Quantum Non-Demolition Gravitational-Wave Detectors

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Standard Quantum Limit from Theory

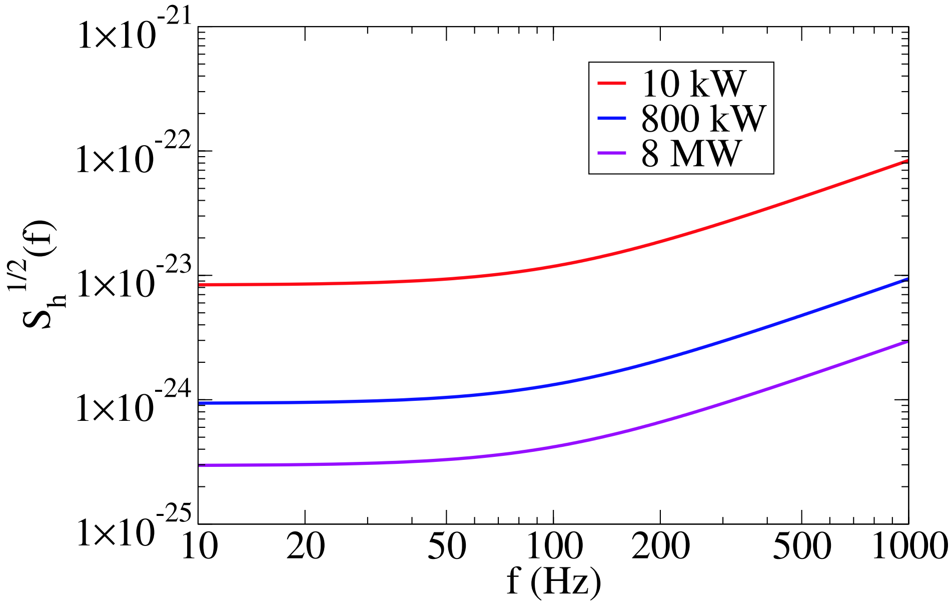
[Braginsky 60s and 70s; Caves late 70s and 80s; Braginsky and Khalili 92; Braginsky, Gorodetsky, Khalili, Matsko, Thorne and Vyatchanin, 01]

- Arises when one tries to detect gravitational wave by continuously measuring free-mass displacement, $\hat{x}$, since $[\hat{x}(t), \hat{x}(t')] \neq 0$
  - Precise measurements on $\hat{x}$ have to perturb $\hat{p}$. Uncertainty Principle.
  - Perturbations in $\hat{p}$ converts to future error in $\hat{x}$

- Limits interferometers with conventional configuration and ordinary readout scheme, like LIGO-I, VIRGO, TAMA, but not GEO 600

- "Enforced" by optical fields, through the complementarity between Shot (Δx) and Radiation-Pressure Noises (Δp), which can be related solely to vacuum fields leaking in from dark port. [Initial $\Psi(x)$ filtered out.]

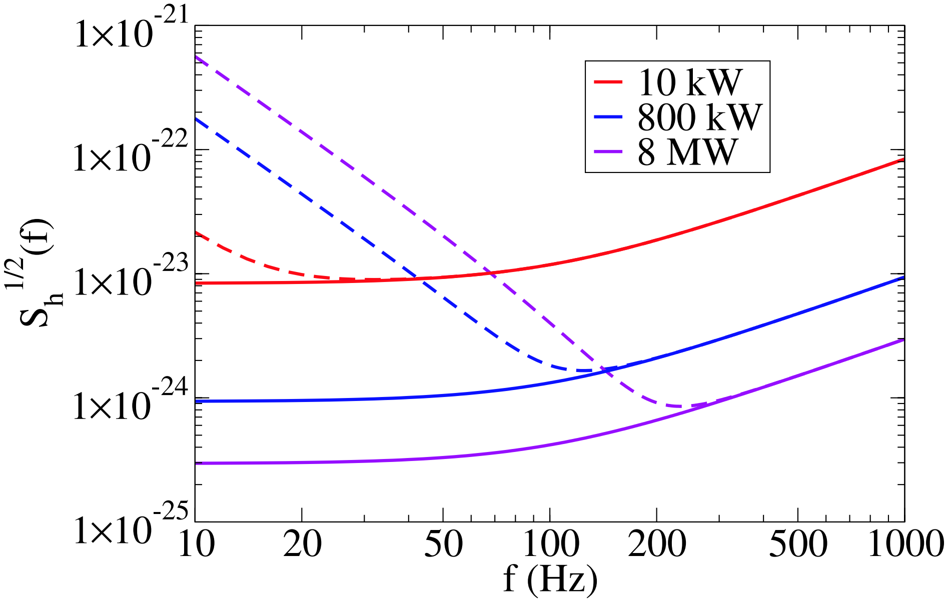
Standard Quantum Limit [expected] in Experiments



$L = 4\,\text{km},\ \gamma_{\text{arm}} = 100\,\text{Hz},\ M = 40\,\text{kg}.$

- Shot Noise $\propto 1/\sqrt{I}$

Standard Quantum Limit [expected] in Experiments



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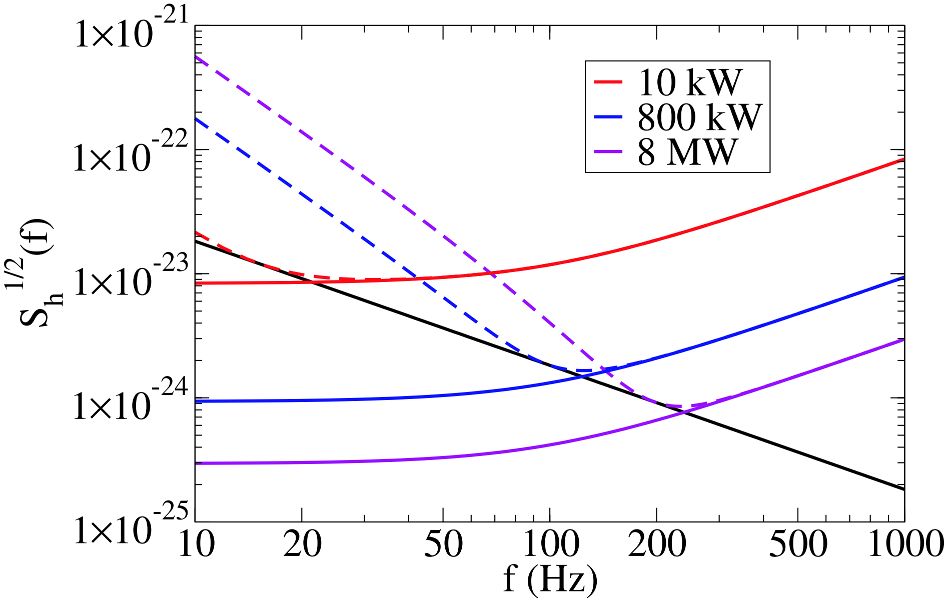
- Shot Noise $\propto 1/\sqrt{I}$
- Rad. Pres. Noise $\propto \sqrt{I}/(M\Omega^2)$

Standard Quantum Limit [expected] in Experiments



$L = 4\,\text{km},\ \gamma_{\text{arm}} = 100\,\text{Hz},\ M = 40\,\text{kg}.$

- Shot Noise $\propto 1/\sqrt{I}$
- Rad. Pres. Noise $\propto \sqrt{I}/(M\Omega^2)$
- Standard Quantum Limit

$$\sqrt{S_h^{\text{SQL}}} = \sqrt{\frac{8\hbar}{M\Omega^2 L^2}}$$

Beating the Standard Quantum Limit

[Braginsky 70s; Caves lates 70s and 80s; Braginsky and Khalili 90s; Kimble, Levin, Matsko, Thorne and Vyatchanin 00; Buonanno and Chen 00s; Braginsky, Gorodetsky, Khalili and Thorne, 00; Purdue 01; Purdue and Chen 02; Chen 02; Khalili 02]

Not a fundamental limit, since it's not necessary to measure the free-mass displacement continuously. Alternatively, one can

- Modify test-mass dynamics [“Optical Bar” Detectors, Detuned Signal-Recycling interferometers]
- Measure quantities that have $[\hat{o}(t), \hat{o}(t')] = 0$ [Quantum Non-Demolition Observable, e.g., free-mass momentum]
- Manipulate the input [squeezing] and output [*variational readout*] optical fields

Modifying the input-output optics of conventional interferometers

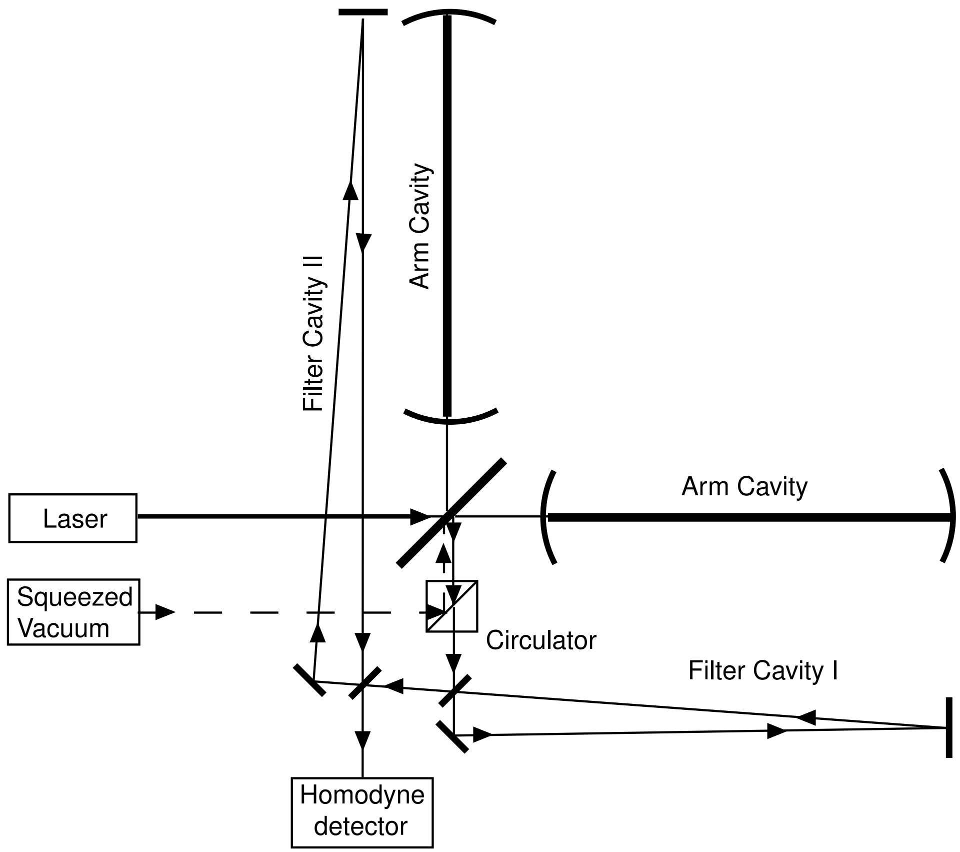
[Kimble, Levin, Matsko, Thorne and Vyatchanin, 00]

- Inject Squeezed Vacuum into the dark port to decrease shot noise.

- Removal of Radiation-Pressure noise by detecting the appropriate [frequency dependent] output quadrature.

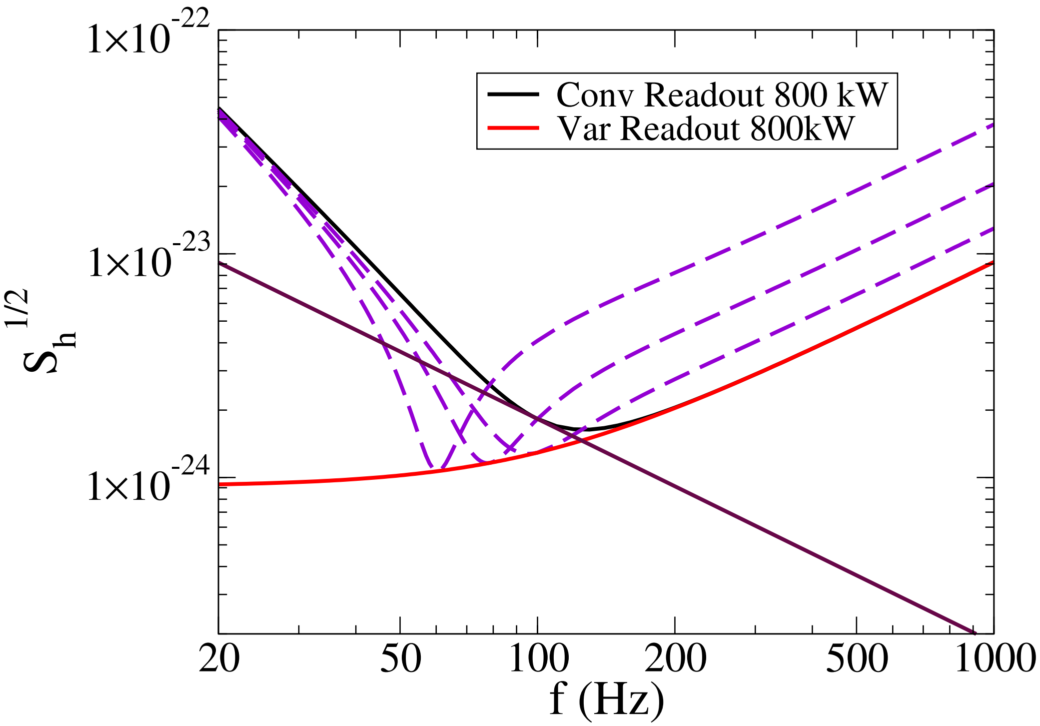
- Two detuned FP cavities with $\sim 100\,\mathrm{Hz}$ offset and linewidth proposed to achieve frequency dependence. Kilometer in length required due to in-cavity loss.

Squeezed-variational conventional interferometer

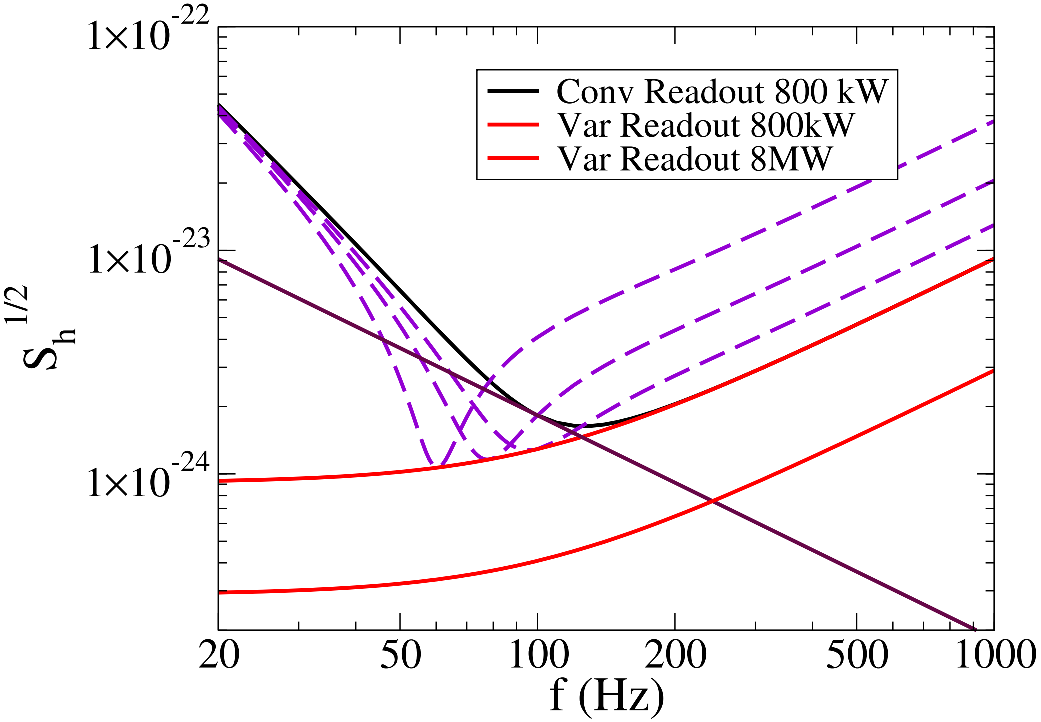


[Kimble, Levin, Matsko, Thorne and Vyatchanin, 01]

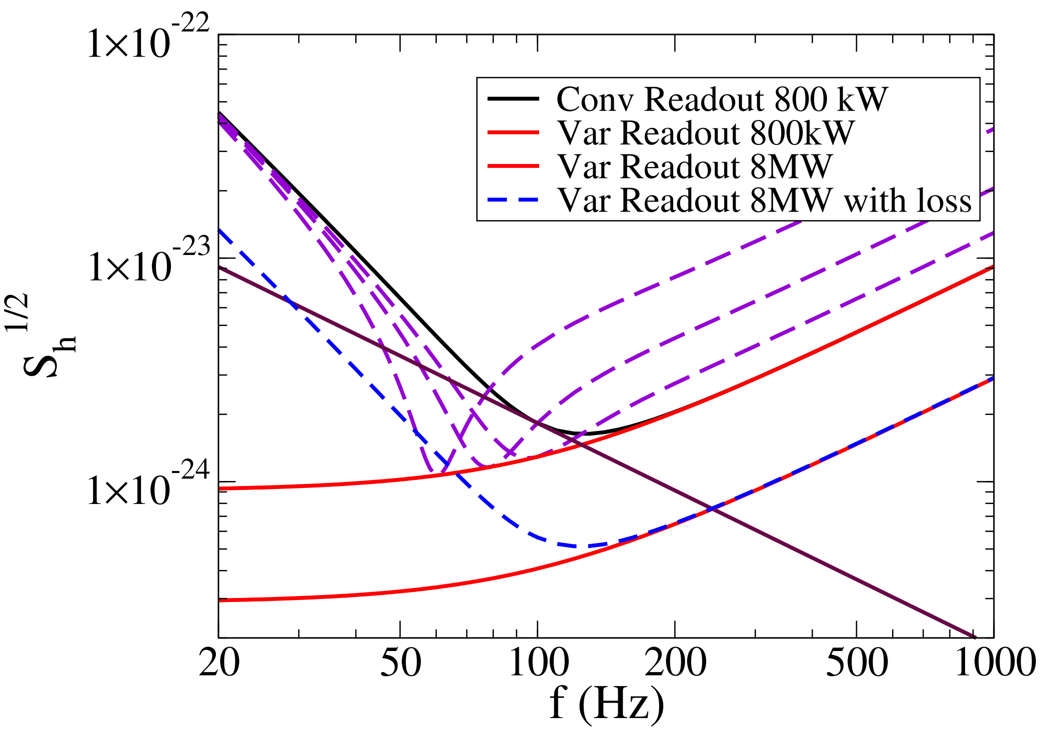
Squeezed-variational conventional interferometer, cont'd



Squeezed-variational conventional interferometer, cont'd



Squeezed-variational conventional interferometer, cont'd



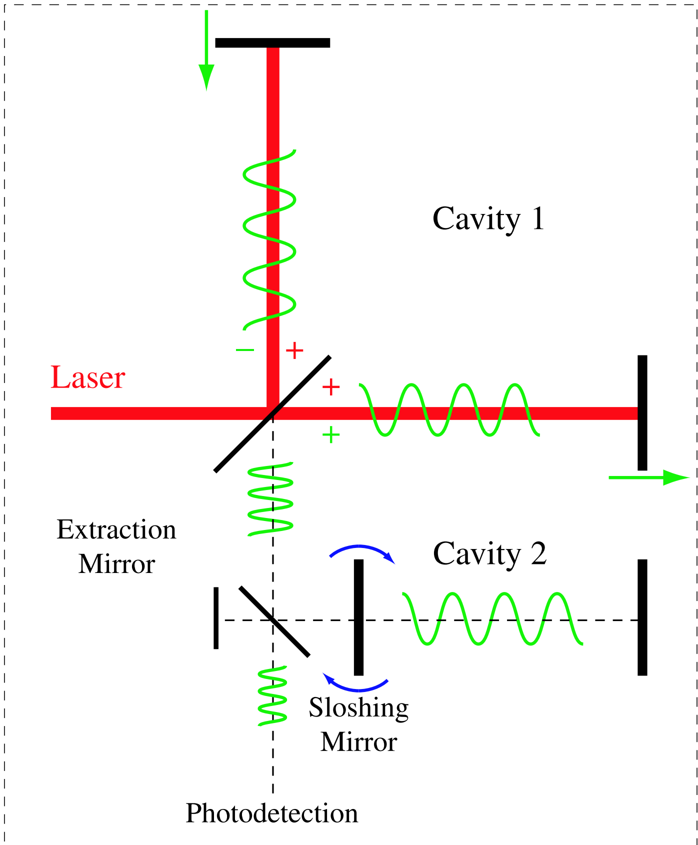
Susceptible to loss! Power can be lowered by e^{2R}.

Speed-Meter Interferometers

[Braginsky and Khalili, 90s; Braginsky, Gorodetsky, Khalili and Thorne, 00; Purdue 01; Purdue and Chen 02; Chen 02; Khalili 02]

- Measure free-mass speed, which is closely related to momentum [QND observable]
- Broad-band QND performance can be obtained using ordinary homodyne detection. Variational output may improve performance.
- Realized by adding one additional "sloshing" cavity [again, km-scale due to requirements on loss] to an ordinary Michelson interferometer.
- Realized automatically by all Sagnac interferometers

Michelson Speed Meter



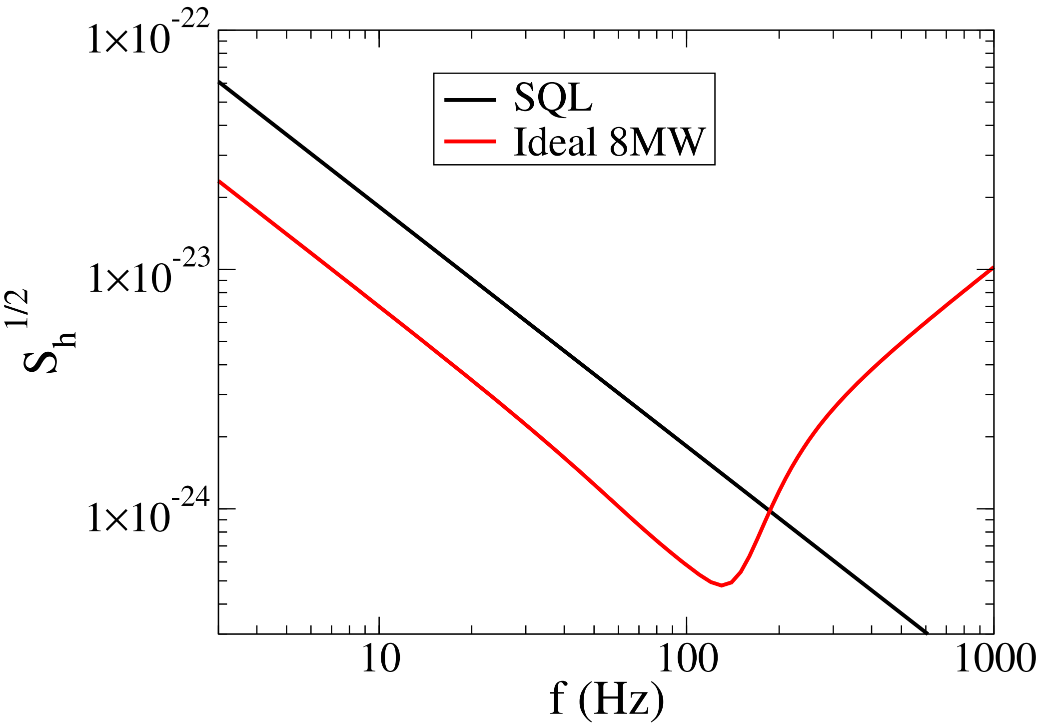
- Additional with tuned to carrier. Very narrow bandwidth

- SR outside the sloshing-cavity BW; RSE inside the sloshing-cavity BW

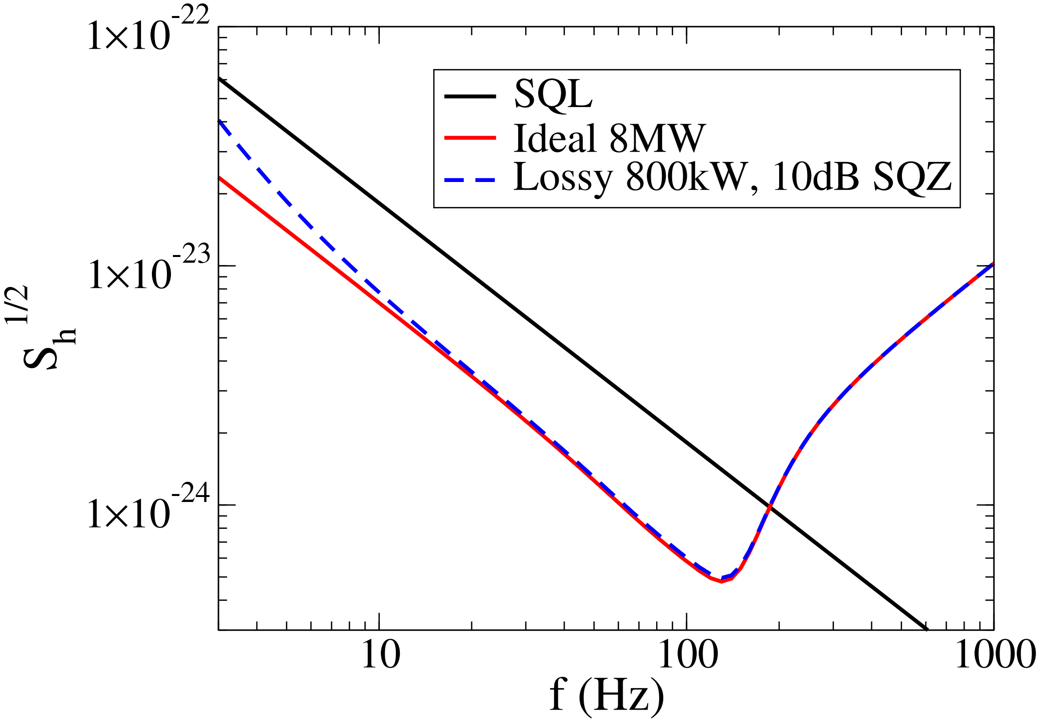
- Linear frequency response to position at low frequencies $\Rightarrow$ speed measurement

- Ordinary homodyne detection already gives broadband QND performance.

Michelson Speed Meter, cont'd

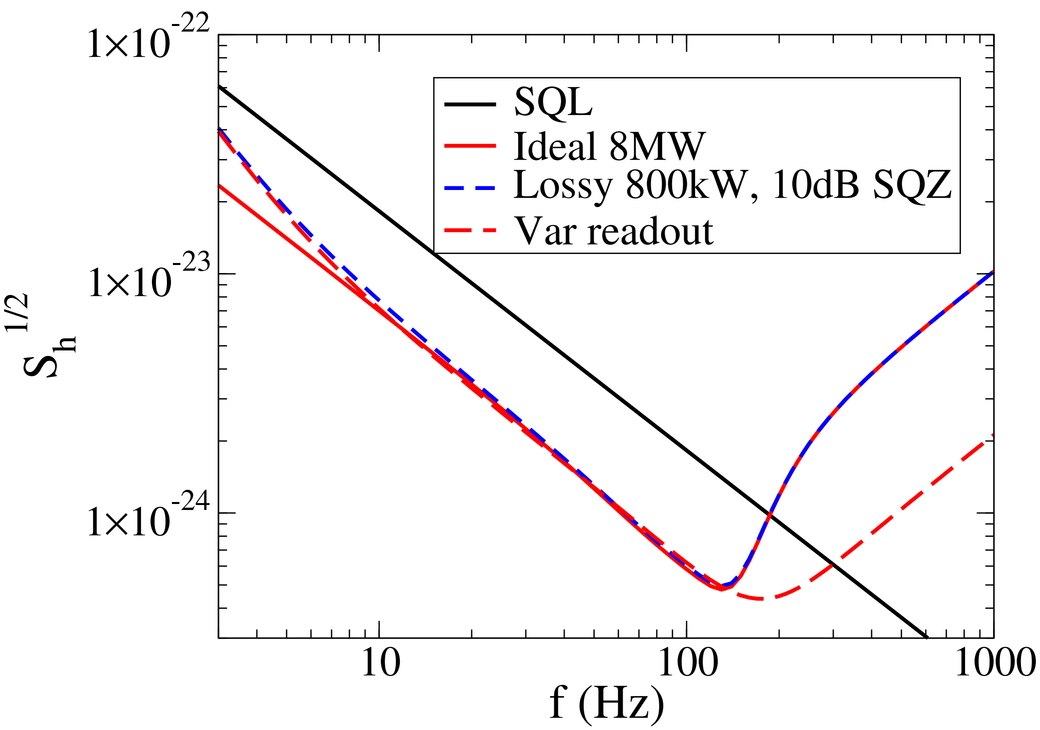


Michelson Speed Meter, cont'd



Less susceptible to loss, power can be lowered by e^{2R}

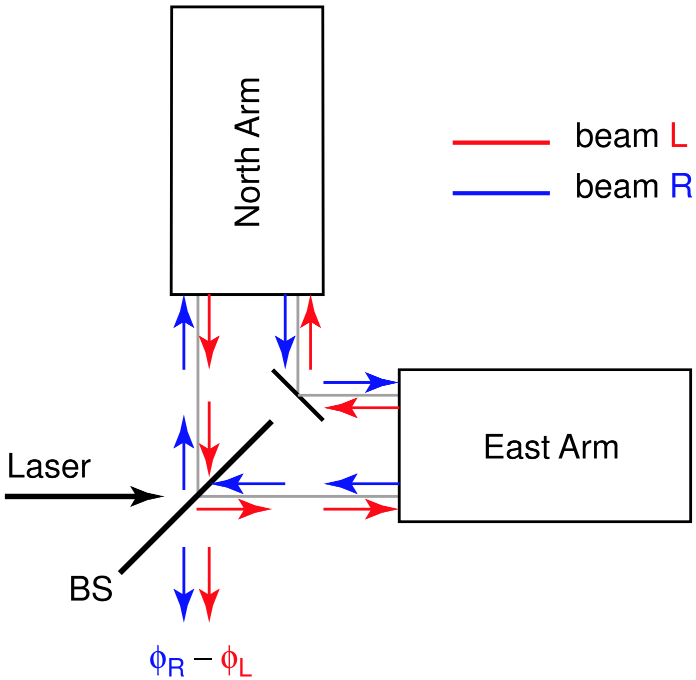
Michelson Speed Meter, cont'd



Less susceptible to loss, power can be lowered by e^{2R}

KLMTV filters (2, kilometer-scale) enhance performance

Sagnac Speed Meter



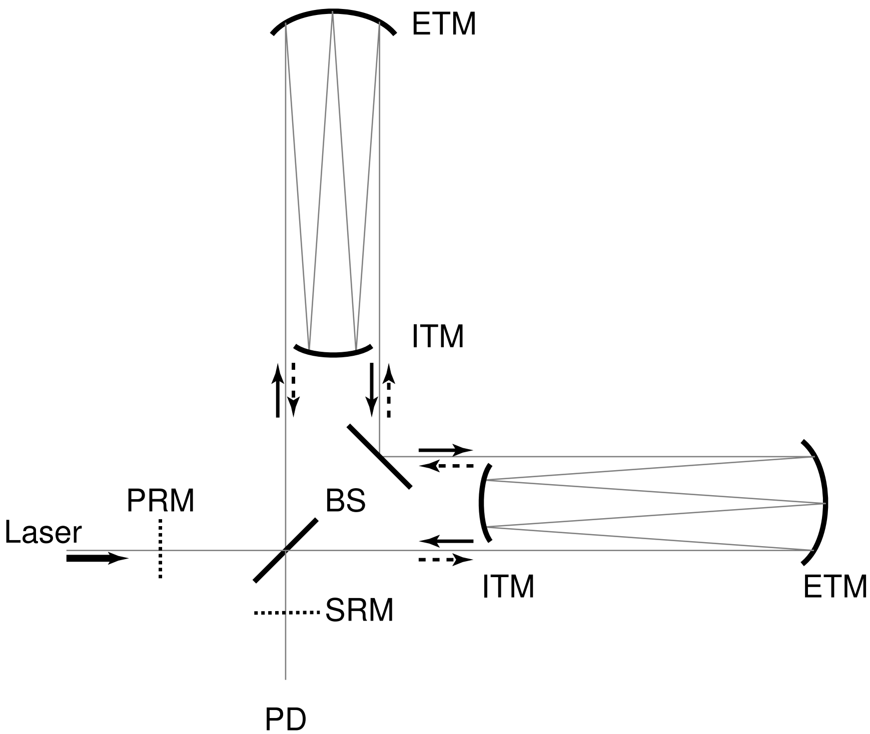
Each photon stays inside each arm for τ:

$$\phi_{\mathsf{R}}(t) = X_{\mathsf{N}}(t-\tau) + X_{\mathsf{E}}(t)$$
$$\phi_{\mathsf{L}}(t) = X_{\mathsf{E}}(t-\tau) + X_{\mathsf{N}}(t)$$

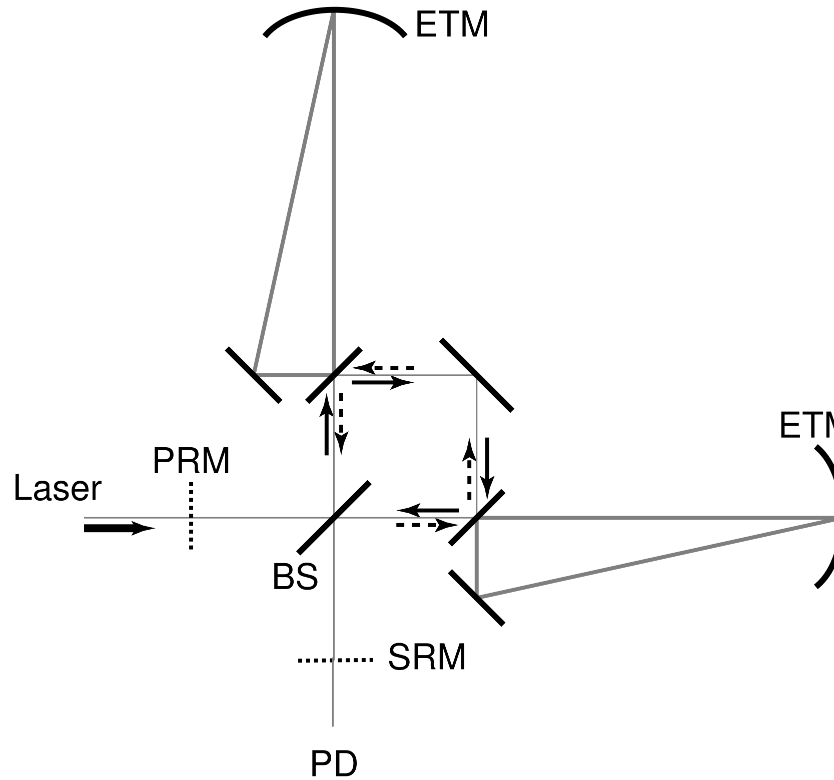
Upon recombination:

$$\begin{aligned} \phi_{\mathsf{R}} - \phi_{\mathsf{L}} &= \left[X_{\mathsf{E}}(t) - X_{\mathsf{E}}(t-\tau)\right] \\ &\quad - \left[X_{\mathsf{N}}(t) - X_{\mathsf{N}}(t-\tau)\right] \\ &\sim \dot{X}_{\mathsf{diff}} \end{aligned}$$

Sagnac Speed Meter configurations

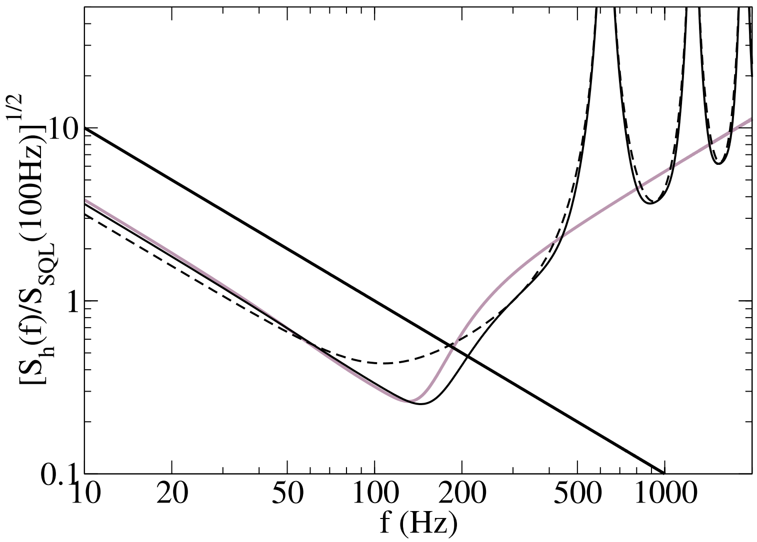


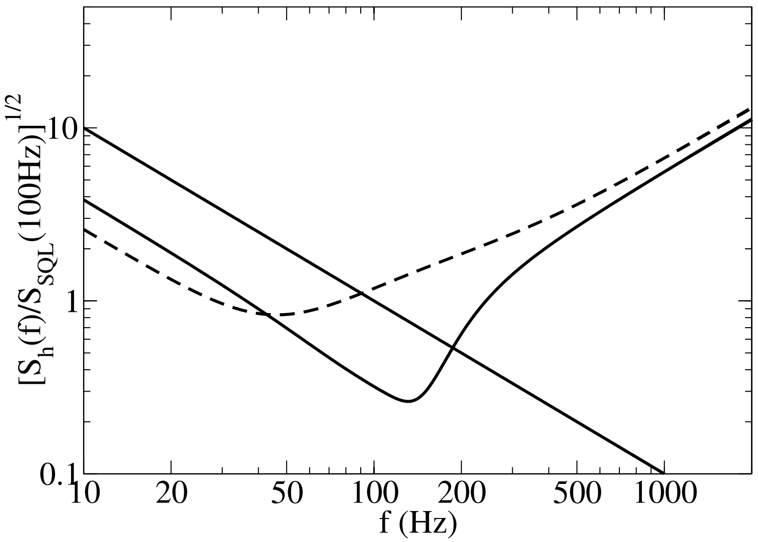
[Optical delay lines]



[Ring cavities]

Sagnac Speed Meter Performance





[Optical delay lines]

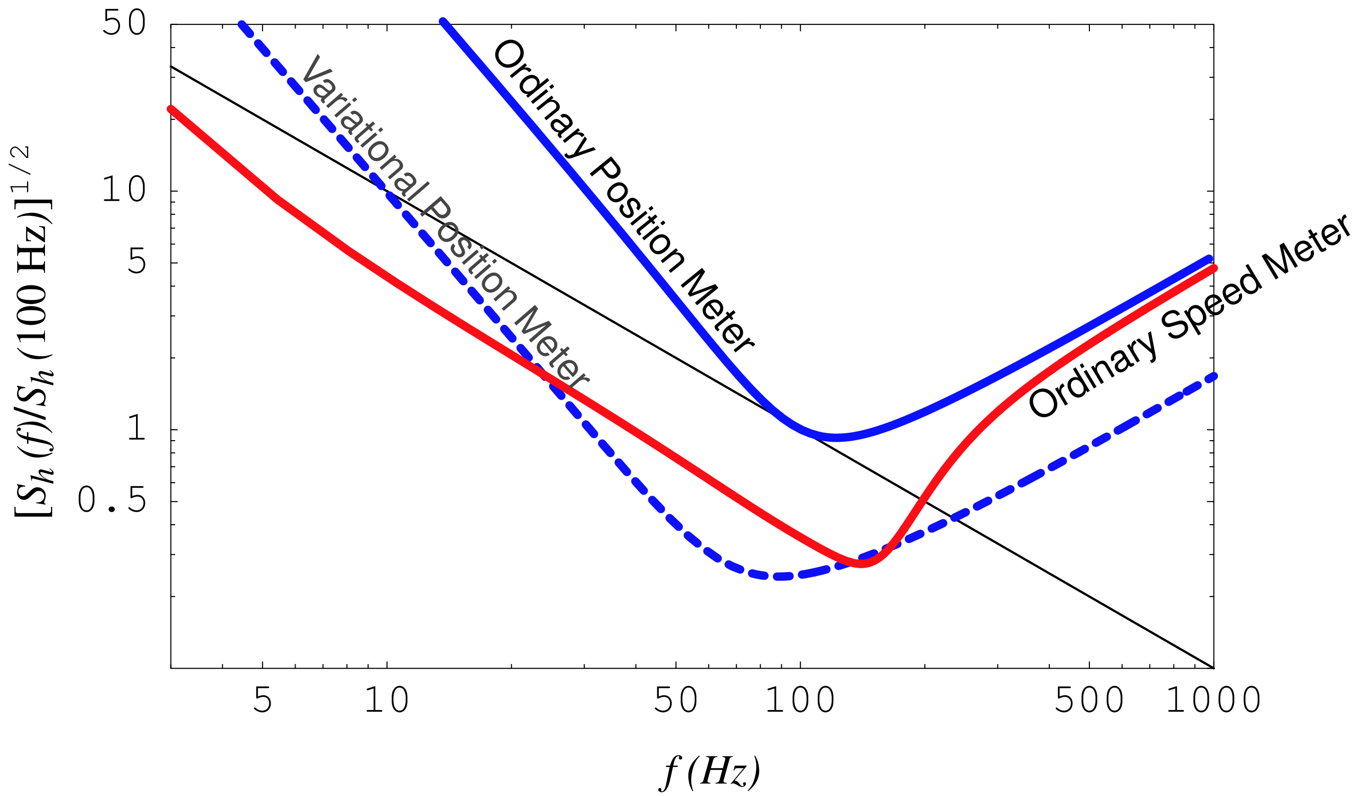
$L = 4\,\mathsf{km}$, $\mathcal{B} = 60$, $\rho_{\mathsf{SR}} = 0.09$.

[Ring cavities]

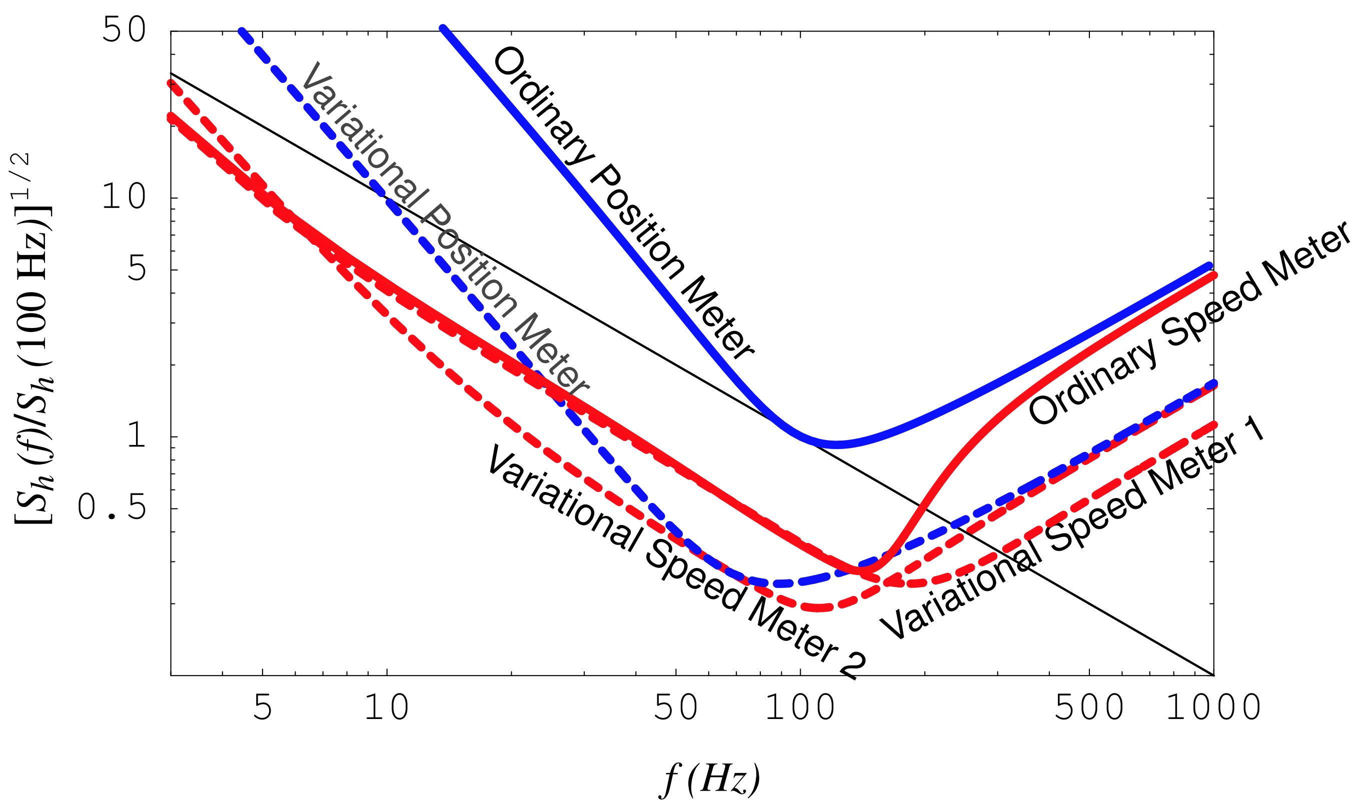
$L = 4\,\mathsf{km}$, $T_{\mathsf{arm}} = 0.056$, $\rho_{\mathsf{SR}} = 0.27$

[$800\,$kW and $10\,$dB squeezing]

Comparison between Speed Meter and Position Meter



Comparison between Speed Meter and Position Meter



Ordinary Pos Meter $<$ Ordinary Speed Meter $<$ Var Pos Meter $<$ Var Speed Meter

High power and Low loss

- High power required to lower the shot noise. For LIGO parameter ($L = 4\,\mathrm{km}$), broadband detectors [BW $> 100\,\mathrm{Hz}$] [in all above configurations] require

$$I_{\text{circ}} = e^{-2R}\,\left[S_{\text{SQL}}^{40\,\text{kg}}/S_h\right]\,\times 800\,\text{kW}$$

- Low loss required to preserve the squeezed state [injected and *ponderomotive*]

$$\sqrt{S_h/S_{\text{SQL}}} > (e^{-2R}\epsilon)^{1/4}$$

with $e^{-2R} \sim 0.1$, and $\epsilon \sim 0.01$, limited to factor of ~ 30 in power.

Input and output optics for detuned SR interferometers?

[Somiya 02; Mueller 02; Buonanno, Chen and Mavalvala, 03; Harms et al. 03; Buonanno and Chen, unpublished]

- Frequency-dependent squeezing cannot give global improvement
- Fully optimal input-output optics requires both variational input squeezing and variational readout not accessible by KLMTV filters.
- Two sub-optimal frequency-dependent schemes
  - Fixed input SQZ + variational readout *[Buonanno and Chen, unpublished]*
  - Ordinary homodyne detection + variational input SQZ *[Harms, Chen, Chelkowsi, Frazen, Vahlbruch, Danzmann and Schnabel, 03]*

  Both realizable by two KLMTV filters; improve sensitivity by e^{2R}

Frequency-dependent input squeezing for *LIGO-2.5* ??

Why LIGO-2.5 but not LIGO-3:

- Sensitivity not as good as, e.g., Speed Meter or Squeezed-Variational Conventional Interferometer
- More straightforward to implement than speed meters or variational readout schemes
- Less susceptible to loss [to be verified]