Coherent Quantum Noise Cancellation for Opto-mechanical Sensors

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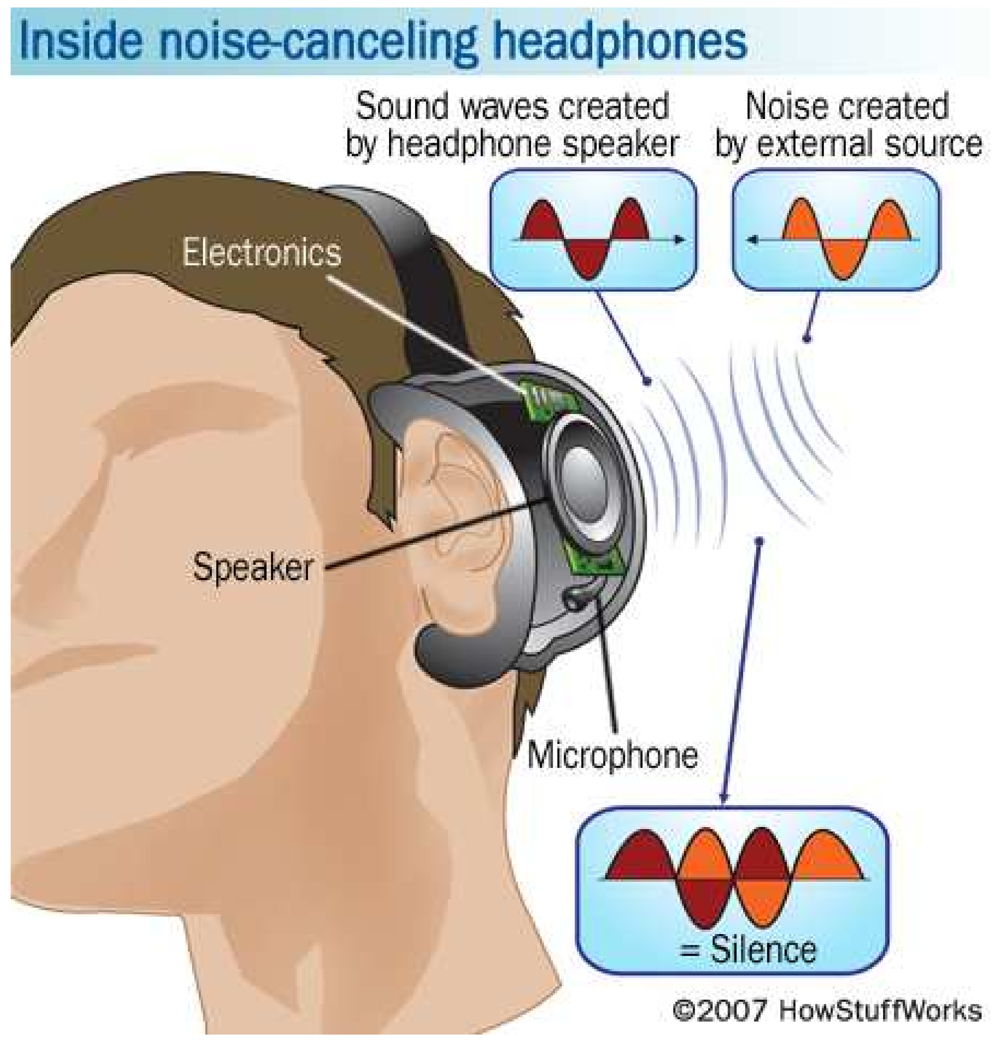
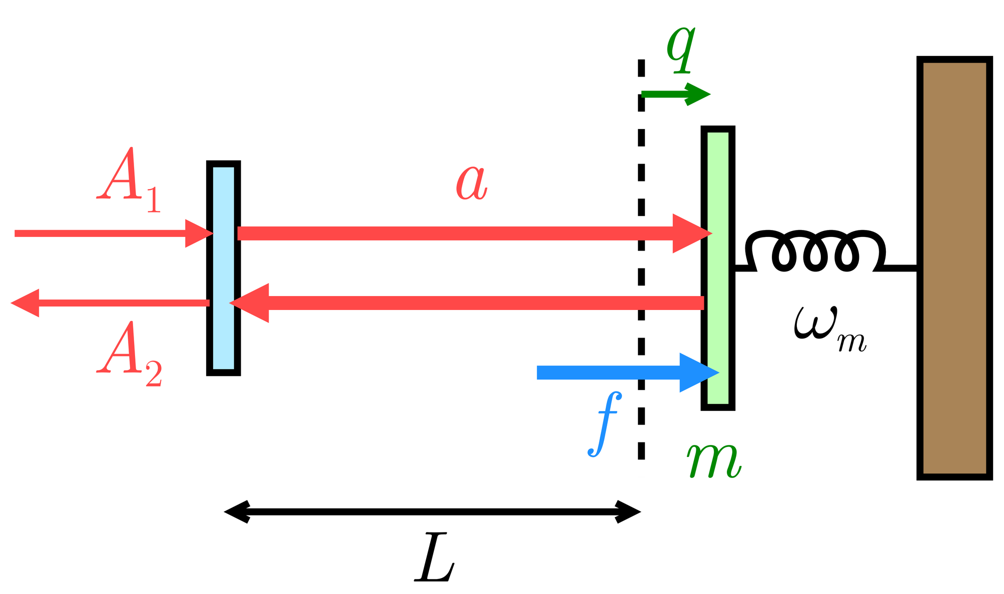
Noise Cancellation



Opto-mechanical Sensor

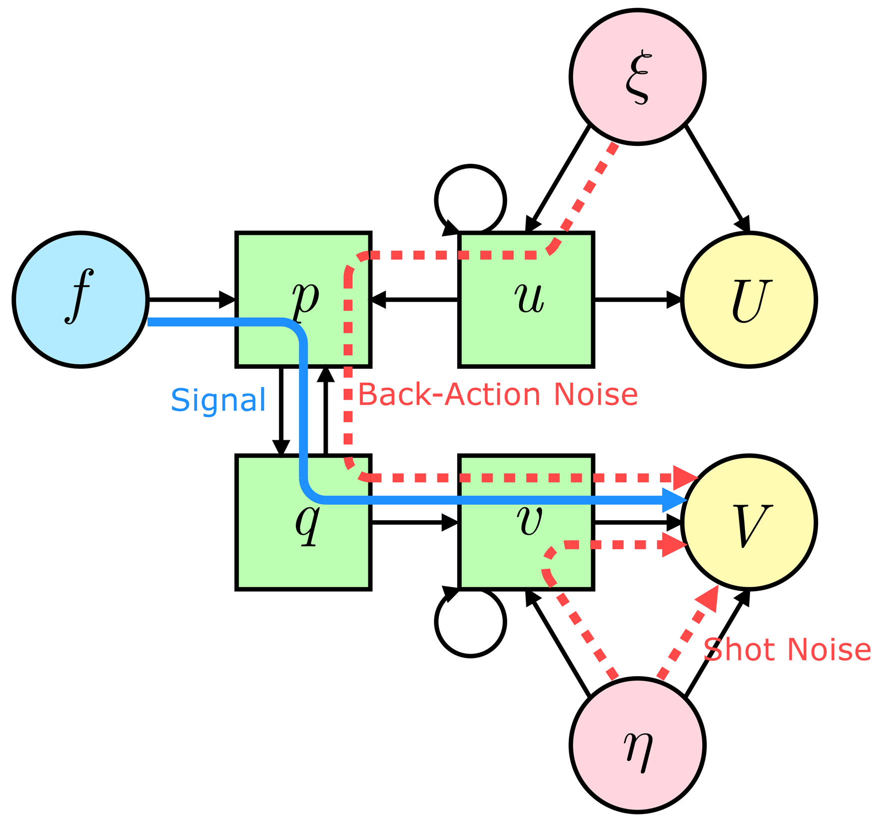


Equations of Motion

- Single optical mode, linearized:

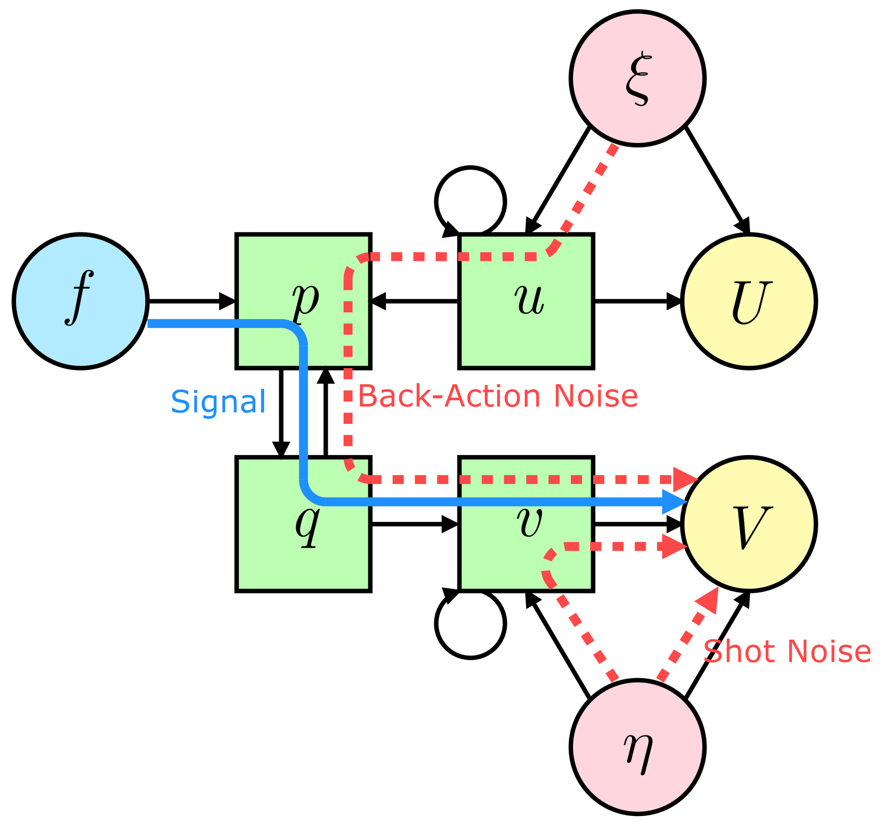
$$\frac{dq}{dt} = \frac{p}{m}, \tag{1}$$
$$\frac{dp}{dt} = -m\omega_m^2 q + f + \hbar\gamma u, \quad \gamma \equiv \frac{\sqrt{2}\omega_0|\alpha|}{L}, \tag{2}$$
$$\frac{du}{dt} = -\frac{\kappa}{2}u + \sqrt{\frac{\kappa}{2}}\xi, \tag{3}$$
$$\frac{dv}{dt} = \gamma q - \frac{\kappa}{2}v + \sqrt{\frac{\kappa}{2}}\eta, \tag{4}$$
$$U = 2|\beta| + \sqrt{2\kappa}u - \xi, \tag{5}$$
$$V = \sqrt{2\kappa}v - \eta. \tag{6}$$

Equivalent Flowchart Representation



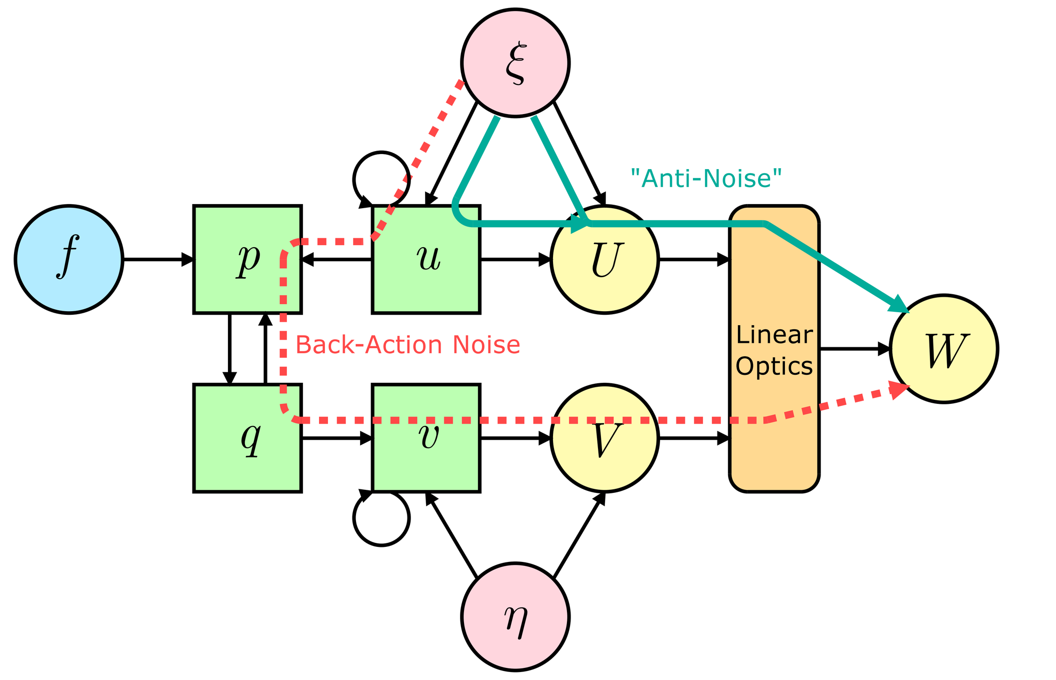
- f = applied force, p = momentum, q = position,
- u = intra-cavity photon-number quadrature, v = intra-cavity phase quadrature
- U, V = travelling wave quadratures,
- ξ, η = quadrature white noises from outside cavity
- Blue arrow: flow of signal to output
- Red arrows: flow of noise to output
- System is linear, signal and noise add at output.
- Standard Quantum Limit (SQL) because of both noise contributions from ξ and η

Input Squeezing



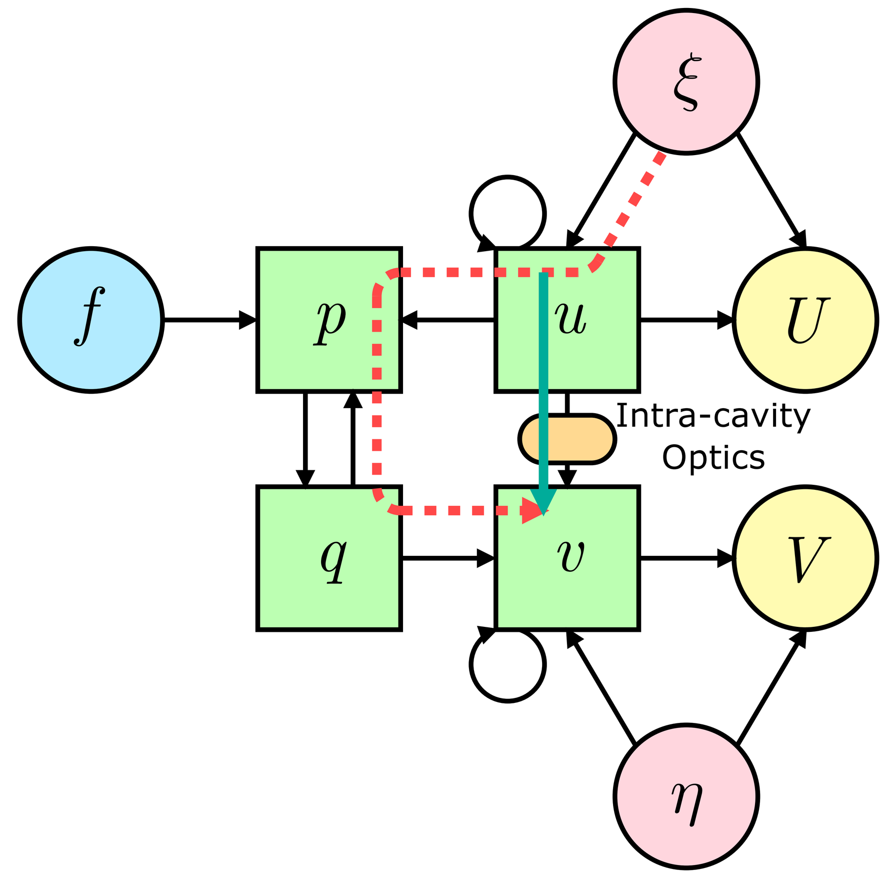
- Caves (PRD **23**, 1693 (1981)): Squeeze η, but then ξ is increased, reach SQL with less power
- Unruh (in *Quantum Optics, Experimental Gravitation, and Measurement Theory*, edited by P. Meystre and M. O. Scully (Plenum, New York, 1982), p. 647.): Squeeze the sum of the red arrows, beat SQL

Variational Output Measurement



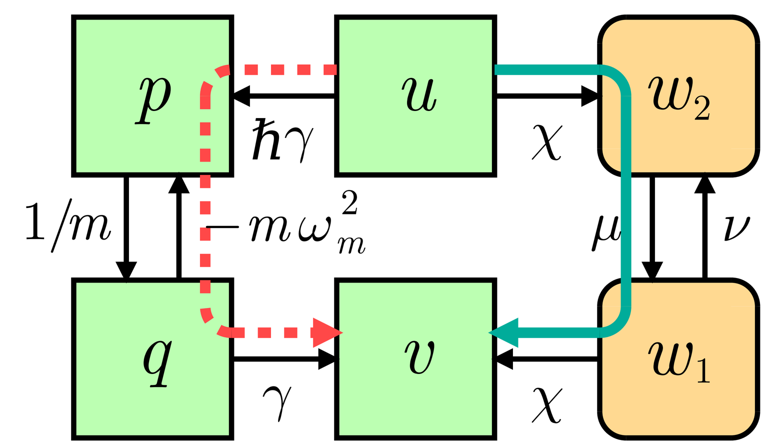
- Kimble *et al.* (PRD **65**, 022002 (2001)): add Fabry-Perot cavities at the output to introduce an anti-noise path
- an example of broadband Coherent Quantum Noise Cancellation (QNC).

Intra-cavity Optical Processing



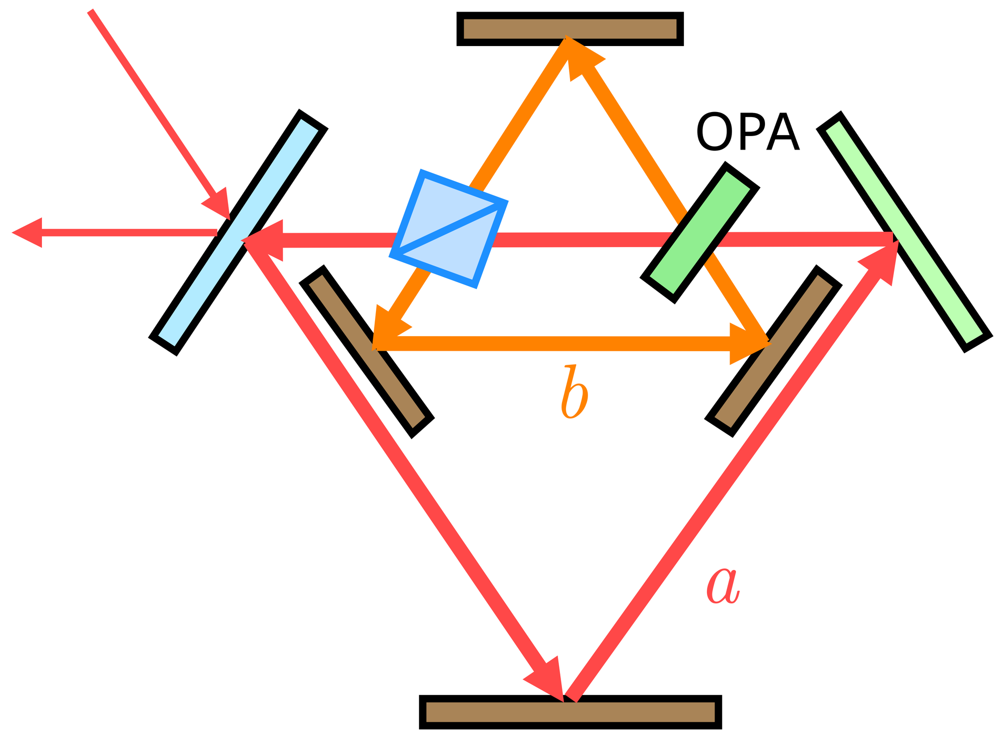
- Introduce optical squeezing to undo the ponderomotive squeezing

Broadband QNC Design



- Introduce artificial ponderomotive squeezing with negative effective mass

Optical Implementation



- Less optical cavities than previous schemes

Conclusion

- Flowcharts: can be generalized to arbitrary linear quantum systems.
- Coherent Quantum Noise Cancellation
- An example of Coherent *Feedforward* Quantum Control, can be combined with quantum filtering/smoothing for quantum sensing.

References

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- C. M. Caves, Phys. Rev. D **23**, 1693 (1981).
- W. G. Unruh, in *Quantum Optics, Experimental Gravitation, and Measurement Theory*, edited by P. Meystre and M. O. Scully (Plenum, New York, 1982), p. 647.
- Kimble *et al.*, Phys. Rev. D **65**, 022002 (2001).
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