Quantum advantage by filtering in optical metrology

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Quantum metrology is the field of using quantum states to accurately estimate unknown quantities, such as magnetic and gravitational fields, distances or time. Often, one cannot measure probes as fast as one can create them. This can lead to detector saturation and information loss. To mitigate this issue, we design a filter to distil all information from many probes into few.

The ability to, via measurements, estimate an unknown parameter θ encoded in N probes, $\rho_\theta{}^{\otimes N}$, is quantified by the quantum Fisher information $\mathcal{I}(\theta|\rho_\theta{}^{\otimes N})$. The quantum Fisher information lower-bounds the variance of every unbiased estimator θ_e of θ via the Cramer-Rao bound: $\mathrm{Var}(\theta_e) \geq 1/\mathcal{I}(\theta|\rho_\theta{}^{\otimes N})$. We show that the quantum Fisher information about θ encoded in $\rho_\theta{}^{\otimes N}$ can be compressed into $\rho_\theta^\star{}^{\otimes M}$, where $M \ll N$ [1]. Moreover, M/N can be made *arbitrarily* small, and the compression can happen *without loss* of information [2].

We experimentally deploy our theory to improve quantum-metrology methods for polarimetry, a common task in optics. We use single photons to probe the strength, θ, of an unknown polarisation rotation. (See Fig. 1.) Direct measurements of the probes yield 1 unit of Fisher information per detected photon. By designing a distillation filter we increased this to >200 units per detection [3]. Thus, our input source could operate at 200 times the detector's saturation intensity, dramatically reducing our θ-estimate's variance. (See Fig. 2.)

The ability to perform this information distillation, we show, stems from nonclassical negativity in a quasiprobability representation of quantum metrology. We demonstrate, theoretically and experimentally, that the more negativity a filter introduces in the quasiprobability representation, the larger the distilled quantum Fisher information can be. Our methods can be used in diverse quantum metrology settings. Even if multiple parameters of $\rho_{(\theta_1,\ldots,\theta_N)}$ are unknown, a filter can be designed to harness negativity and boost the Fisher information per detection.

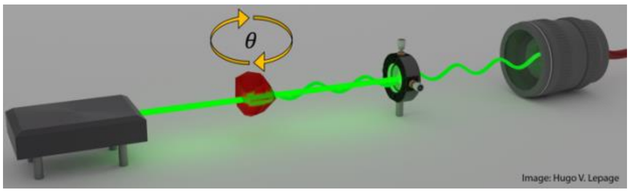

Figure 1: Artistic depiction of our filtered metrology protocol.

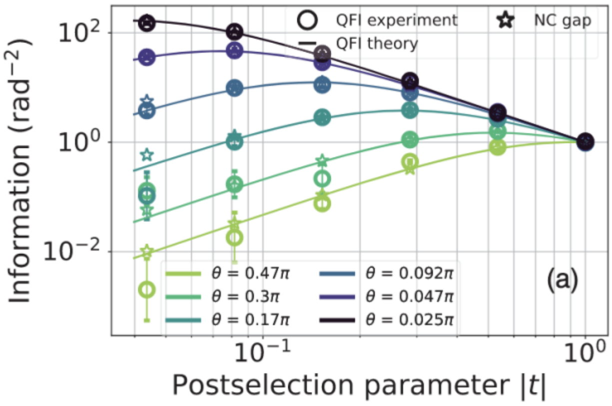

Figure 2: The Fisher information per detected photon vs. the filter's transmission amplitude $|t|$. When no filtering takes place ($|t| = 1$), the detected photon carries 1 unit of information. Using negativity-boosted filtering, we increase this to >200 units of information per detected photon. The success of the compression is sensitive to the filter settings; this figure shows the data obtained with a filter optimised for $\theta \approx 0$. When $\theta \geq 0.17\pi$, the filter can be detrimental.

References

[1] D. Arvidsson-Shukur, et al., *Nat. Comms.*, 11 (2020), 3775
[2] J. Jenne, D. Arvidsson-Shukur, *PRA*, 106, (2022), 042404
[3] N. Lupu-Gladstein, et al., *PRL*, 128 (2022) 220504