon arrival rate in a laser beam follows a Poissonian distribution, meaning the power on a photodiode fluctuates around a mean value. This results in the so-called "shot noise," which limits the precision with which changes in the interferometer's output power can be measured. Reducing shot noise can be achieved by increasing the laser power, as fluctuations scale more slowly than the photon flux. This strategy has been employed and additional power enhancements are planned in upcoming instrument upgrades. Nonetheless, it presents two notable limitations: on one hand, it increases radiation pressure, a random force arising from fluctuations in the arrival times of photons on the interferometer's test masses (i.e., the mirrors), which causes random motion of the mirrors masking the effect of gravitational waves. Moreover, elevated laser power induces thermal effects that deform the interferometer mirrors, introducing optical aberrations which substantially degrade sensitivity and may compromise detector operation.

Figure 2. Timeline of experimentally achieved squeezed-light levels since the first demonstration in 1985, showing steady improvements in noise reduction over time.
From wikipedia: https://commons.wikimedia.org/wiki/File:Squeezed-light-timeline.svg



But light is not just particles; it is also a wave. When we apply quantum mechanics to light, by quantizing the electromagnetic field, we get a different and powerful view of quantum noise. This insight came from the physicist Carlton Caves in the 1980s. While investigating how laser radiation pressure affected detectors, Caves developed a fully quantum picture of quantum noise in the interferometer and realized that it actually comes from the vacuum fluctuations [2]. Such fluctuations, also known as "zero-point fluctuations" allow virtual particles (like photons) to be created and destroyed temporarily, due to Heisenberg's uncertainty principle. They are also responsible for laser spontaneous emission, the Lamb shift, and the Casimir effect (a force between two metal plates in vacuum).

In a fully quantum picture, laser light can be described by a coherent state. Such a state is characterized by the fact that its phase and its amplitude (which are two canonically conjugate variables) have the minimum possible uncertainty allowed by the Heisenberg principle. This laser state can be represented in the phase–amplitude plane as a circle displaced from the origin by an amount corresponding to the laser's amplitude. A vacuum state is also a coherent state, a state with minimum uncertainty, with zero amplitude and its representation in the phase-amplitude plane is a circle cantered in the origin (See Fig. 3 left panel). The key point to keep in mind is that laser and vacuum are much alike when it comes to considering their fluctuations; the only difference is that these fluctuations occur around a given amplitude for the laser and around zero

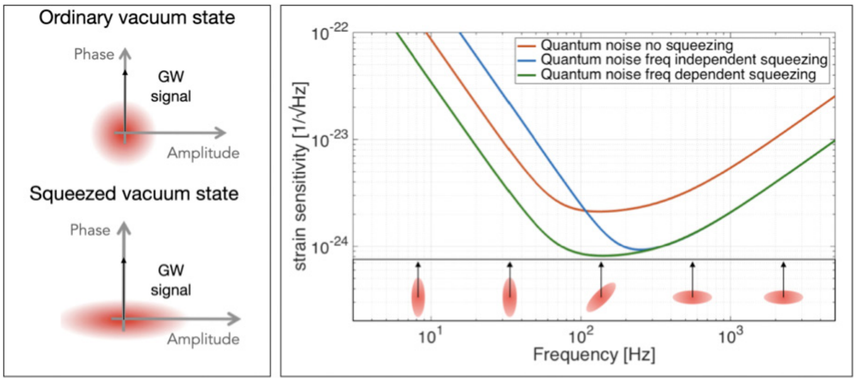


Figure 3. Left panel: Phase–amplitude quadrature representation of a coherent vacuum state (top) and a squeezed vacuum state (bottom). In the coherent case, uncertainties are equal in both quadratures, while in the squeezed case noise is reduced in one quadrature and increased in the other. Right panel (top): Quantum noise reduction achieved by injecting frequency-independent phase squeezing (blue) versus frequency-dependent squeezing (green). Frequency-independent squeezing reduces noise only at high frequencies, increasing it at low frequencies, while frequency-dependent squeezing provides broadband noise suppression. Right panel (bottom): Rotation of the squeezing angle by 90° across the frequency spectrum, caused by optomechanical coupling with the interferometer's suspended test masses. This rotation misaligns the low-noise quadrature with the gravitational-wave signal when only frequency-independent squeezing is used.

for the vacuum. Since such fluctuations are responsible for quantum noise, we cannot limit ourselves to consider those that enter the interferometer with the laser from the bright port but we should also take into account those entering with the vacuum from the output port. Surprisingly enough, while the fluctuations from the laser cancel out when the two beams interfere at the beam splitter, those entering from the output port do not, they recombine with the laser power in the arms and become the ultimate responsible for the quantum noise (See Fig. 1).

This insightful picture of interferometer quantum noise also enabled Caves to propose a fascinating solution: we should manipulate the vacuum fluctuations entering through the output port to "reshape" them and reduce their harmful effects.

We have to say "reshape" and not just "reduce" because in a coherent state, amplitude and phase fluctuations cannot be arbitrarily reduced. In fact, the Heisenberg principle dictates that the product of the uncertainty for two conjugate quadratures (as phase and amplitude in this case) cannot be lower than a given amount. What we can do is to reduce the fluctuation in one quadrature at the expenses of the other. Such a manipulated state, known as squeezed state, has uneven fluctuation in the two quadratures, and can be represented by an ellipse instead of that of a circle (See Fig 3, left panel). It is important to notice that since the interferometer measures phase changes, the uncertainty circle must be squeezed along the appropriate direction to reduce noise. In 1981, Caves proposed this groundbreaking approach to reduce quantum noise without increasing the laser power. In his paper, *"Quantum-Mechanical Noise in an Interferometer"*, he wrote:

"Experimenters might then be forced to learn how to very gently squeeze the vacuum before it can contaminate the light in the interferometer."

It took nearly 40 years of experimental development before squeezing began to be routinely used in LIGO and Virgo. This squeezing is generated using an Optical Parametric Oscillator (OPO), which consists of a nonlinear crystal inside an optical cavity, pumped by a laser at twice the frequency of the light used for the interferometric detection. In the case of LIGO and Virgo, which operate in the near infrared at 1064 nm, the pump laser for the OPO is a green light at 532 nm. The OPO is operated below threshold (meaning the pump power is too low to generate a bright output beam) and the nonlinear crystal inside it enables a process called parametric down-conversion, where energy from the pump can virtually split into pairs of lower-frequency photons. Although no real light is emitted, this interaction modifies the quantum fluctuations of the vacuum field exiting the OPO. The result is a squeezed vacuum state, where noise is reduced in one quadrature (e.g. the phase) and increased in the other one [3].

It sounds simple, but it is much more challenging in practice. Over the years, researchers have progressively increased the level of squeezing produced, that is the ratio between the reduced fluctuations and those of standard vacuum, usually expressed in dB (see Fig.2). However, achieving a significant reduction of quantum noise in the detectors is made difficult by several reasons.

One is that squeezed states are extremely fragile: any optical loss encountered by the squeezed beam reduces its squeezing level. In fact, quantum mechanics tells us that losses cause the squeezed vacuum to recombine with ordinary vacuum, degrading the effect proportionally to the importance of the loss. Optical losses occur everywhere in the interferometer: from transmission through Faraday isolators and anti-reflective mirror coatings, to scattering caused by surface imperfections, and the light picked off for extracting control signals. Minimizing these sources of loss as much as possible is essential to fully exploit the beneficial effect of squeezing on quantum noise. To give an idea, achieving high levels of quantum noise reduction (around 10 dB) requires keeping total optical losses below 8% along the entire optical path.

Another challenge concerns frequency. Virgo and LIGO operate at low frequencies (10 Hz–10 kHz), a range dominated by various disturbances such as electronic, acoustic, and laser frequency noise. Squeezing is far much easier to achieve at MHz frequencies, where these ●●●

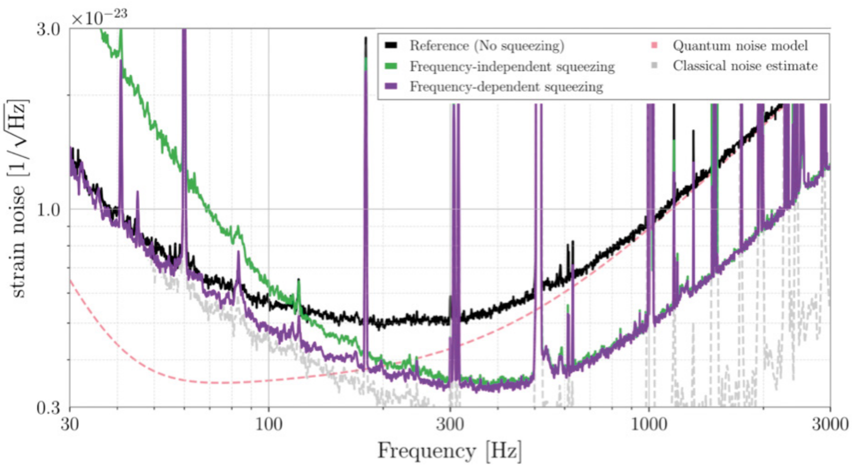


Figure 4. Observation of frequency-dependent squeezing in the LIGO Livingston detector. Noise spectra without squeezing (black) are compared to measurements with frequency-independent (green) and frequency-dependent (purple) squeezing. Frequency-independent squeezing reduces shot noise by 5.8 dB near 1 kHz but increases radiation pressure noise at low frequencies. While, frequency-dependent squeezing yields a 1–2 dB broadband noise reduction from ~60 Hz to 1 kHz, enhancing sensitivity across the whole band. Figure from [8].

disturbances are far less significant. The world is much quieter in the MHz region, with respect to the forest of disturbances in the Virgo-LIGO operation bandwidth. It took, then, decades to learn how to produce a high level of squeezing in the frequency band relevant for gravitational-wave detectors. Finally in April 2019, after months of prototyping and commissioning, squeezed vacuum is injected into Virgo and LIGO. Quantum noise drops by 3 dB: the same effect as doubling laser power. This increases detection rate by up to 50% for the LIGO–Virgo network. It is a great experimental success [4,5].

However, a closer look at the sensitivity below 50 Hz reveals a slight increase in noise when squeezing is injected. The reason is subtle: the reduced-noise quadrature (the minor axis of the squeezing ellipse), which is aligned with the phase quadrature to match the gravitational-wave signal, undergoes a 90-degree rotation at low frequencies due to the opto-mechanical interaction with the suspended test masses.

This means that, at low frequencies, the fluctuations (i.e., the noise) are actually amplified compared to the case where standard vacuum is injected. In practice, the effect is similar to that of a power increase, though without the drawbacks of mirror heating and other issues discussed above. Although the sensitivity degradation induced at low frequency because of this effect was barely observable during Observation Run 3 due mainly to the presence of technical noises, it is expected to become more and more detrimental as the detectors approach their design sensitivity.

Fortunately, a solution was found to enable broadband quantum noise reduction: the injection of frequency-dependent squeezed (FDS) vacuum, in which the squeezing ellipse rotates as a function of frequency to compensate for the rotation induced by the interferometer (see Fig.3, right panel). Such rotation of the squeezing ellipse can be obtained reflecting the frequency independent squeezed states by an optical cavity (known as filter cavity) operated slightly out of its resonant condition. In practice this rotation is produced by the cavity's asymmetric reflection of the upper and lower sidebands of the vacuum field. A detailed explanation and quantitative discussion can be found in [6]. Squeezing angle rotation in the region of interest for gravitational wave detectors has been demonstrated with a full-scale filter cavity prototype in 2020 [7].

For the next observation run (O4), started in May 2023, these frequency-dependent squeezed states have been produced combining the frequency independent squeezed state previously used in Virgo and LIGO with 300 m long suspended filter cavities. LIGO is currently injecting frequency dependent squeezing, obtaining an impressive broadband quantum noise reduction (See Fig. 4) reaching up to 5.8 dB at high frequency and producing an increase in the detection rate of 65%. [8]. As for Virgo, despite the successful construction of the frequency dependent squeezing source [9], it is not yet

Figure 5. View inside the Virgo tunnel showing the filter cavity vacuum pipe running alongside the north arm of the interferometer.

injected into the interferometer, as the low-frequency sensitivity is not yet good enough to take advantage of it. Squeezing will be a key technology also for future detectors. Over the coming years, Virgo, LIGO, KAGRA, and third-generation detectors like the Einstein Telescope will continue improving the squeezing performances aiming to push squeezing levels up to 10 dB, corresponding to a noise reduction by a factor of three. To this purpose ongoing R&D efforts are focusing on reducing losses and adapting squeezing states to different detector configurations. Moreover, the community is investigating alternative quantum noise reduction techniques such as speed-meters, conditional frequency-dependent squeezing, white-light-cavity based schemes or quantum teleportation [10,11].
In conclusion, although quantum principles impose fundamental constraints on the sensitivity of gravitational wave detectors, they also enable strategies to circumvent the Heisenberg limit (of course without violating it!) through the implementation of squeezing techniques. What is truly fascinating is that by exploiting the principles of quantum mechanics at microscopic scales, we can significantly enhance our capacity to investigate the universe at a much larger scale. ●

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