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Towards quantum-enhanced gravitational wave detection using entangled light and atomic spin oscillator

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We explore the idea of quantum noise reduction in contemporary gravitational wave detectors (GWDs), outlined in [1,2]. In that theoretical proposal, the measurement on the GWD should be performed in a reference frame of the auxiliary quantum system, which has the same response to the quantum noise. If the reference quantum system acts as a harmonic oscillator with an effective negative mass and approaches the dynamics of a free mass, the broadband reduction of the quantum noise in the hybrid system is possible. To implement the "parallel" measurement on the GWD and the reference oscillator, these two systems should be probed using an entangled state of light.

The talk will present progress towards the experimental realization of this protocol. We have built and characterized the hybrid quantum system, comprising an EPR-entangled state of two optical modes at different wavelengths, one of which is coupled to the atomic spin ensemble. The two entangled modes are chosen to match the wavelengths required for an efficient interaction with the GWD interferometer and the Cs atomic ensemble, respectively [3]. In turn, the spin system is prepared in the regime of the quantum oscillator [4] with the possibility to switch the sign of the effective mass. In particular, we demonstrate that the measurement performed on one of the entangled modes probing the spin ensemble creates a *frequency-dependent conditional squeezing* in the second entangled mode.

The non-classical state of the hybrid system, presented here, exhibits high tunability and, in particular, preserves the quantum features in the frequency range approaching the upper part of the audio band. Further optimization of the low-frequency performance can make our source of frequency-dependent squeezing practically compatible with state-of-the-art GWDs in the interferometric configuration. More generally, we envision potential applications in a broad field of quantum metrology, where the quantum noise of light needs to be manipulated or reduced.

[1] F. Ya. Khalili and E. S. Polzik. Phys. Rev. Lett. 121, 031101 (2018).
[2] E. Zeuthen, F. Ya. Khalili and E. S. Polzik. Phys. Rev. D100, 062004 (2019).
[3] T. B. Brasil et al.. Nature Comm. 13, 4815 (2022).
[4] J. Jia et al. Nature Comm. 14, 6396 (2023).

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