Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement

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In continuously monitored systems the standard quantum limit is given by the trade-off between shot noise and back-action noise. In gravitational-wave detectors, such as Advanced LIGO, both contributions can be simultaneously squeezed in a broad frequency band by injecting a spectrum of squeezed vacuum states with a frequency-dependent squeeze angle. This approach requires setting up an additional long baseline, low-loss filter cavity in a vacuum system at the detector’s site. Here, we show that the need for such a filter cavity can be eliminated, by exploiting Einstein–Podolsky–Rosen (EPR)-entangled signals and idler beams. By harnessing their mutual quantum correlations and the difference in the way each beam propagates in the interferometer, we can engineer the input signal beam to have the appropriate frequency-dependent conditional squeezing once the out-going idler beam is detected. Our proposal is appropriate for all future gravitational-wave detectors for achieving sensitivities beyond the standard quantum limit.

Detection of gravitational waves from merging binary black holes (BBH) by the Laser Interferometer Gravitational-wave Observatory (LIGO) opened the era of gravitational-wave astronomy. The future growth of the field relies on the improvement of detector sensitivity, and the vision for ground-based gravitational-wave detection is to improve, eventually by a factor $\sim 30$ in amplitude in the next 30 years\textsuperscript{4,5}. This will eventually allow us to observe all BBH mergers that take place in the universe, thereby informing on the formation mechanism of BBH, the evolution of the universe\textsuperscript{5,7}, and the way gravitational waves propagate through the universe\textsuperscript{8,9}. Higher signal-to-noise ratio observations of BBH will allow demonstrations and tests of the effects of general relativity in the strong gravity and nonlinear regimes\textsuperscript{10,11}. Besides BBH, gravitational waves from neutron stars are highly anticipated, as well as an active program of joint gravitational-wave and electromagnetic observations\textsuperscript{2,13}. Finally, improved sensitivity may lead to detection of more exotic sources\textsuperscript{14}, as well as surprises.

A key towards better detector sensitivity is to suppress quantum noise, which arises from the quantum nature of light and the mirrors, and is driven by vacuum fluctuations of the optical field entering from the dark port of the interferometer\textsuperscript{15-18}. There are two types of quantum noise: shot noise, the finite displacement resolution due to the finite number of photons, and radiation-pressure noise, which arises from the photons randomly impinging on the mirrors. In the broadband configuration of Advanced LIGO, we measure the phase quadrature of the carrier field at the dark port—the quadrature that contains the gravitational-wave signal. In this case, shot noise is driven by phase fluctuations of the incoming optical field, whereas radiation-pressure noise is driven by amplitude fluctuations. The trade-off between these two types of noise, as dictated by the Heisenberg uncertainty principle, gives rise to a sensitivity limitation called the standard quantum limit (SQL)\textsuperscript{19-21}.

One way to improve the sensitivity of LIGO with minimal modification to its optical configuration is to inject squeezed vacuum into the dark port\textsuperscript{3,22-24}. More than 10 dB of squeezing down to audio sideband frequency ($10$ Hz to $10$ kHz) has been demonstrated in the lab\textsuperscript{25-30}, while moderate noise reductions have been demonstrated in the large-scale interferometers GEO 600 (ref. 31) and LIGO\textsuperscript{32}. However, squeezed vacuum generated by a nonlinear crystal via optical parametric amplification (OPA) is independent of frequency for audio sidebands: within the gravitational-wave frequency band, we can only ‘squeeze’ a fixed quadrature—fluctuations in the orthogonal quadrature are amplified by the same factor, as required by the Heisenberg uncertainty principle. This does not allow broadband improvement of sensitivity beyond the SQL\textsuperscript{19,33}, such as the example shown in Fig. 1; instead, a frequency-dependent quadrature must be squeezed for each sideband frequency. Starting off from frequency-independent squeezing, we must rotate the squeezed quadrature in a frequency-dependent way\textsuperscript{34,35}; for the broadband configuration of Advanced LIGO, this rotation angle needs to gradually transition by $\pi/2$ at a frequency scale of 50 Hz (ref. 35). Kimble et al.\textsuperscript{36} proposed to achieve such rotation by filtering the field with two Fabry–Perot cavities; Khalili further showed that it is often sufficient to use one cavity with bandwidth and detuning (from the carrier frequency) roughly at the transition frequency\textsuperscript{36,37}. However, the narrowness of the bandwidth requires the filter cavity to be long to limit impact from optical losses; the current plan for Advanced LIGO is to construct an approximately 16-m-long filter cavity\textsuperscript{38,39}, and approximately 300-m-long cavities have been studied for KAGRA\textsuperscript{40} and for the Einstein Telescope\textsuperscript{41}. Alternative theoretical proposals for creating narrowband filter cavities were

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entanglement and the dual use of the interferometer as both the gravitational-wave detector and the filter, eliminating the need for external filter cavities.

As shown in Fig. 2, our strategy is divided into the following steps. We first detune the pumping frequency of the OPA away from $2\omega_0$ (where $\omega_0$ is the carrier frequency of the interferometer) to $\omega_p = 2\omega_0 + \Delta$, with $\Delta$ a radiofrequency of a few MHz, creating two EPR-entangled beams: the signal beam around the carrier frequency $\omega_0$, and the idler beam around $\omega_0 + \Delta$. Then the idler beam, being far detuned from the carrier, sees the interferometer as a simple detuned cavity, and experiences frequency-dependent quadrature rotation (see Fig. 3), which can be optimized by adjusting $\Delta$ with respect to the lengths of interferometer cavities. When travelling out of the interferometer, the collinear signal and idler beams are separated and filtered by the output mode cleaners and measured by beating with local oscillators at frequencies $\omega_0$ and $\omega_0 + \Delta$, respectively. Finally, the homodyne measurement of a fixed quadrature of the out-going idler beam conditionally squeezes the input signal beam in a frequency-dependent way, thereby achieving the broadband reduction of quantum noise. Practically, benefit of the conditional squeezing of the signal beam is obtained, as we apply a Wiener filter to the photocurrent of the idler and subtract it from the photocurrent of the signal beam. Without optical losses, using parameters in Table 1 (with a 15 dB squeezed vacuum in particular), we obtain the solid black curve in Fig. 4, with $\sim$11–12 dB improvement over the entire frequency band.

We shall next discuss more details of the configuration, as well as discussed, but they are strongly limited by thermal noise and/or optical losses $^{42-44}$.

In this paper, we propose a novel strategy to achieve broadband squeezing of the total quantum noise via the preparation of EPR entanglement and the dual use of the interferometer as both the gravitational-wave detector and the filter, eliminating the need for external filter cavities.
as the impact of optical losses; further details are provided in Supplementary Methods.

EPR entanglement by detuning the OPA

For an OPA pumped at \( \omega_0 \), it is often convenient to study quadrature fields around \( \omega_0/2 \), which are linear combinations of the upper and lower sideband fields at \( \omega_0/2 \pm \Omega \), with \( \xi \) quadrature defined by:

\[
\hat{c}_\xi(\Omega) = \left( e^{-i\Omega/2} \hat{c}_{\omega_0/2 + \Omega} + e^{i\Omega/2} \hat{c}_{\omega_0/2 - \Omega} \right) / \sqrt{2}
\]

(1)

Here \( \hat{c}_\omega \) and \( \hat{c}_\omega^\dagger \) are the annihilation and creation operators for the optical field at \( \omega \); we use \( \hat{c}_{\omega_0/2} \) to stand for \( \hat{c}_{\omega_0/2 + \Omega} \) and \( \hat{\xi} = \hat{c}_\xi + \hat{c}_\xi^\dagger \sin \xi \). For a squeeze factor \( r \) and squeezing angle \( \theta \), the orthogonal quadratures \( \hat{\xi}_s \) and \( \hat{\xi} + \hat{\xi}_s \) have uncorrelated fluctuations, with spectra given by

\[
S_{\xi_s} = e^{-2r}, \quad S_\xi + \hat{\xi}_s = e^{2r}
\]

(2)

Compared with vacuum, fluctuations in \( \hat{\xi}_s \) are suppressed by \( e^{2r} \), and those in \( \hat{\xi}_s + \hat{\xi}_s \) are amplified by \( e^{2r} \). This is due to the entanglement between the upper and lower sidebands, \( \omega_0/2 \pm \Omega \), generated by the optical nonlinearity. However, any pair of sideband fields with frequencies \( \omega_0 \) and \( \omega_0 \pm \Omega \) within the squeezing bandwidth (usually >MHz) from \( \omega_0 \), and satisfying \( \omega_0 + \omega_0 = \omega_0 \), are entangled; in particular, for the proposed OPA (Fig. 2) with pumping frequency \( \omega_{\text{pump}} = 2\omega_0 + \Delta \), we have entanglement between \( \omega_0 + \Omega \) and \( \omega_0 - \Omega \), as well as \( \omega_0 + \Delta \) and \( \omega_0 - \Delta \), as shown in the upper panel of Fig. 5. As it turns out, this entanglement is equivalent to an EPR-type entanglement\(^{14-17}\) between quadratures around \( \omega_0 \) (consisting of the \( \omega_0 \pm \Omega \) sidebands, denoted by \( \hat{\xi}_s(\Omega) \)) and those around \( \omega_0 + \Delta \) (consisting of \( \omega_0 + \Delta \pm \Omega \) sidebands, denoted by \( \hat{\xi}_s(\Omega) \)). In terms of the four fields, \( \hat{\xi}_s(\Omega) \) and \( \hat{\xi}_s(\Omega) \), they are mutually uncorrelated, and have spectra

\[
S_{\xi_s} = e^{2r}, \quad S_{\xi + \xi_s} = e^{2r}
\]

(3)

In other words, for \( r \gg 1 \), fluctuations in \( \hat{\xi}_s \) and \( \hat{\xi}_s \) are both much below the vacuum level, as in the original EPR situation. In this way (lower panel of Fig. 5), if we detect \( \hat{\xi}_s = \hat{\xi}_s \cos \theta + \hat{\xi}_s \sin \theta \), we can predict \( \hat{\xi}_s = \hat{\xi}_s \cos \theta - \hat{\xi}_s \sin \theta \) with a very good accuracy, while not providing any information for the annihilation operator \( \hat{\xi} \). More precisely, given measurement data of the idler quadrature \( \hat{\xi}_s \), the signal beam will be conditionally squeezed, with conditional spectra

\[
S_{\xi_s} = \cosh(2r), \quad S_{\xi + \xi_s} = \cosh(2r)
\]

(4)

where the squeeze angle is \( -\theta \), and the squeeze factor is \( \log(\cosh(2r))/2 \). For significant squeezing, \( e^{2r} \gg 1 \), this corresponds to 3 dB less squeezing than before detuning the pump field.

Improvement of detector sensitivity

As shown in Fig. 1, after signal beam \( \hat{\xi}_s \) and idler beam \( \hat{\xi}_s \) are fed into the interferometer, we detect phase quadratures of the out-going signal and the idler beams, \( \hat{\xi}_s \) and \( \hat{\xi}_s \), after they are separated and

Table 1 | Sample parameters for Advanced LIGO.

| Parameter       | Value                      |
|-----------------|----------------------------|
| \( \lambda \)   | 1.064 nm                   |
| \( T_{\text{SRM}} \) | 0.35                      |
| \( T \)         | 0.014                      |
| \( L_{\text{arm}} \) | ~4 km                      |
| \( L_{\text{SRC}} \) | ~50 m                      |
| \( \gamma \)    | 40 kg                      |
| \( I_{\text{c}} \) | 650 kW                     |
| \( \Delta \)    | -15.3 MHz                  |
| \( r \)         | 1.23 (15 dB)               |

See Supplementary Methods for details.

Figures 3 and 4 | The differential mode of the interferometer as seen by the signal (upper panel) and idler (lower panel) beams.  

Figure 4 | Sensitivity enhancement. a. Quantum-noise-limited sensitivity of Advanced LIGO configurations with conditional frequency-dependent squeezing by using a 15 dB squeezer at MHz frequencies (see Table 1), assuming no loss (black), and assuming arm cavity loss

epsilon = 100 ppm and sideband cavity loss epsilon = 2,000 ppm, plus an identical input and output loss epsilon = 1% (red), 5% (blue) and 10% (purple). b. The sensitivity improvement factor measured in terms of dB.
In particular, we include losses in the arm cavities, at the input.

In Fig. 4, we plot noise spectra of interferometers with optical losses.

Discussions

in Table 1.

the black curve shows the actual noise spectrum for the parameters

where conditional squeezing provides a \cosh 2r suppression. In reality, we get less suppression since the interferometer, acting as a single cavity, does not exactly realize \Phi_{\text{act}} for the idler beam. In Fig. 4, the black curve shows the actual noise spectrum for the parameters in Table 1.

Best predicted quadrature

Figure 5 | Spectral decomposition of EPR-entangled beams (upper panel) and the quantum statics of the signal and idler beams (lower panel).

filtered by the output mode cleaners (Fig. 2). For the signal beam (upper panel of Fig. 3), we have\(^5\):

which consists of shot noise, radiation-pressure noise, and signal, with \(\beta = \arctan(\Omega / \gamma)\), where \(\gamma\) is the bandwidth of the interferometer seen by the signal beam,

and \(\Theta = [8\omega_0 L_c/(mL_c)]^{1/3}\).

Here we need to squeeze the \(\delta_{\text{act}}(t)/\sqrt{\kappa}\) quadrature of the input signal beam, which requires detecting \(b_{\text{act}}(t)/\sqrt{\kappa}\). If we detect \(B_j\), we will need the interferometer (lower panel of Fig. 3) to apply a rotation of \(\Phi_{\text{act}} = \arctan \kappa\) to the idler beam so that \(\hat{B}_j = \hat{b}_{\text{act}}(t)/\sqrt{\kappa}\). This can be realized approximately by adjusting the detuning \(\Delta\) and the length of signal recycling cavity and arm cavity (see Supplementary Methods for details), if \(\Theta \ll \gamma\). To achieve the sensitivity provided by conditional squeezing, we need to compute the best estimate of \(\hat{A}_j\) from \(\hat{B}_j\), and subtract it from \(\hat{A}_j\). If a rotation by \(\Phi_{\text{act}}\) is realized exactly, we will have a noise spectrum of

where conditional squeezing provides a \cosh 2r suppression. In reality, we get less suppression since the interferometer, acting as a single cavity, does not exactly realize \(\Phi_{\text{act}}\) for the idler beam. In Fig. 4, the black curve shows the actual noise spectrum for the parameters in Table 1.

Discussions

In Fig. 4, we plot noise spectra of interferometers with optical losses. In particular, we include losses in the arm cavities, at the input port, and during readout. As it turns out, the current 100 ppm arm cavity loss and 2,000 ppm signal recycling cavity loss\(^{35}\) have only a small effect on the noise (for details, see Supplementary Methods). When the input loss and the readout loss are both around 10%, the sensitivity improvement is only roughly 3 dB, which corresponds to an amplitude improvement \(\sim 1.4\). However, for a lower loss of 5%, which is promising in the near future\(^{35,48,49}\), we can gain \(~6\) dB or a factor of approximately two improvement in amplitude. This corresponds to an increase of sensitive sky volume by a factor of eight. Compared to the traditional scheme with a filter cavity\(^{35}\), our input and detection losses are doubled, because signal and idler beams experience the same amount of loss during propagation. Although we do suffer less from loss in the filter cavity compared to the design based on an auxiliary filter cavity (since arm cavities have less loss), this higher level of input and detection losses is the price we have to pay in this scheme for eliminating the additional filter cavity.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Y.M., H.M. and Y.C. formulated the idea; Y.M. performed the analysis of the idea and wrote the initial draft, which was later revised by Y.C.; B.H.P. checked Y.M.’s calculation; M.E., J.H., R.S. and C.Z. provided important experimental parameters for doing theoretical analysis and gave valuable comments on Y.M.’s calculations and initial/revised draft.

Additional information

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Competing financial interests

The authors declare no competing financial interests.