UNIVERSITY OF BIRMINGHAM

INSTITUTE OF GRAVITATIONAL WAVE ASTRONOMY

LSC LIGO Scientific Collaboration

Quantum Techniques in Laser Interferometric Gravitational-wave Detectors

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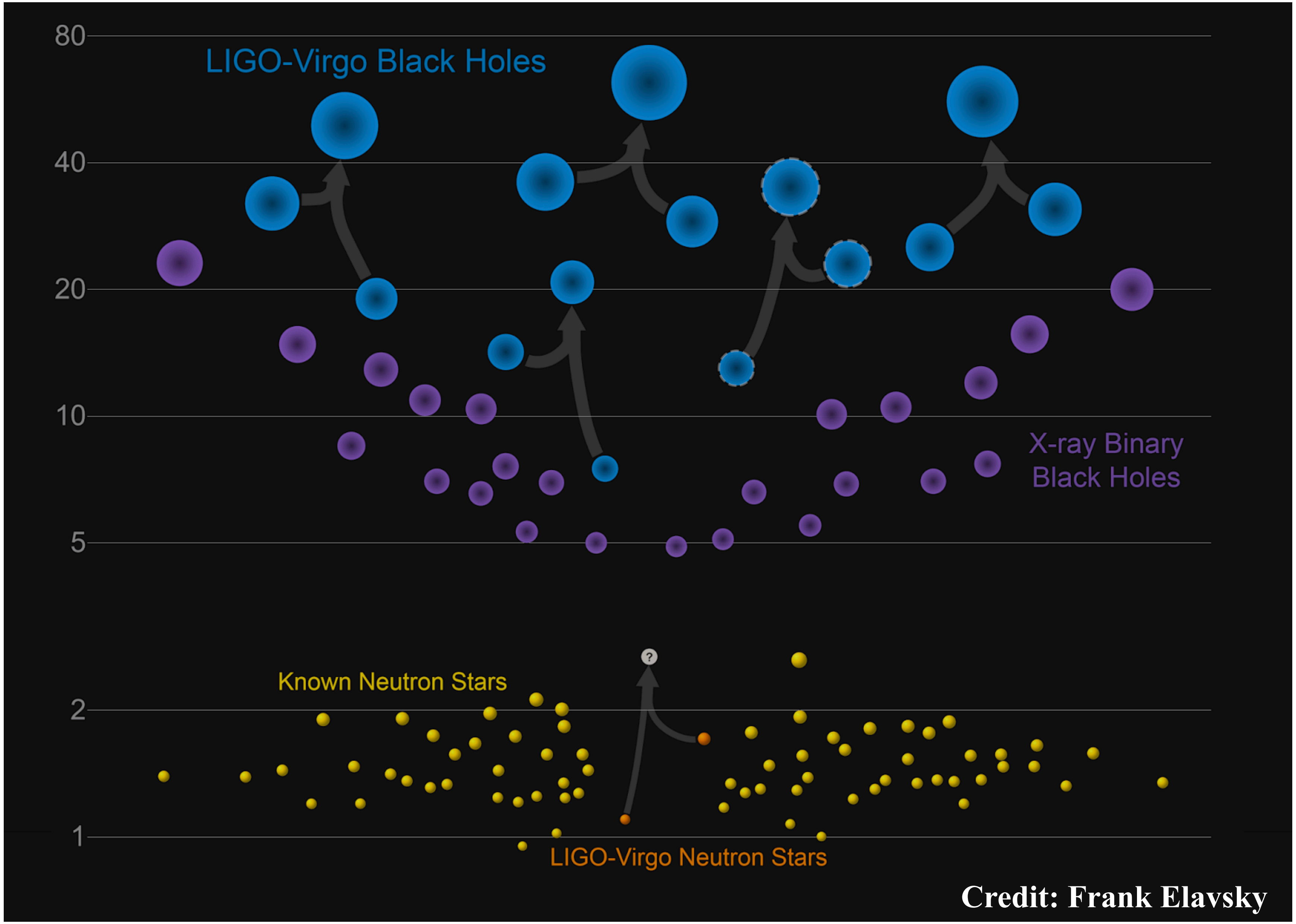
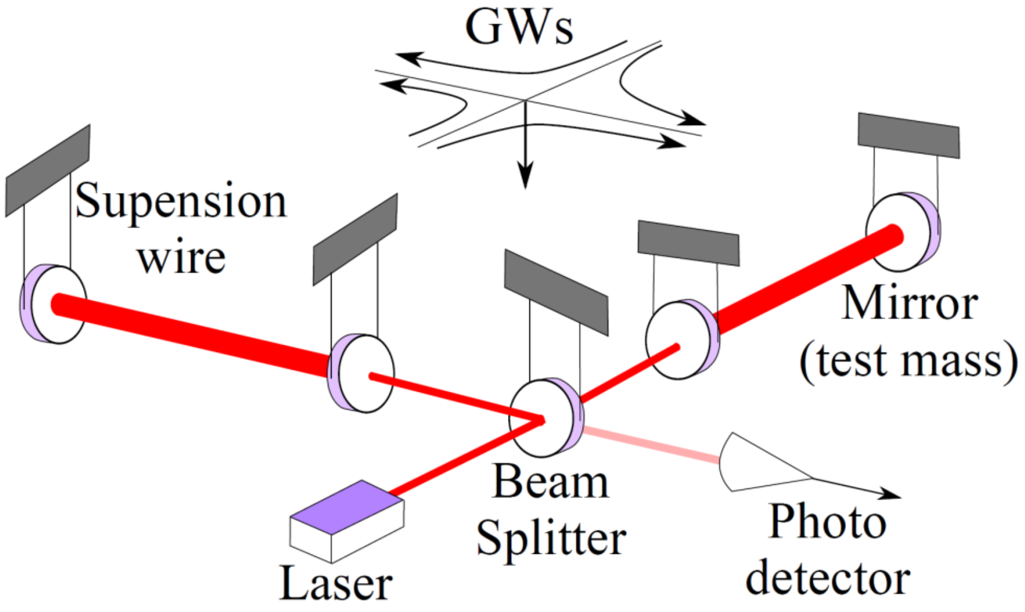
Gravitational-wave discoveries



Why Quantum?



Strain sensitivity of km size detector:

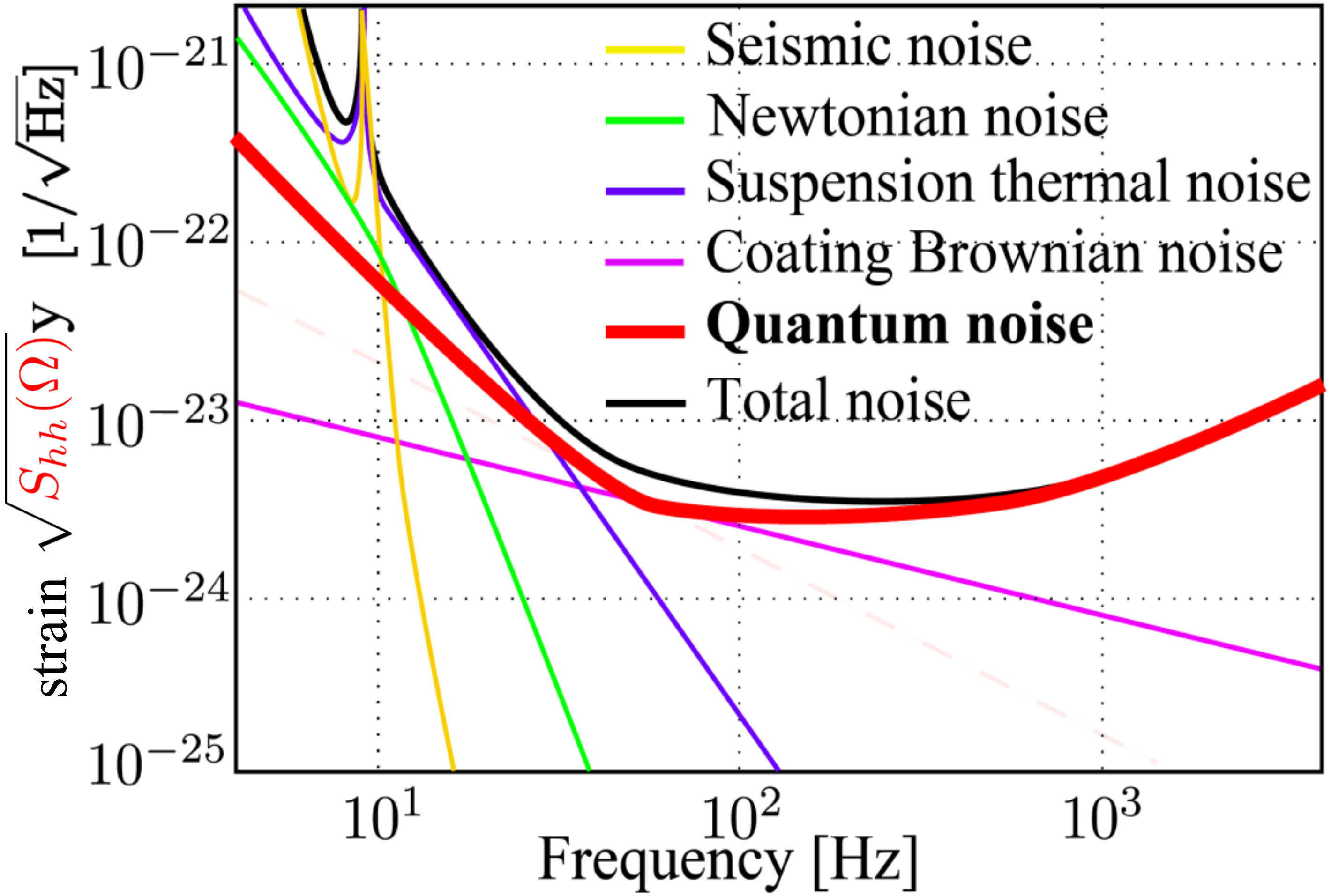
$$h = \frac{\Delta L}{L} \sim 10^{-22} \quad \Rightarrow \quad \Delta L \sim 10^{-19}\mathrm{m}$$

de Broglie wavelength of kg size test mass: $\lambda_{\mathrm{d}} \sim \sqrt{\hbar/(2\pi\, m\, f)}|_{100\mathrm{Hz}} \sim 10^{-19}\,\mathrm{m}$

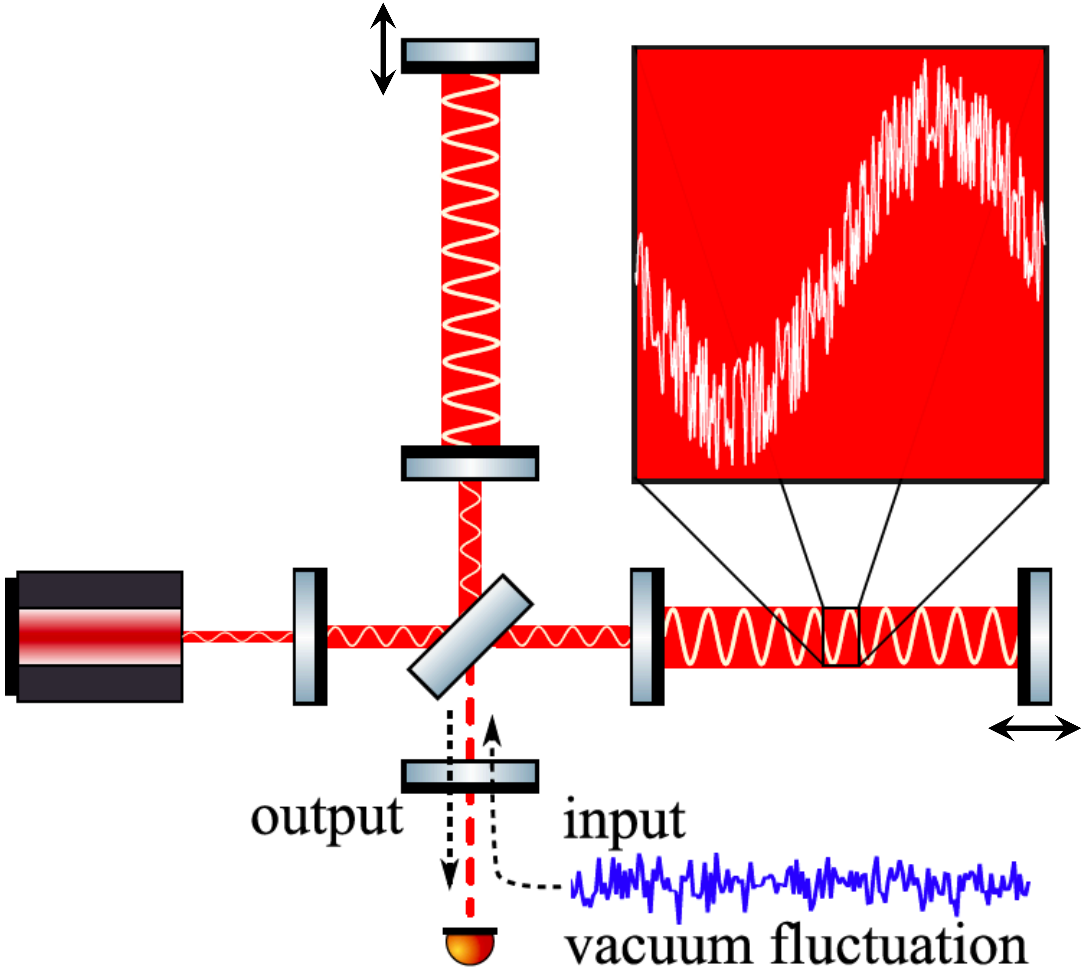
Quantum effects are indeed important!

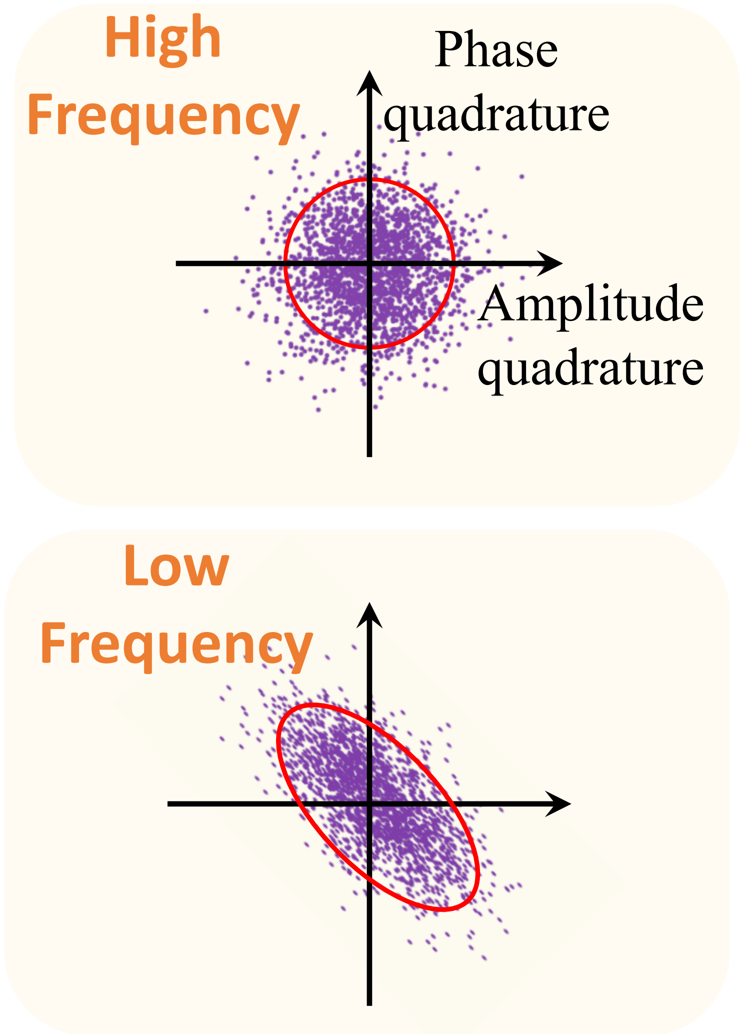
Why Quantum?

Advanced LIGO design sensitivity curve [1]:



Origin of quantum noise



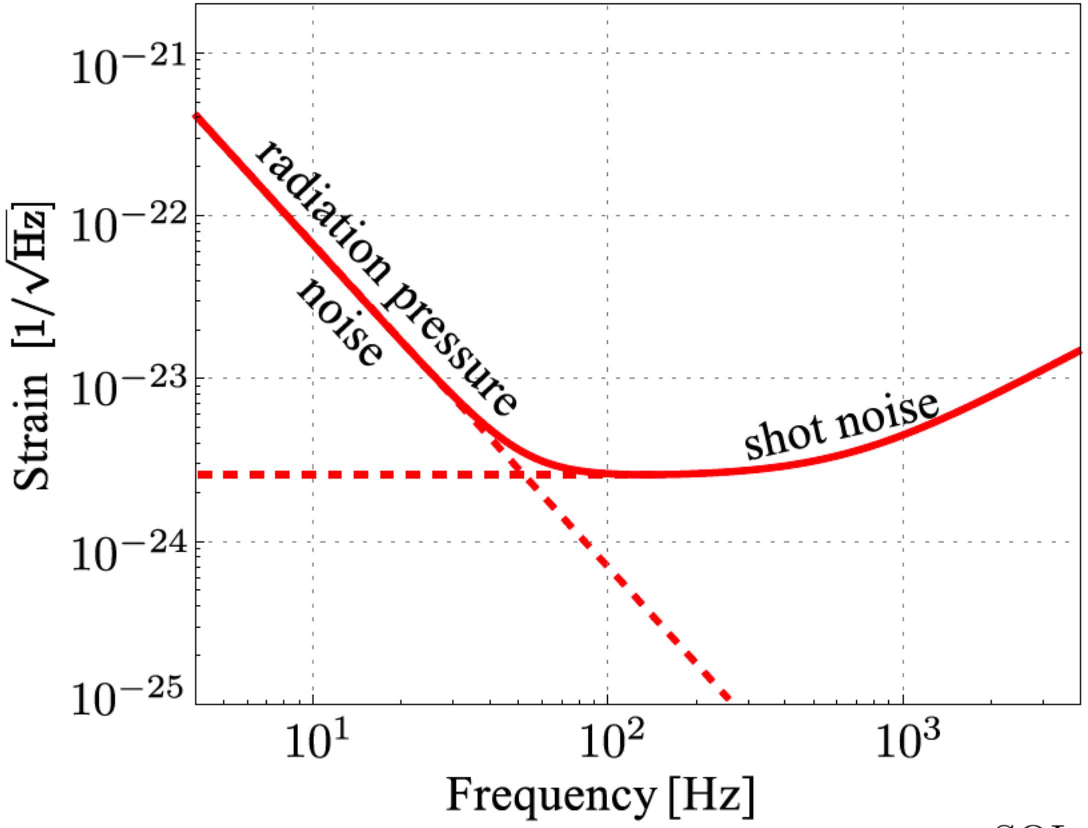


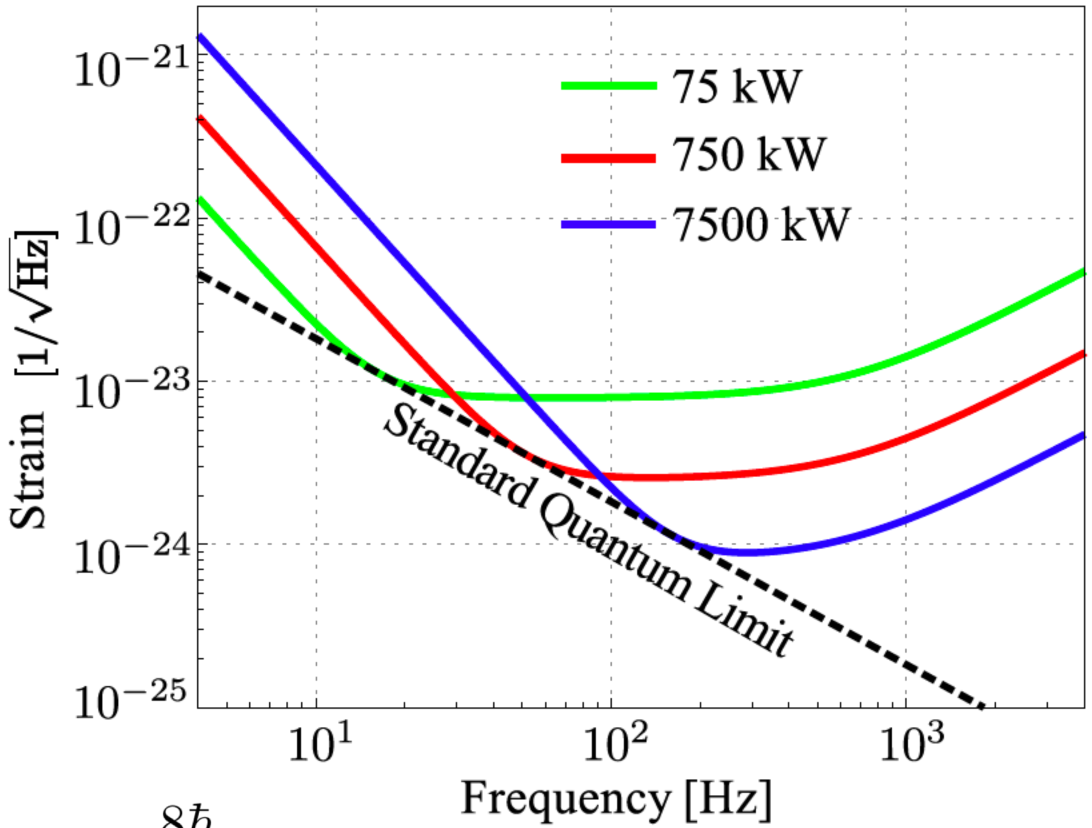
Ponderomotive (anti-)squeezing [2,3]
(manifestation of quantum back action)

Standard Quantum Limit (SQL)

Phase fluctuation ⇨ shot noise

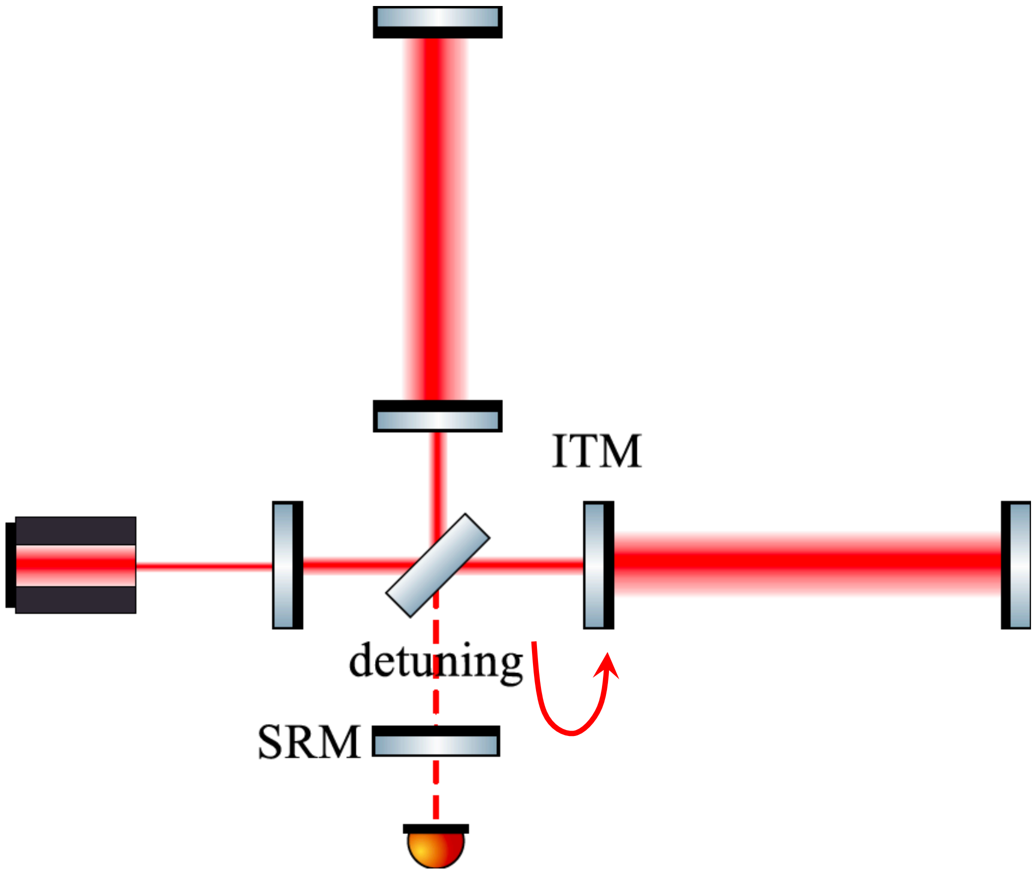
Amplitude fluctuation ⇨ Radiation pressure (back action) noise



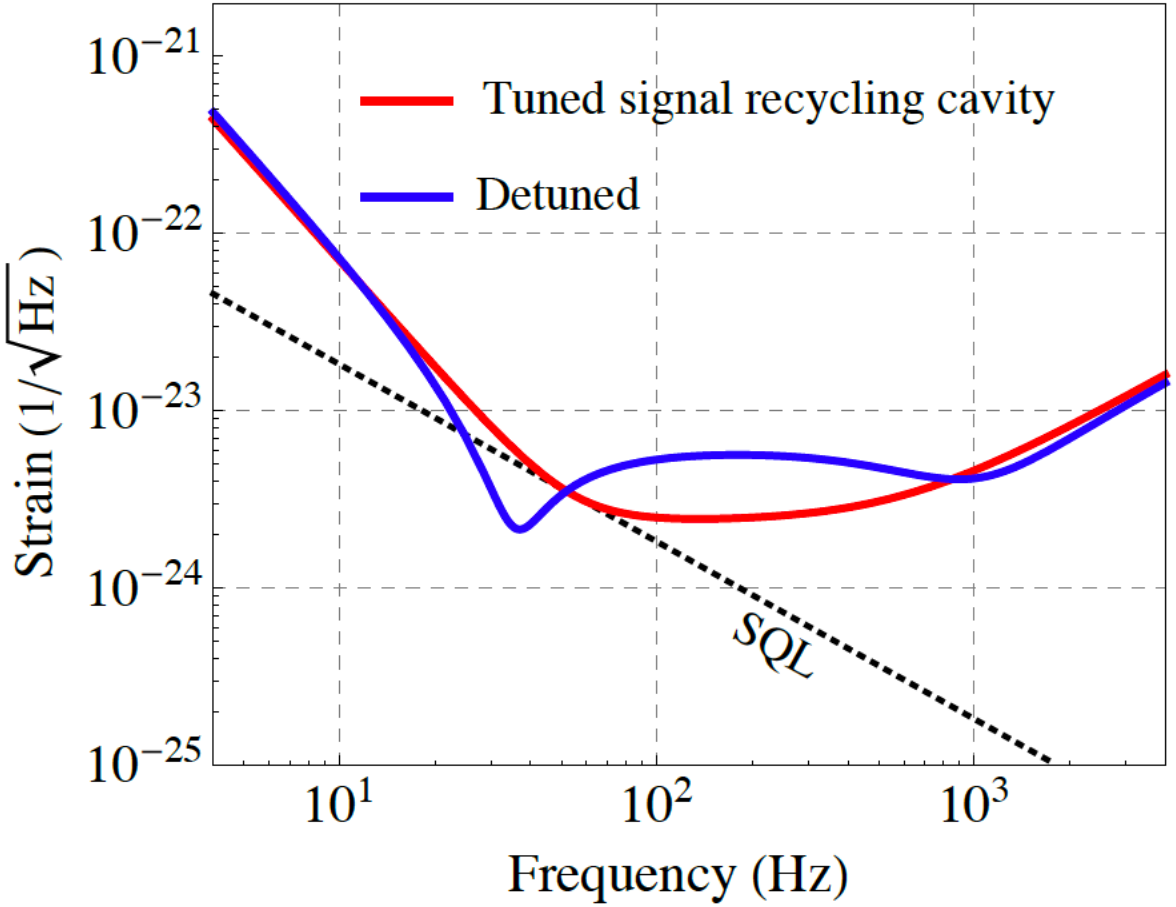


$$S_{hh}^{\mathrm{SQL}}(\Omega) = \frac{8\hbar}{M\Omega^2 L_{\mathrm{arm}}^2} \quad [4] \qquad \Omega = 2\pi f$$

Surpassing the SQL by detuning the SRC

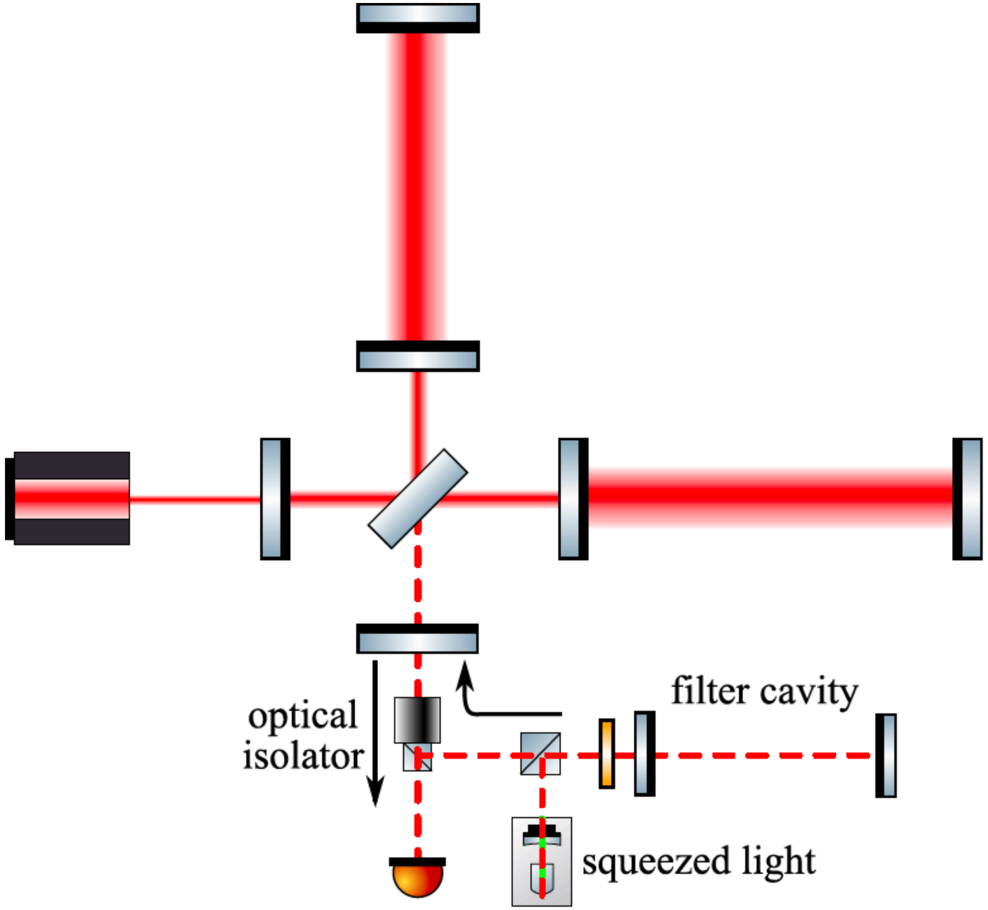


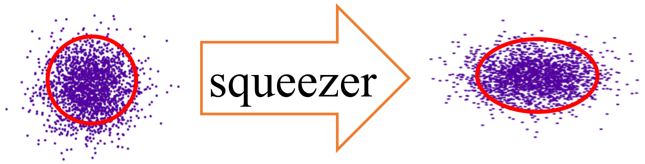
SRM: Signal recycling mirror
ITM: Input test mass mirror
SRC: Signal recycling cavity

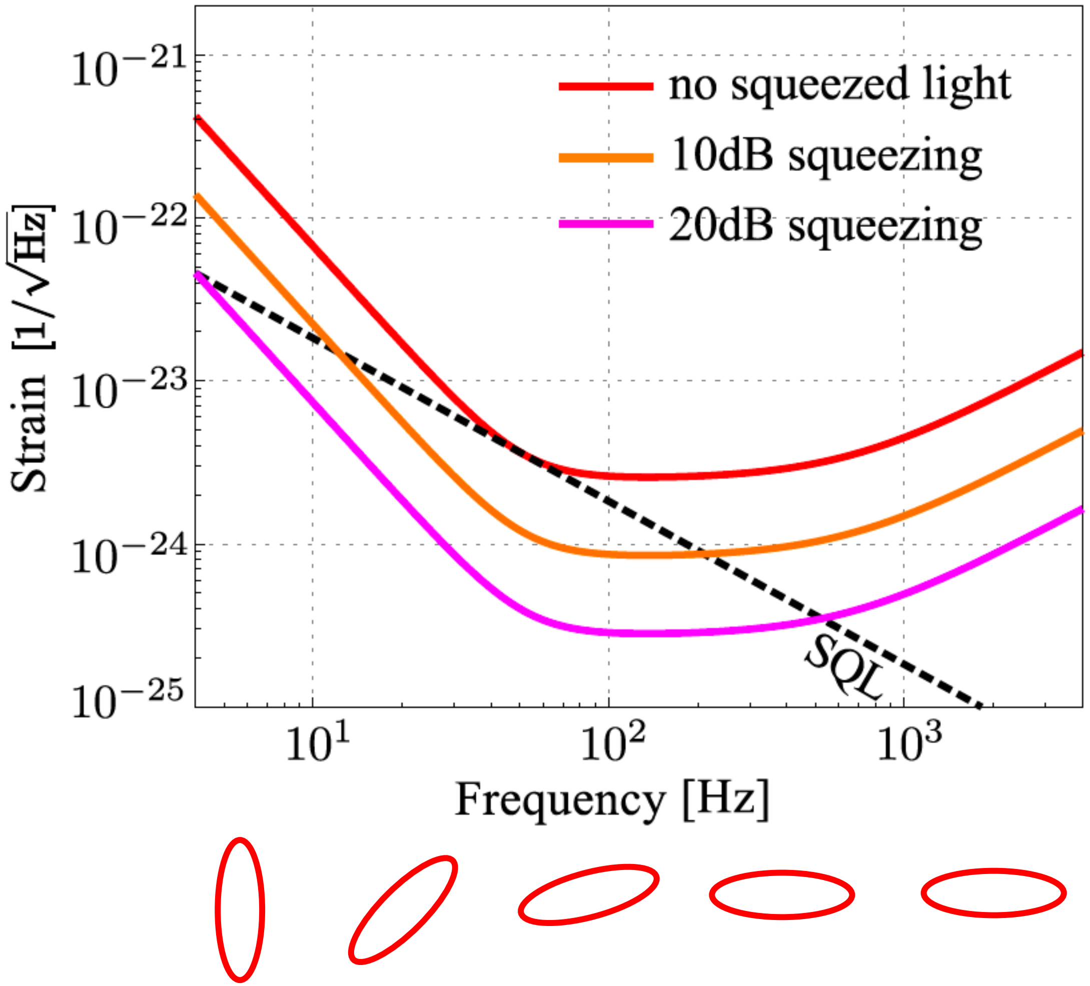


Take advantage of the internal ponderomotive squeezing (back action as a resource) [5, 6]

Input-filtering: Frequency-dependent squeezing



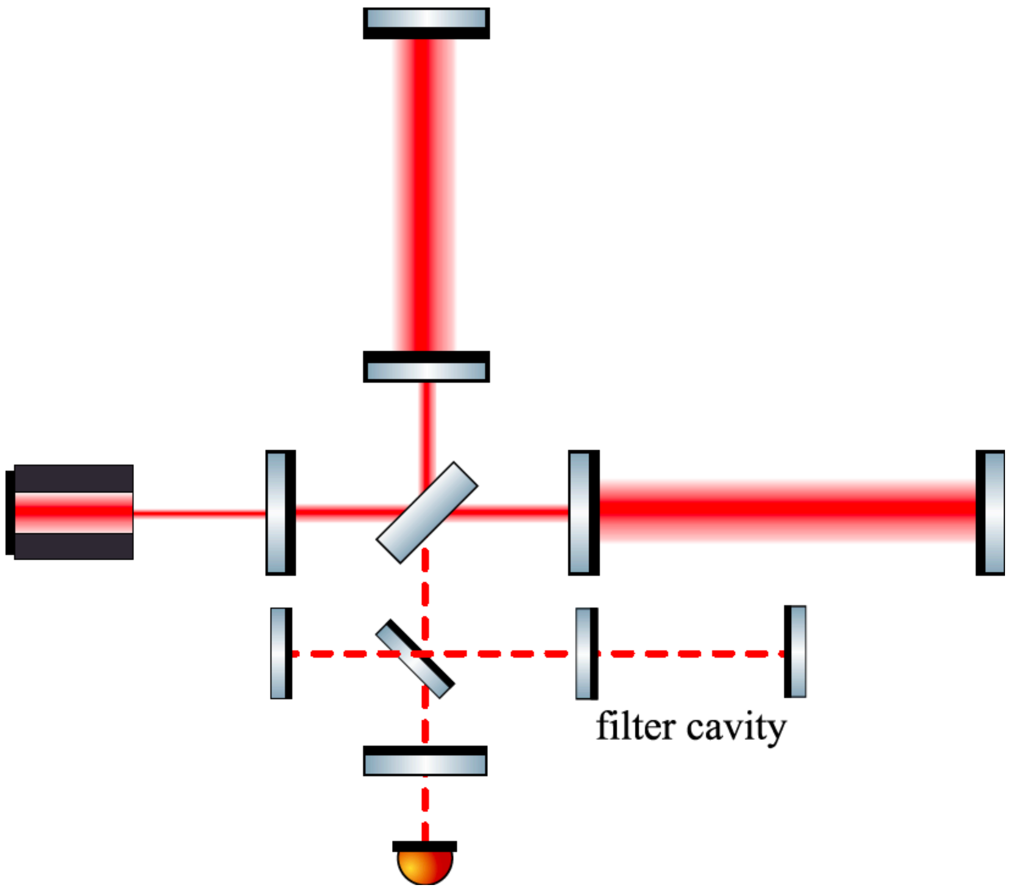


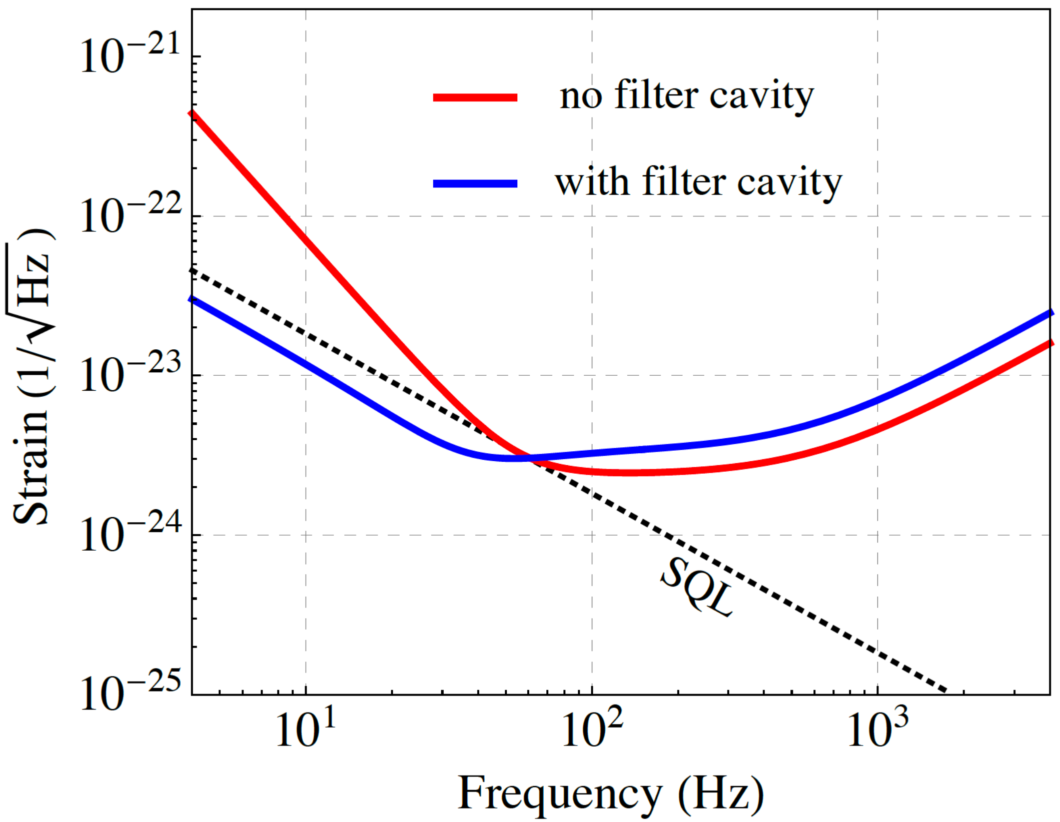


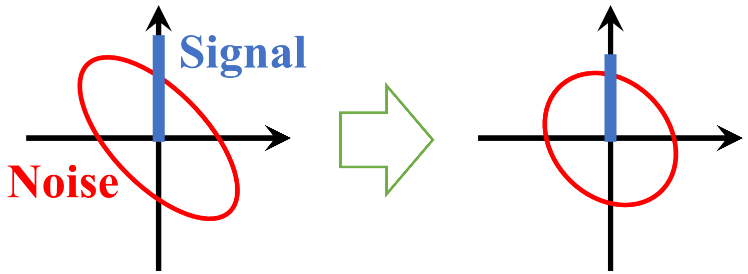
Filter cavity rotates input squeezing angle [7]

counteracts ponderomotive (anti-)squeezing

Intra-cavity filtering: Speed meter



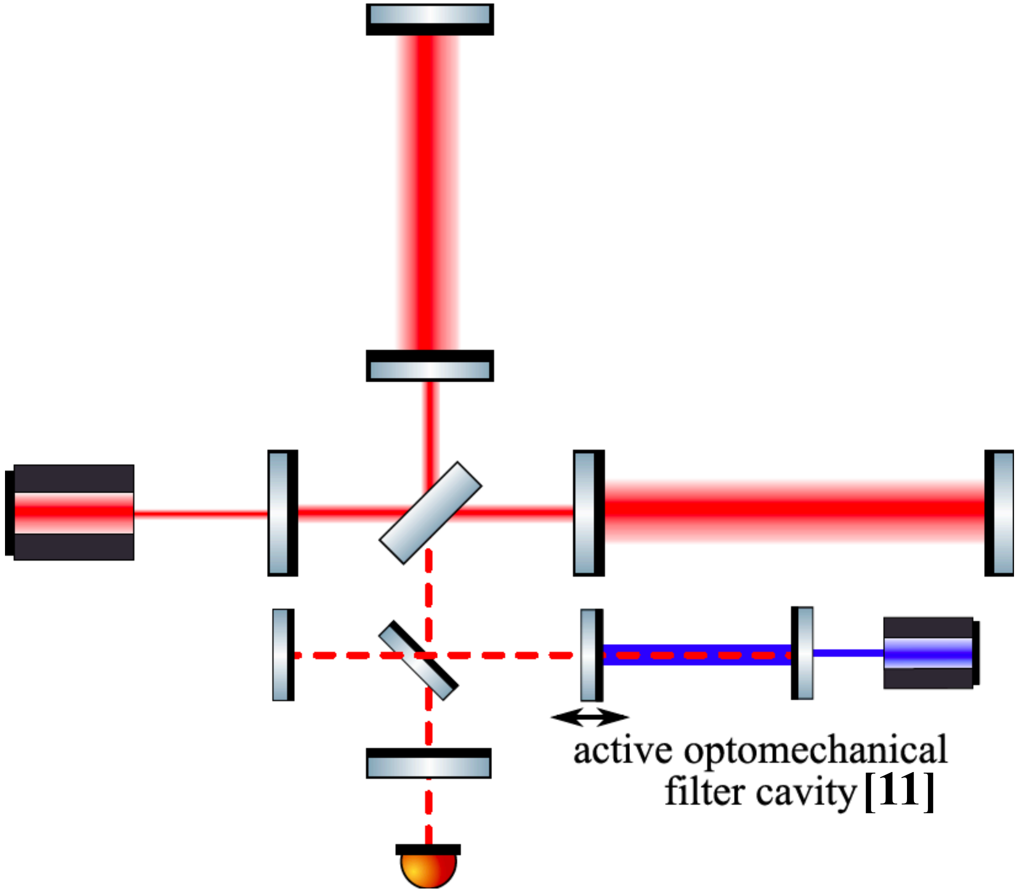


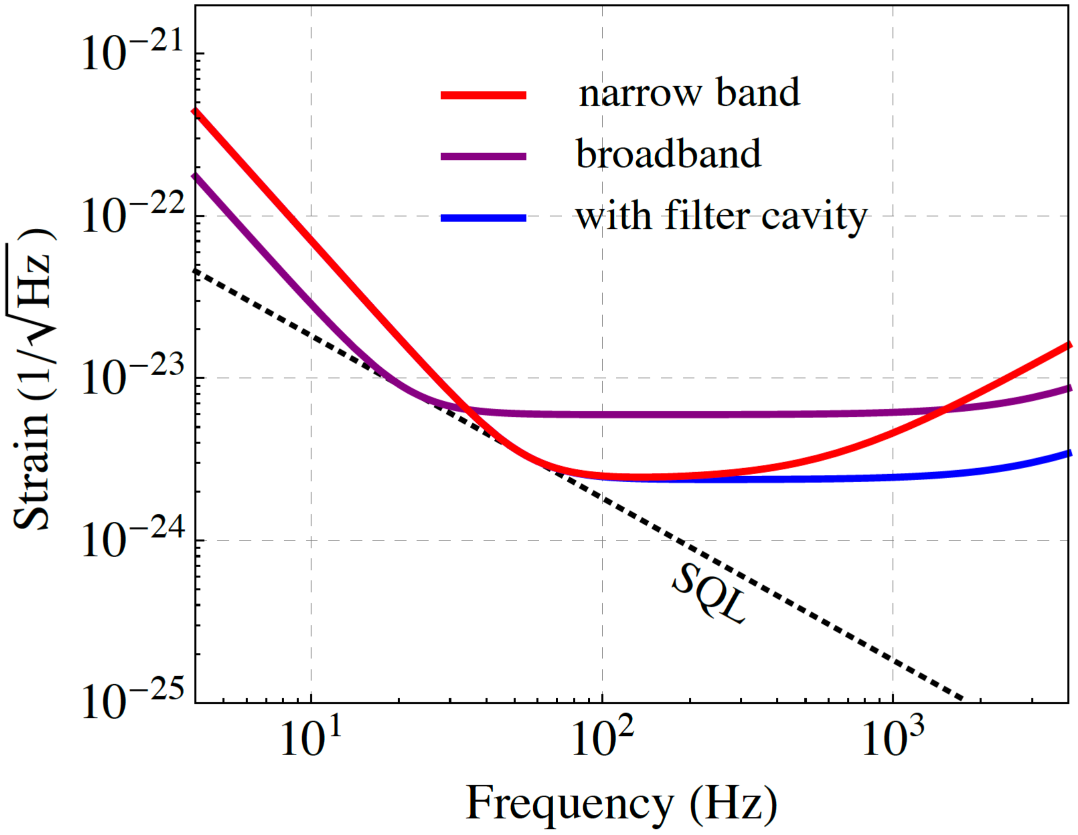


Sacrificing the signal response but decreasing the ponderomotive (anti-)squeezing more [8]

An equivalent realisation with Sagnac [9, 10]

Intra-cavity filtering: White-light cavity ("fast light")

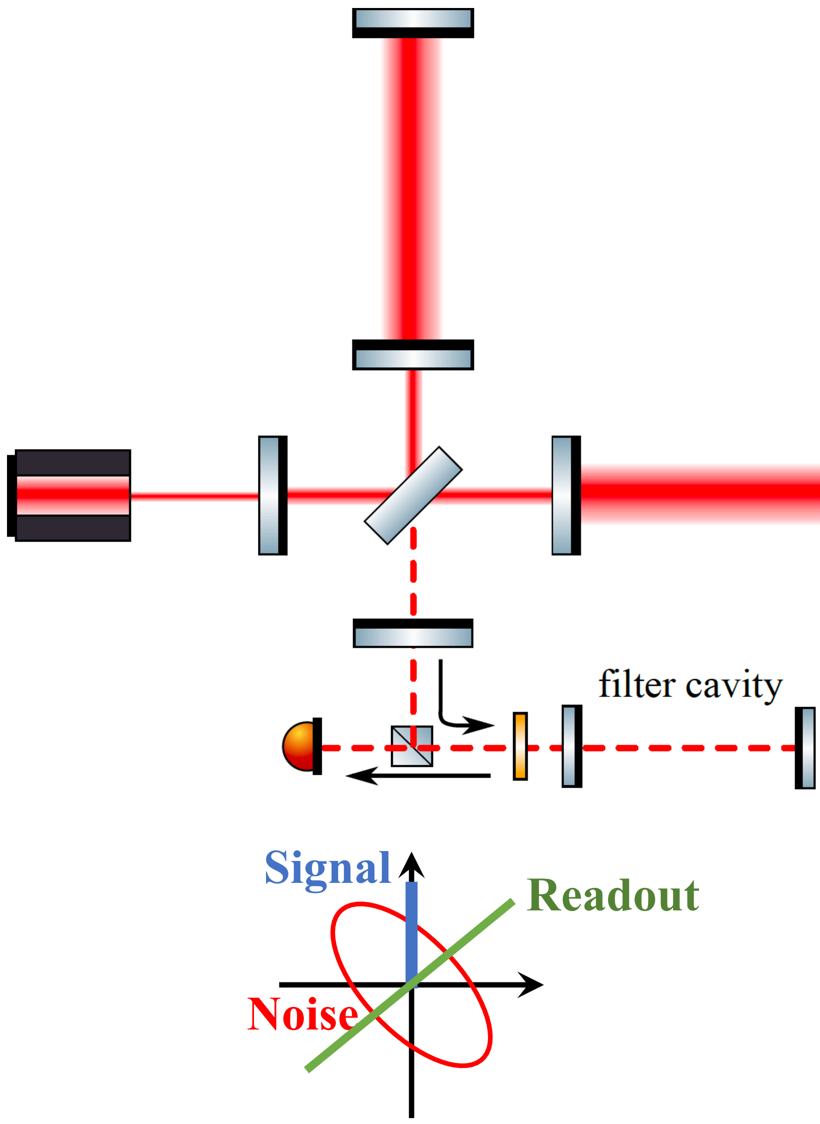


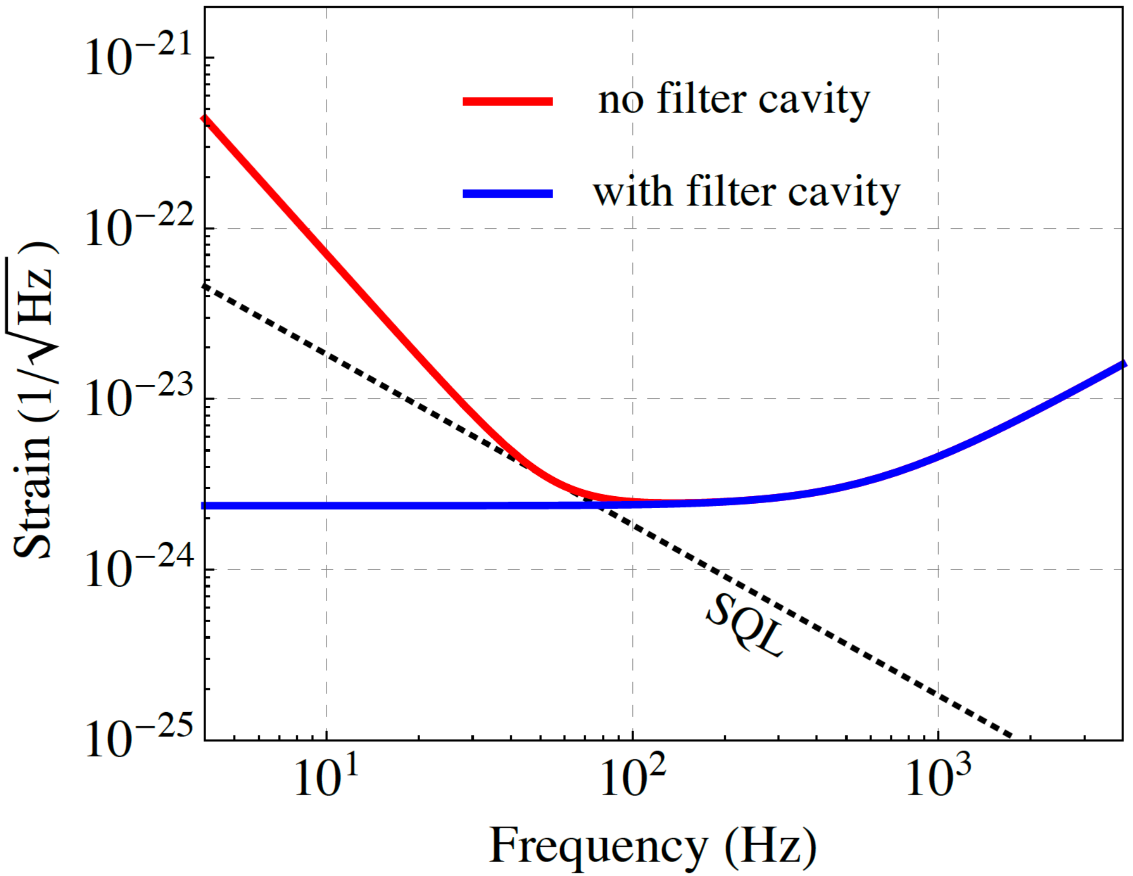


Can be realised also with
active atomic system [12, 13]

Enhancing the bandwidth without reducing the peak sensitivity

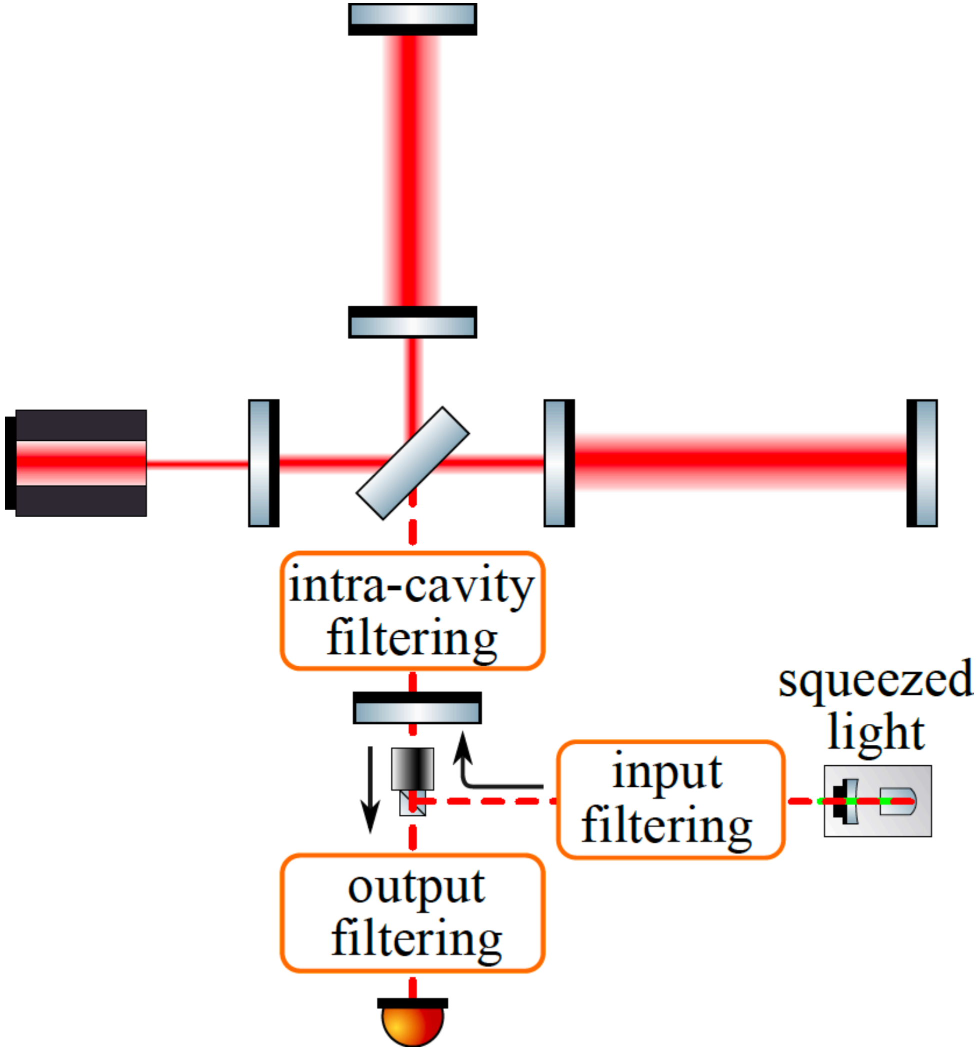
Output filtering: Frequency-dependent readout





Read out the optimal quadrature that has the maximum SNR [7]

General case



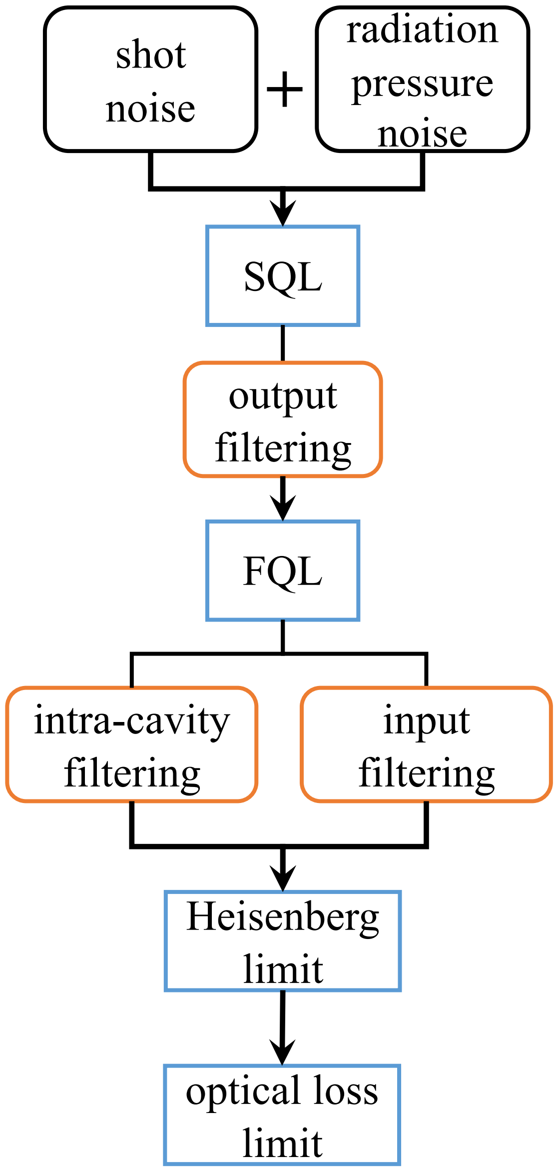
Each filtering module can be a cascade of passive/active filter cavities. **Infinite combinations!**

Question:

How do we combine techniques in a **systematic** way?

What is the **optimal** scheme?

A unified framework



Fundamental Quantum Limit (FQL) [6, 14 - 16]

$$S_{hh}^{\mathrm{FQL}}(\Omega) = \frac{\hbar^2 c^2}{2L_{\mathrm{arm}}^2 S_{PP}(\Omega)} = \frac{2\hbar^2}{S_{EE}(\Omega)}$$

Intuition: time-energy uncertainty relation

$$\Delta t \geq \hbar/\Delta E$$

Heisenberg Limit (all photons entangled)

$$S_{EE} \propto N_{\mathrm{photon}}^2 \text{ rather than } N_{\mathrm{photon}}$$

$$N_{\mathrm{photon}}^{\mathrm{LIGO}} \sim 10^{20}$$

Optical loss limit [17, 18]

$$S_{EE} \propto N_{\mathrm{photon}}/\epsilon \qquad \epsilon_{\mathrm{LIGO}} \sim 10^{-4}$$

This framework applies to other linear quantum measurements.

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