Snowmass2021 - Letter of Interest

Ground-Based Gravitational-Wave Detectors as Advanced Quantum Sensors

Thematic Areas:

■ (IF1) Instrumentation Science: Quantum Sensors
■ (IF2) Instrumentation Science: Photon Detectors
□ (IF3) Solid State Detectors and Tracking
□ (IF4) Trigger and DAQ
□ (IF5) Micro Pattern Gas Detectors (MPGDs)
□ (IF6) Calorimetry
□ (IF7) Electronics/ASICs
□ (IF8) Noble Elements
■ (IF9) Instrumentation Science: Cross Cutting and Systems Integration
■ (CF2) Dark Matter: wave-like
■ (TF10) Quantum Information Science

Contact Information:
Lee McCuller (*MIT*) [mcculler@mit.edu]

Authors:
Lee McCuller, David Shoemaker, Peter Fritschel, Lisa Barsotti, Matthew Evans, Nergis Mavalvala

Abstract:

Gravitational wave (GW) detectors such as advanced LIGO are now enhancing astrophysics observations with quantum squeezing to lower broadband imprecision noise [1, 2, 3], and, while the ultimate profitability of squeezing is limited by optical losses[4], squeezing also faces limitations from back-action noise of the optomechanical detector - 40kg testmass mirrors in a recycled Michelson interferometer [5, 6]. To overcome backaction limits, LIGO plans to employ the technique of frequency dependent squeezing [7, 8]. Proposals for the next generation of detectors[9, 10, 11] continue to use interferometry as their experimental platform with incremental improvements to quantum noise through squeezing to achieve sensitivity goals. We write to express two interests. The first is towards the continued development of optical interferometry and optomechanics as a platform both for gravitational-wave science as well as for light dark matter searches[12, 13, 14, 15, 16, 17]. Our second interest is to further quantum sensing enhancements both from incremental gains in squeezing as well as novel ways to mitigate or circumvent degradation of quantum noise limits from losses, for example by research towards entangled readouts, manipulating bandwidth limits, advanced interferometer configurations, and the preparation of non-Gaussian states in resonant detectors.

1 GW Interferometers within the Quantum Sensing Landscape

Existing and proposed gravitational wave (GW) interferometer observatories are evolving not only via improved mechanical isolation, optics advances and mirror substrate development, but now also through quantum technologies. In the realm of gravitational wave interferometers, the maturation of optical squeezing to enhance astrophysics and the concurrent development towards frequency-dependent squeezing shows the potential to overcome quantum imprecision and back-action, but with a known ceiling from optical loss and decoherence.

Interferometric gravitational wave detectors are configured as Michelson interferometers to continuously record a timeseries of the optical power incident on a photodetector and infer when the modulating field represents that a gravitational wave has passed. These interferometers are additionally enhanced with resonant cavities for two separate purposes: to increase the optical power that sources field modulations and to resonantly enhance differential length signals. Although observed as a timeseries, the signal port and cavities of an interferometer may be viewed as a monitor for photons scattered by modulations of gravitational strain. Large-scale recycled optical interferometers draw an analogy to other resonant detectors such as ADMX or HAYSTAC, which seek to measure photons scattered into a resonant cavity and sensed at either quantum or thermal limits. By this analogy, quantum technology development for resonant detector platforms shows common areas between gravitational wave science and displacement-sensitive interferometers being explored for low threshold energy deposition readout of light dark matter candidates interacting with suspended substrates, as well as detectors where dark matter interacts directly with EM fields.

The following factors are important in determining the quantum noise sensitivity of cavity-enhanced interferometers, and translate to other resonance-enhanced sensors. Each factor presents a limit to detection capability, along with a corresponding research avenue to generically improve sensor performance.

1. Detectors have maximum implementable physical scales such as power, volume, or mass that limit their susceptibility. Quantum states and advanced readouts allow detectors to surpass the usual definition of sensitivity given by the quantum imprecision divided by detector susceptibility.
2. Detectors with high sensitivity/susceptibility become limited by either thermal noise or quantum backaction. Squeezing with filter cavities is a means to reduce backaction. Feedback cooling[18] is a means to reduce thermal noise.
3. Physical scales can impose bandwidth limits in resonant systems, restricting the joint figure-of-merit that integrates detection time, bandwidth, and signal-to-noise. Detector merit might be improved through active modified-dispersion detectors that represent a broader class of quantum improvements than state-preparation/readout that are not so immediately limited by losses.
4. Preparation of Fock, cat, or grid[19, 20] states to enhance phase modulation sensitivity begs the question of what are the fundamental rate limitations by which states may be prepared into and read from resonant systems to gain quantum advantage in detection merit. For contrast, Gaussian state preparation or "squeezing" using parametric amplifiers is continuous and stationary in time, with straightforward frequency domain correlations that may be modeled by covariance matrices in interferometer simulations. These properties are not manifestly shared by alternate quantum resources.

Some of these avenues are being investigated by the GW research represented in the next section, and some, like advanced state preparation, first require the development of enabling technologies such as high throughput, high QE, single photon detectors. We want to express interest that instrumentation research in the light dark matter or other fields to creatively address these limits has likely crossover with GW instrumentation science, and vice versa. Furthermore, it shows areas to communicate existing knowledge on squeezing and to collaborate towards new quantum sensing techniques.

2 R&D Pathways for GW Interferometers

In the previous section we placed gravitational wave interferometers within a generalized view of detectors, but for optical interferometers specifically, the LIGO scientific collaboration and broader GW community is pursuing a number of research directions to overcome the apparent limitations enumerated above. These research directions may be of general interest to the particle physics community. For context, it is worth describing the state of quantum noise in the current and future detectors, using the LIGO and Cosmic Explorer proposed designs as examples. For both detectors, the quantum sensitivity is principally determined by the length, circulating power and readout bandwidth. LIGO is 4km with 0.8 MW and CE is 40 km with 1.4 to 2 MW. Both use the same readout bandwidth of $\sim$500 Hz, but the longer detector must sacrifice some sensitivity due to greater arm delay to preserve the astrophysically motivated band. The test mass mirrors are 40 kg and 320 kg respectively, reducing the prominence of backaction but necessitating more challenging frequency dependent squeezing in the future to compensate what remains.

LIGO currently operates below its design power level, due to challenging integration issues between absorption, thermal lensing, required optical quality, and control of radiation pressure forces. While we make headway towards higher power, squeezing has offered a complementary path to increase sensitivity. A 3 dB improvement is available now, but future upgrades intend to reach 6 dB and next generation detectors aim ultimately for 10 dB. This goal will require optical losses between 5% to 10%, a considerable challenge in its own right and one that must be overcome while developing alternate wavelength detectors.

Distinct from squeezing, the following topics are being investigated for future detectors. Each topic seeks to address various aspects from the limiting factors above. Together, these topics define some avenues where broader instrumentation science may benefit from crosstalk with GW interferometer research.

1. Alternate interferometer configurations: Particularly, non-demolition or back-action evading configurations such as speed meters [21, 22]. These may gain in importance if investigated to complement alternative (non-squeezing) state preparation that could exacerbate backaction or be difficult to compensate with the same filter cavity methods used to enhance squeezing.
2. Active, modified dispersion cavities [23, 24, 25, 26]: Here, nonlinear or active unstable components are incorporated not in the readout but the detector itself to modify the dynamics of signal generation. This can lead to more extreme integration requirements, but for potentially the great benefit of expanding the science case due to greater sensing bandwidth.
3. Back-action avoidance using entanglement of Gaussian states[27, 28, 29], where the correlation properties of squeezing observed at multiple ports or multiple frequencies is exploited to change the effective observable, generally to mitigate backaction.
4. Negative mass backaction compensation [30, 31] uses atomic ensembles and optical frequency conversion to synthesize an effective negative mass interaction as a means to nullify backaction of positive mass mirrors. The expanding toolbox of high-Q microwave cavities and microwave-optical nonlinear elements may enable analogous approaches through new customizable interactions.

For GW detectors, the goal of this research is ultimately to improve our astrophysical reach. This requires not just demonstrating that the concepts work, but that they will integrate with the needs (and losses) of complex detectors. We look to incrementally improve and mature squeezing techniques for optical interferometers, while speculating about the possibility of mitigating losses and decoherence further through non-Gaussian states and blue sky quantum research. To push into new frontiers of quantum sensing and instrumentation, we anticipate the need to collaborate towards integrating novel hardware, expertise and methods. We express our interest towards defining future crossover and collaboration for quantum readouts of displacement-sensing energy deposition detectors and resonant EM cavity experiments.

References

[1] M. Tse *et al.* (LIGO Collaboration), "Quantum-enhanced advanced ligo detectors in the era of gravitational-wave astronomy," Phys. Rev. Lett. **123**, 231107 (2019)

[2] F. Acernese *et al.* (Virgo Collaboration), "Increasing the astrophysical reach of the advanced virgo detector via the application of squeezed vacuum states of light," Phys. Rev. Lett. **123**, 231108 (2019)

[3] J. Lough *et al.*, "First demonstration of 6 dB quantum noise reduction in a kilometer scale gravitational wave observatory," (2020), arXiv:2005.10292 [physics.ins-det]

[4] H. Miao, N. D. Smith, and M. Evans, "Quantum limit for laser interferometric gravitational-wave detectors from optical dissipation," Phys. Rev. X **9**, 011053 (2019)

[5] H. Yu *et al.* (LIGO Scientific, Detector subgroup), "Quantum correlations between light and the kilogram-mass mirrors of LIGO," Nature **583**, 43–47 (2020)

[6] F. Acernese *et al.* (VIRGO Collaboration), "Quantum back-action on kg-scale mirrors - observation of radiation pressure noise in the advanced virgo detector," in preparation (2020)

[7] L. McCuller *et al.*, "Frequency-dependent squeezing for advanced ligo," Phys. Rev. Lett. **124**, 171102 (2020)

[8] Y. Zhao *et al.*, "Frequency-dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors," Phys. Rev. Lett. **124**, 171101 (2020)

[9] D. Reitze *et al.*, "Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO," in *Bulletin of the American Astronomical Society*, Vol. 51 (2019) p. 35, arXiv:1907.04833 [astro-ph.IM]

[10] M. Punturo *et al.*, "The einstein telescope: a third-generation gravitational wave observatory," Classical and Quantum Gravity **27**, 194002 (2010)

[11] R. X. Adhikari, "Gravitational radiation detection with laser interferometry," Rev. Mod. Phys. **86**, 121–151 (2014)

[12] D. Carney *et al.*, "Mechanical Quantum Sensing in the Search for Dark Matter," (2020) arXiv:2008.06074 [physics.ins-det]

[13] H. Liu, B. D. Elwood, M. Evans, and J. Thaler, "Searching for axion dark matter with birefringent cavities," Phys. Rev. D **100**, 023548 (2019)

[14] I. Obata, T. Fujita, and Y. Michimura, "Optical ring cavity search for axion dark matter," Phys. Rev. Lett. **121**, 161301 (2018)

[15] D. Martynov and H. Miao, "Quantum-enhanced interferometry for axion searches," Phys. Rev. D **101**, 095034 (2020)

[16] W. DeRocco and A. Hook, "Axion interferometry," Phys. Rev. D **98**, 035021 (2018)

[17] H. Grote and Y. V. Stadnik, "Novel signatures of dark matter in laser-interferometric gravitational-wave detectors," Phys. Rev. Research **1**, 033187 (2019)

[18] B. Abbott *et al.* (LIGO Scientific), "Observation of a kilogram-scale oscillator near its quantum ground state," New J. Phys. **11**, 073032 (2009)

[19] D. Gottesman, A. Kitaev, and J. Preskill, "Encoding a qubit in an oscillator," Phys. Rev. A **64**, 012310 (2001)

[20] K. Duivenvoorden, B. M. Terhal, and D. Weigand, "Single-mode displacement sensor," Phys. Rev. A **95**, 012305 (2017)

[21] S. L. Danilishin *et al.*, "A new type of quantum speed meter interferometer: measuring speed to search for intermediate mass black holes," (2017), 10.1038/s41377-018-0004-2, arXiv:1702.01029 [gr-qc]

[22] S. L. Danilishin, F. Y. Khalili, and H. Miao, "Advanced quantum techniques for future gravitational-wave detectors," Living Rev. Rel. **22**, 2 (2019), arXiv:1903.05223 [gr-qc]

[23] H. Miao, Y. Ma, C. Zhao, and Y. Chen, "Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters," Phys. Rev. Lett. **115**, 211104 (2015)

[24] J. Bentley, P. Jones, D. Martynov, A. Freise, and H. Miao, "Converting the signal-recycling cavity into an unstable optomechanical filter to enhance the detection bandwidth of gravitational-wave detectors," Phys. Rev. D **99**, 102001 (2019)

[25] V. Adya *et al.*, "Quantum enhanced kHz gravitational wave detector with internal squeezing," Class. Quant. Grav. **37**, 07LT02 (2020)

[26] M. Korobko, Y. Ma, Y. Chen, and R. Schnabel, "Quantum expander for gravitational-wave observatories," Light: Science & Applications **8**, 118 (2019), arXiv:1903.05930 [quant-ph]

[27] Y. Ma *et al.*, "Proposal for Gravitational-Wave Detection Beyond the Standard Quantum Limit via EPR Entanglement," Nature Phys. **13**, 776 (2017), arXiv:1612.06934 [quant-ph]

[28] J. Südbeck, S. Steinlechner, M. Korobko, and R. Schnabel, "Demonstration of interferometer enhancement through Einstein-Podolsky-Rosen entanglement," Nature Photonics **14**, 240–244 (2020), arXiv:1908.09602 [quant-ph]

[29] M. J. Yap, P. Altin, T. G. McRae, B. J. J. Slagmolen, R. L. Ward, and D. E. McClelland , "Generation and control of frequency-dependent squeezing via Einstein-Podolsky-Rosen entanglement," Nature Photonics **14**, 223–226 (2020)

[30] C. B. Møller *et al.*, "Quantum back-action-evading measurement of motion in a negative mass reference frame," Nature **547**, 191–195 (2017), arXiv:1608.03613 [quant-ph]

[31] E. Zeuthen, E. S. Polzik, and F. Y. Khalili, "Gravitational wave detection beyond the standard quantum limit using a negative-mass spin system and virtual rigidity," Phys. Rev. D **100**, 062004 (2019)