OPTICAL SPEED METER IN GRAVITATIONAL WAVE ANTENNAE

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Report Structure.

- Introduction
- Simplified scheme of speed meter
- Speed meter interferometer for LIGO III
- Conclusion

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SQL & Velocity measurement.

Advanced interferometric GW-detectors should have sensitivity higher than Standard Quantum Limit (SQL) to provide information about astrophysical events in larger area of space.

One of possible ways to overcome the SQL that arises due to due to uncertainty principle, is to perform Quantum Nondemolition (QND) measurement. QND-observable value does not perturbed during the measurement $\Rightarrow$ there is no back action $\Rightarrow$ no SQL.

For free mass momentum $\hat{p}$ is a QND observable, but it is not easy to measure it, therefore it is convenient to measure free mass velocity $\hat{v}$ as it is perturbed only during the measurement and returns to the initial value after it. Provided that there is proper cross correlation between measurement uncertainty of velocity and its perturbation, back action can be eliminated from the output signal $\Rightarrow$ no SQL.

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Simple scheme of speed meter.

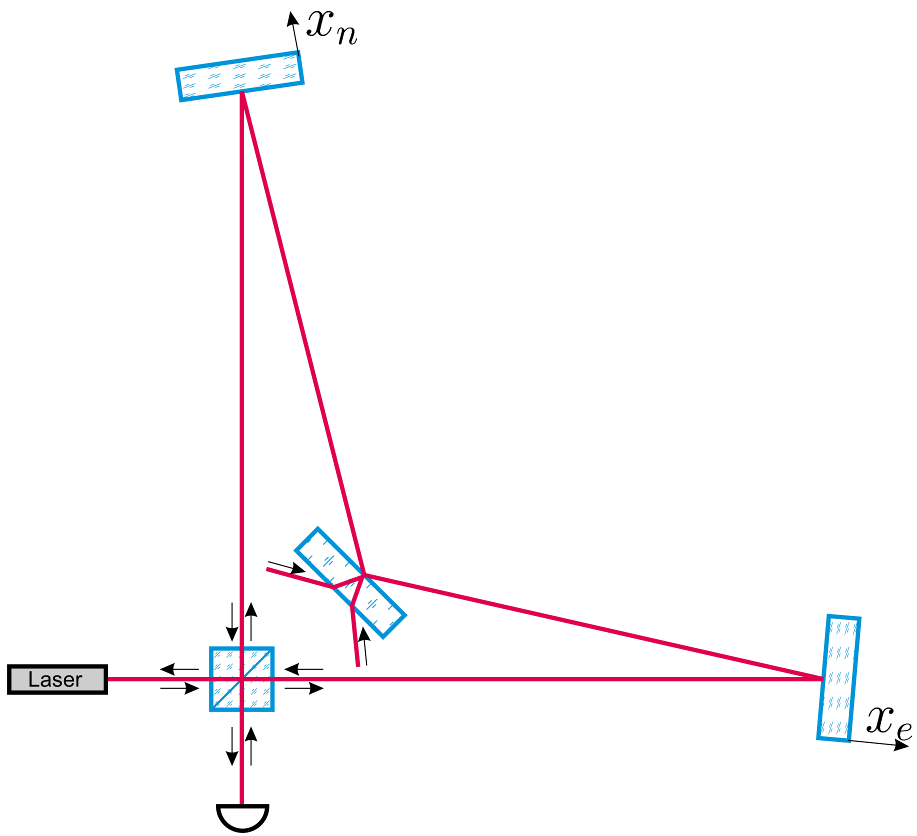

FIG. 1: Simple scheme of speed meter interferometer with optical losses. Central mirror is slightly transparent to account for losses and additional pumping.

How this scheme works?

This scheme measures the difference of test mass coordinates divided by small time interval τ:

$$x(t+\tau) - x(t) \sim \bar{v}\tau \, .$$

In presented simple detector such measurement is performed as follows:

- laser beam is reflected subsequently from both test masses, and time interval is equal to the time between reflections;
- two beams propagating in opposite directions are used, that allows to eliminate any information about initial masses position from the output;
- homodyne readout is used to provide appropriate cross-correlation between measurement and back action noises.

Simple speed meter analysis.

- Additional pumping through central lossy mirror do not create additional noise but slightly increases sensitivity;

- Optical losses (represented by central mirror reflectivity r) decrease sensitivity at frequencies lower than
$$\Omega_{min} \simeq \frac{P_{simple}\sqrt{2(1-r)}}{\tau\sqrt{4P_{simple}-1}};$$

- At higher frequencies sensitivity increases with the increase of optical pumping power ($P_{simple} \sim W$)
$$\xi^2_{\rm HF} = \frac{S_{\rm SM}}{S_{\rm SQL}} = \frac{1}{4P_{simple}r};$$

- Optimal sensitivity at some fixed frequency Ω^* can be reached at optimal pumping power
$$P^{opt}_{simple} \simeq \frac{\Omega^*\tau}{\sqrt{2(1-r)}}.$$

Illustration to the above results.

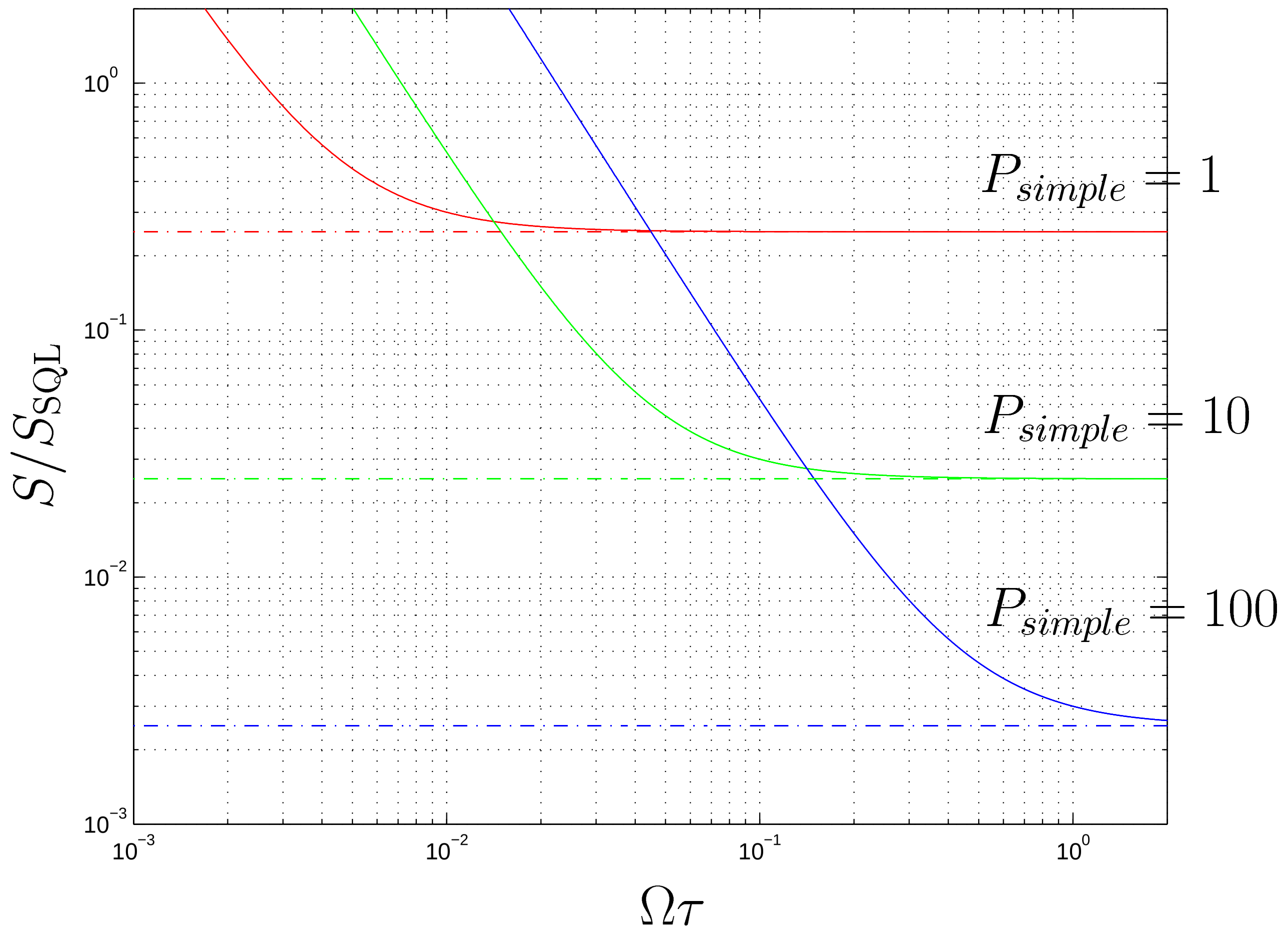

FIG. 2: Typical curves for sensitivity $\xi^2 = S/S_{\rm SQL}$ at different optical powers P_{simple}.

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Speed meter interferometer for LIGO III.

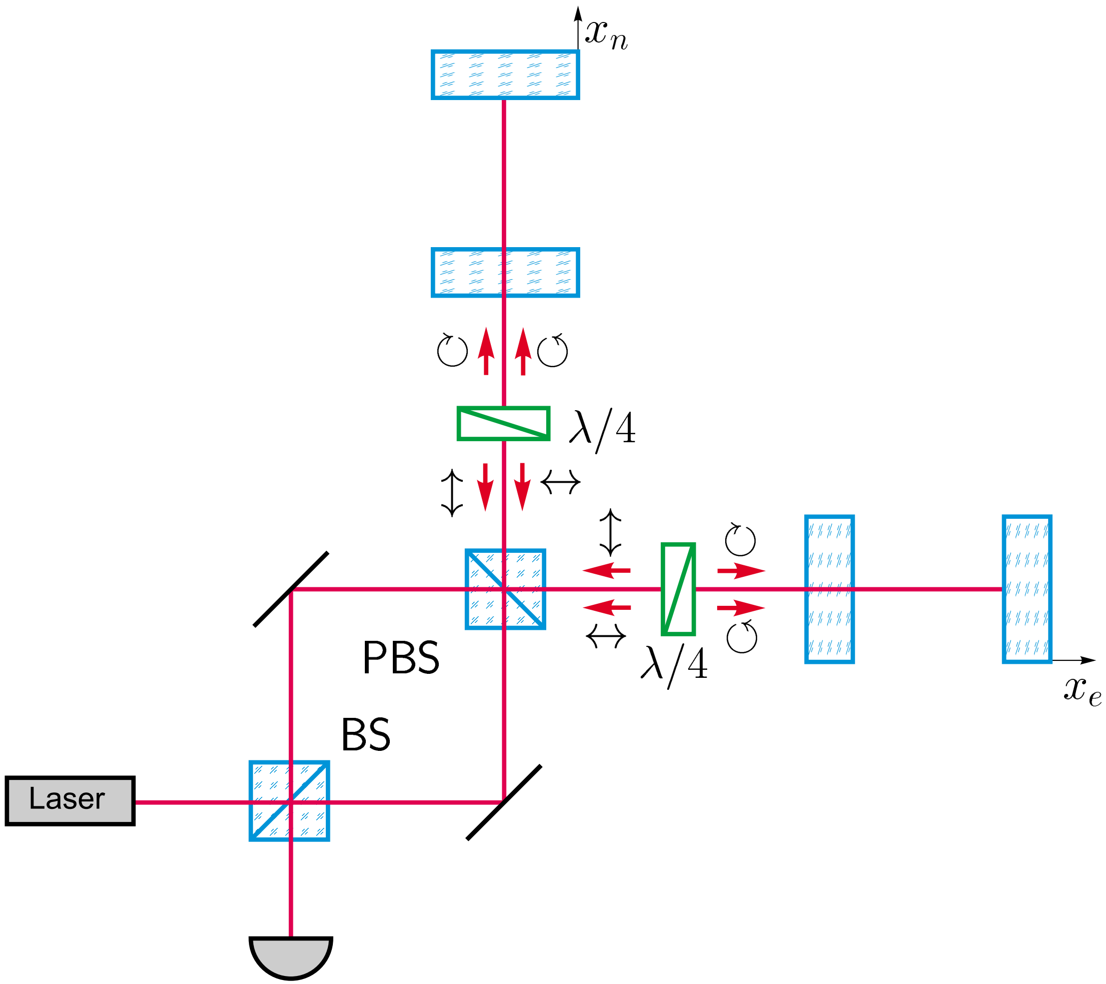

FIG. 3: Optical scheme of speed meter for LIGO III. *[F.Ya. Khalili, 2002, modified]*

The above scheme action.

- Two light beams pass trough the scheme in opposite directions subsequently being reflected from two Fabry-Perot cavities with movable mirrors;
- Polarization beam-splitter (PBS) is necessary to make each beam to pass through both cavities before it leaves;
- Quarter-wave plates $(\lambda/4)$ are necessary to prevent different beams from interaction;
- Optical elements of cavities are supposed to be non-ideal, *i. e.* it have nonzero absorbtion and transmittances;
- Homodyne readout is also supposed to provide proper cross-correlation between shot noise (Δx) and radiation pressure noise (Δp) acting upon the interferometer mirrors.

Speed meter sensitivity for different values of optical losses.

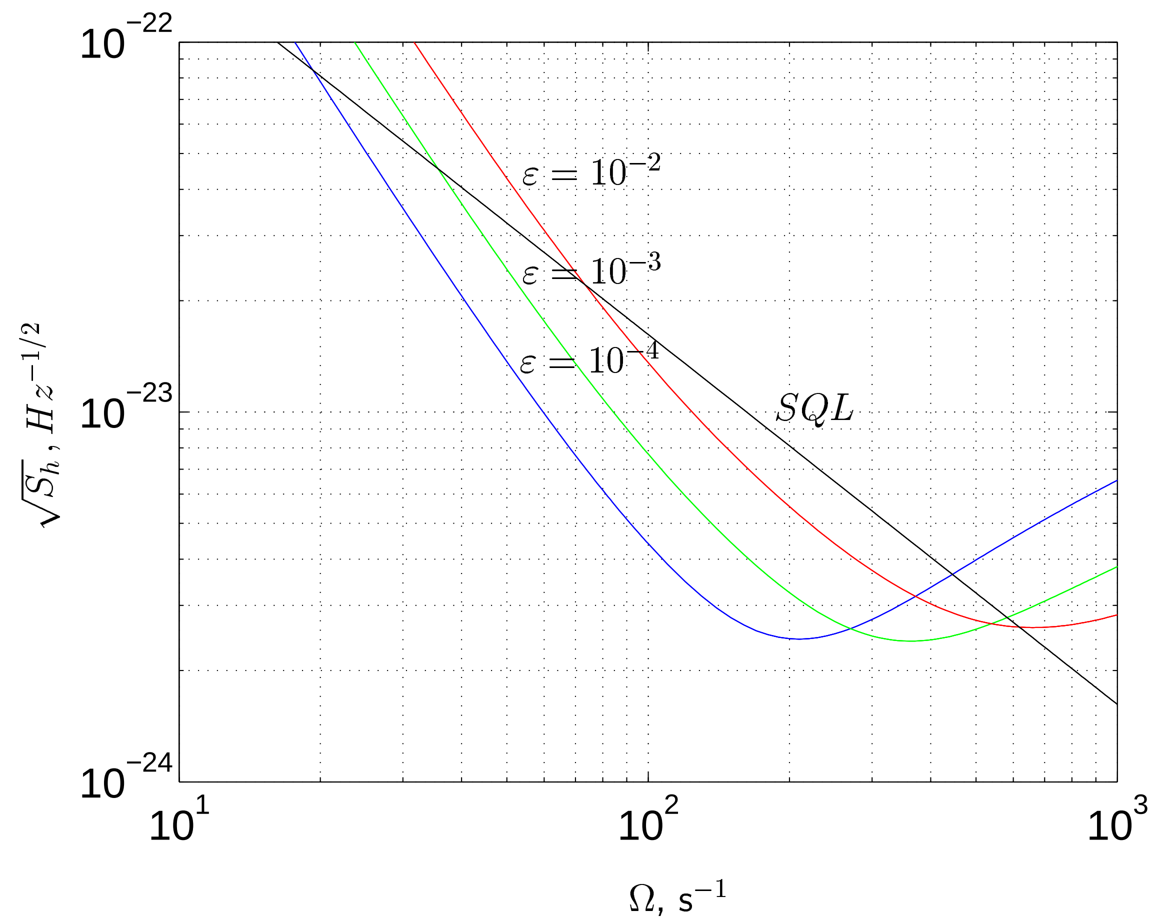

FIG. 4: Typical curves for measurement noise $\sqrt{S_h}$ for different values of optical losses.

Speed meter sensitivity for different values of circulating powers.

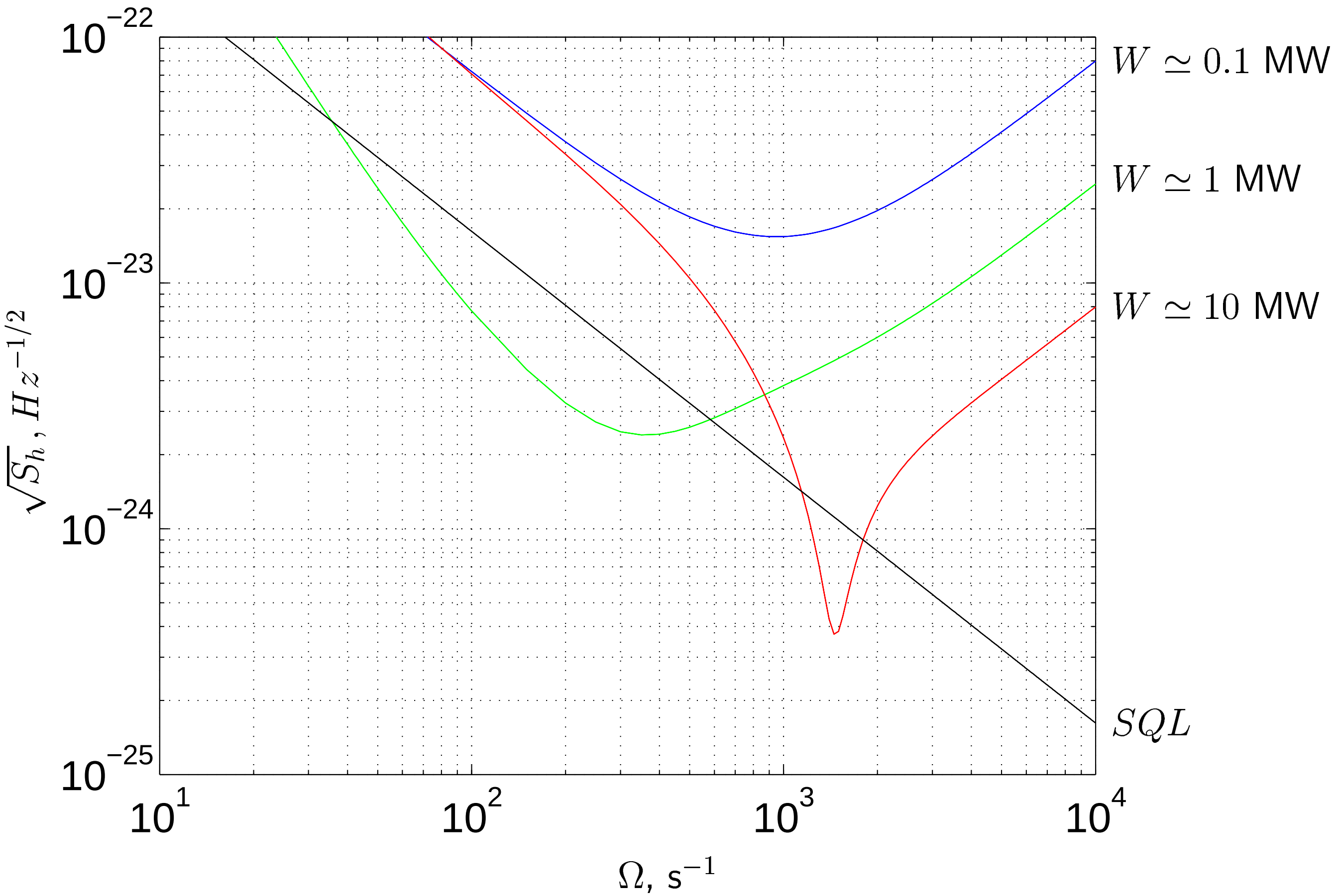

FIG. 5: Typical curves for measurement noise $\sqrt{S_h}$ for different values of circulating powers and fixed value of optical losses $\varepsilon = 10^{-3}$.

Optimal parameters for speed meter.

To make the speed meter operate in the optimal mode at given loss level ε the following parameters should be taken:

- Circulating power $W_{opt} \simeq \dfrac{mL^2\Omega_\circ}{32\omega_\circ\tau\gamma^2}\sqrt{\dfrac{2}{\varepsilon}} \simeq \dfrac{3.05\cdot 10^4}{\sqrt{\varepsilon}}$ W, where $\omega_\circ = 1.77\cdot 10^{15}$ s^{-1} is input light frequency, $\Omega_\circ = 100$ s^{-1} is some fixed optimization frequency, $m = M/4 = 10$ kg is the interferometer reduced mass, $L = 4\cdot 10^3$ m is the FP-cavity length, and $\tau = L/c = 1.33\cdot 10^{-5}$ s;
- Homodyne angle $\Psi_{opt} \simeq -\arctan\left(\dfrac{\Omega_\circ}{\gamma}\sqrt{\dfrac{2}{\varepsilon}}\right)$;
- Additional pumping factor $\eta = 1$.

Then, speed meter quantum noise will be lower than SQL by the factor:

$$\xi^2 \simeq 7.1\sqrt{\varepsilon}\,.$$

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Conclusion.

- Speed meter is susceptible to optical losses at low frequencies;
- At higher frequencies ($\Omega \sim \gamma$) the scheme sensitivity is limited by the finite bandwidth of FP cavities, as fourier components of sideband fluctuations that carry information about the gravitational-wave signal, are cut off by the cavity resonance curve if their frequencies lie far from the resonance frequency;
- The sensitivity of the scheme can be slightly increased if the decrease of classical pumping power because of losses will be compensated by additional pumping;
- Varying pumping power with fixed homodyne angle it is possible to control speed meter frequency band in comparatively wide ranges if losses are not very high;

Therefore, speed meter can be a good candidate for LIGO III detector if internal losses will be reduced.