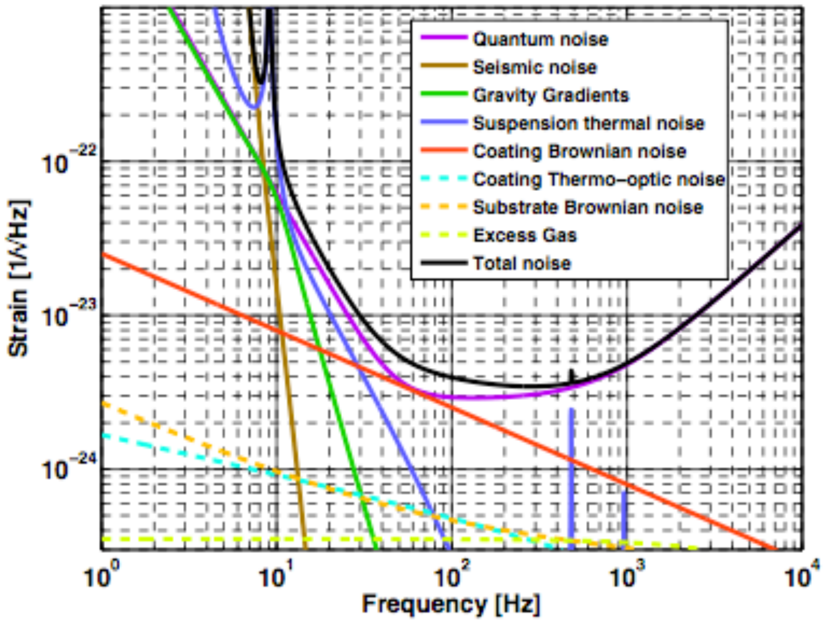
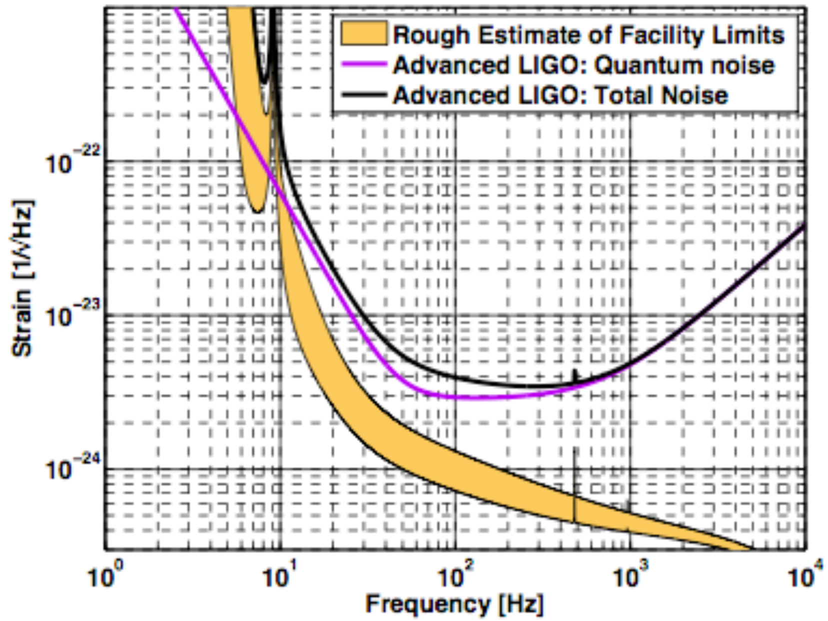




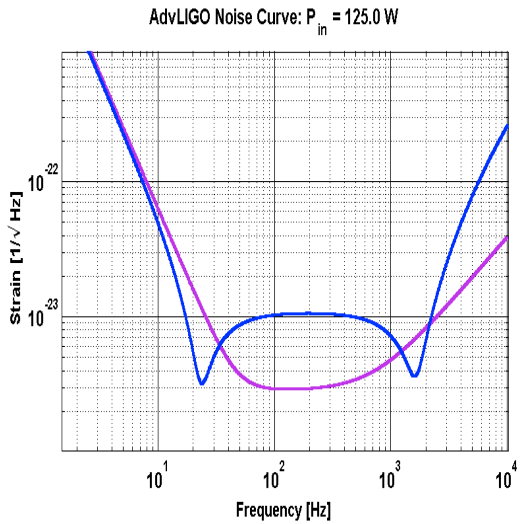
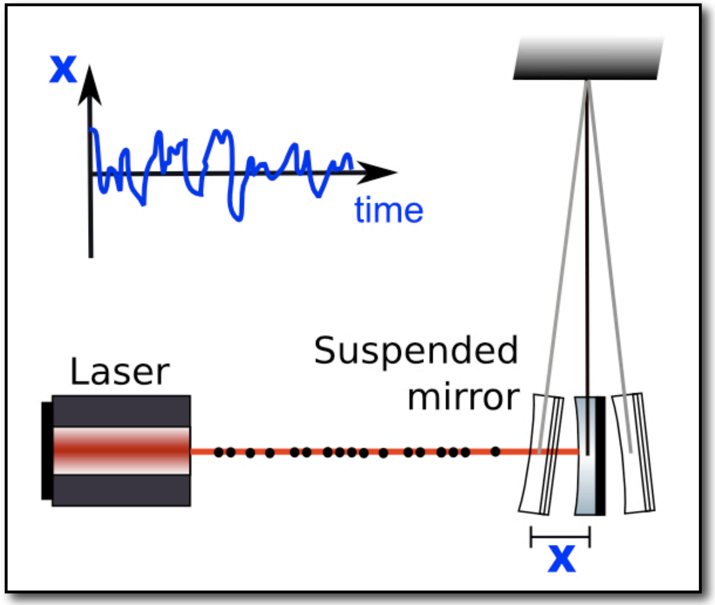


Figure 2. LEFT: Noise budget of Advanced LIGO. This plot was produced using the GWINC [24] and represents the Advanced LIGO broadband configuration described in [23]. RIGHT: Illustrative examples of potential sensitivity limits for Advanced LIGO upgrades. The upper boundary of the orange area is given by seismic, gravity gradient and residual gas noise equal to the Advanced LIGO baseline design and coating and suspension thermal noise being improved by a factor 2 each. In contrast the lower boundary is calculated assuming a coating noise improvement of a factor 4, a suspension thermal noise reduction of a factor 5, a gravity gradient subtraction of a factor 10 and a seismic noise level reduced by a factor 100. Please note that quantum noise is not included in the orange region.

What is quantum noise?

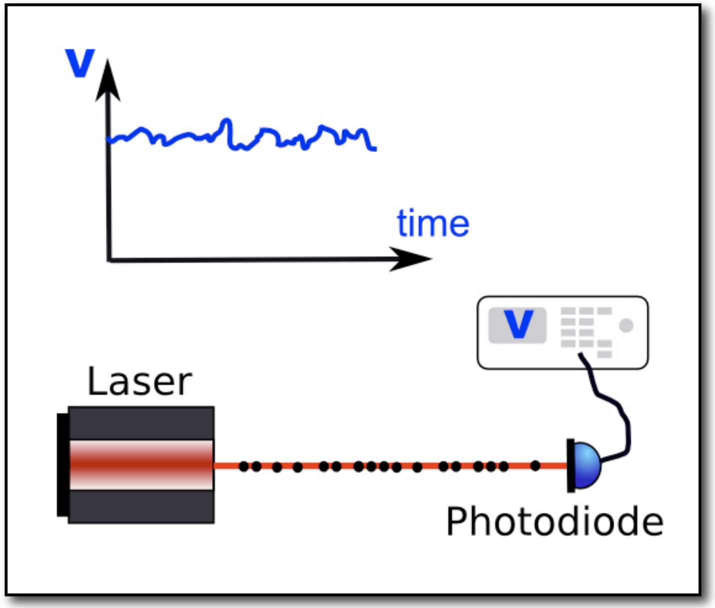
- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
- The photons in a laser beam are not equally distributed, but follow a Poisson statistic.



$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

wavelength
optical power
Arm length
Mirror mass



photon radiation pressure noise

photon shot noise

The Standard Quantum Limit (SQL)

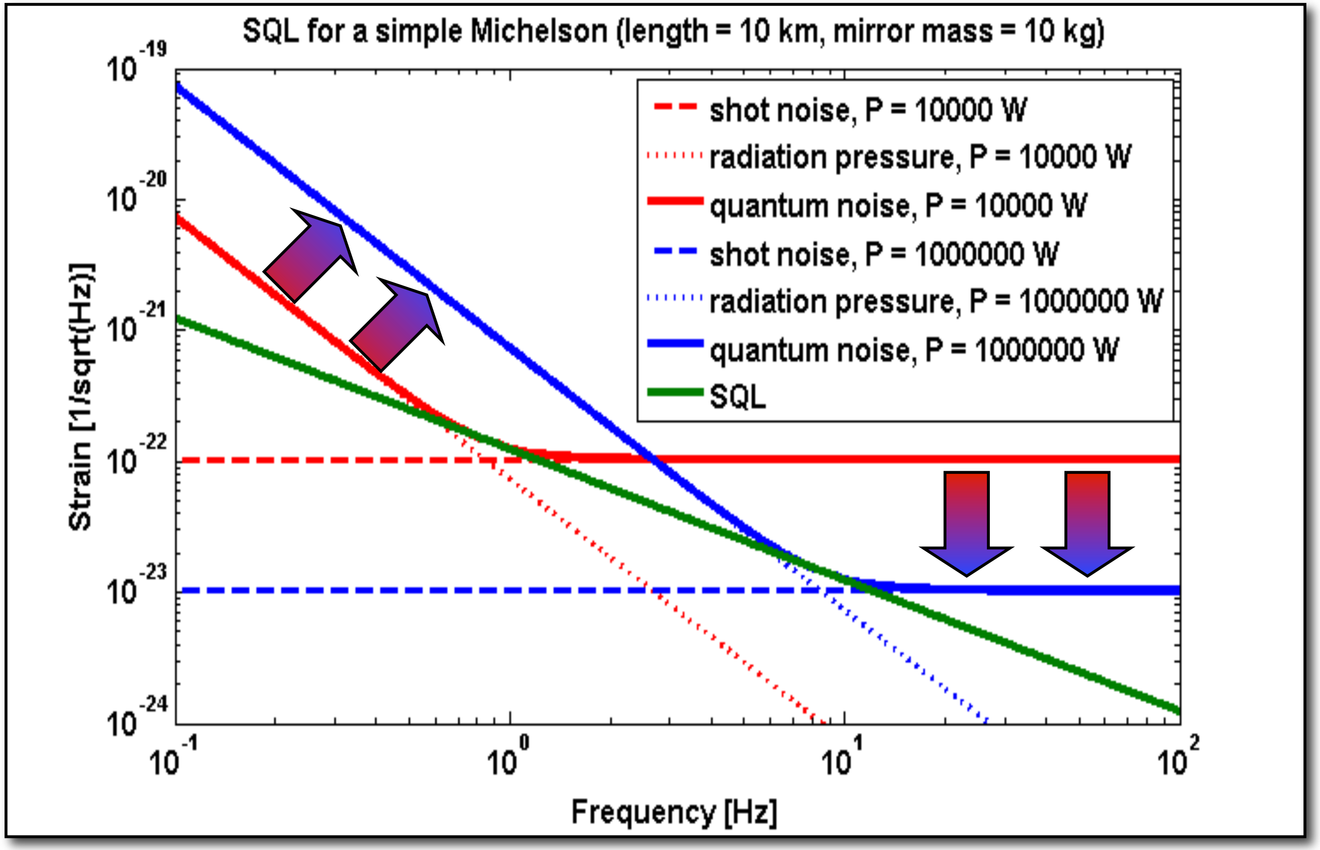
- While shot noise contribution decreases with optical power, radiation pressure level increases:

$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

wavelength, optical power, Arm length

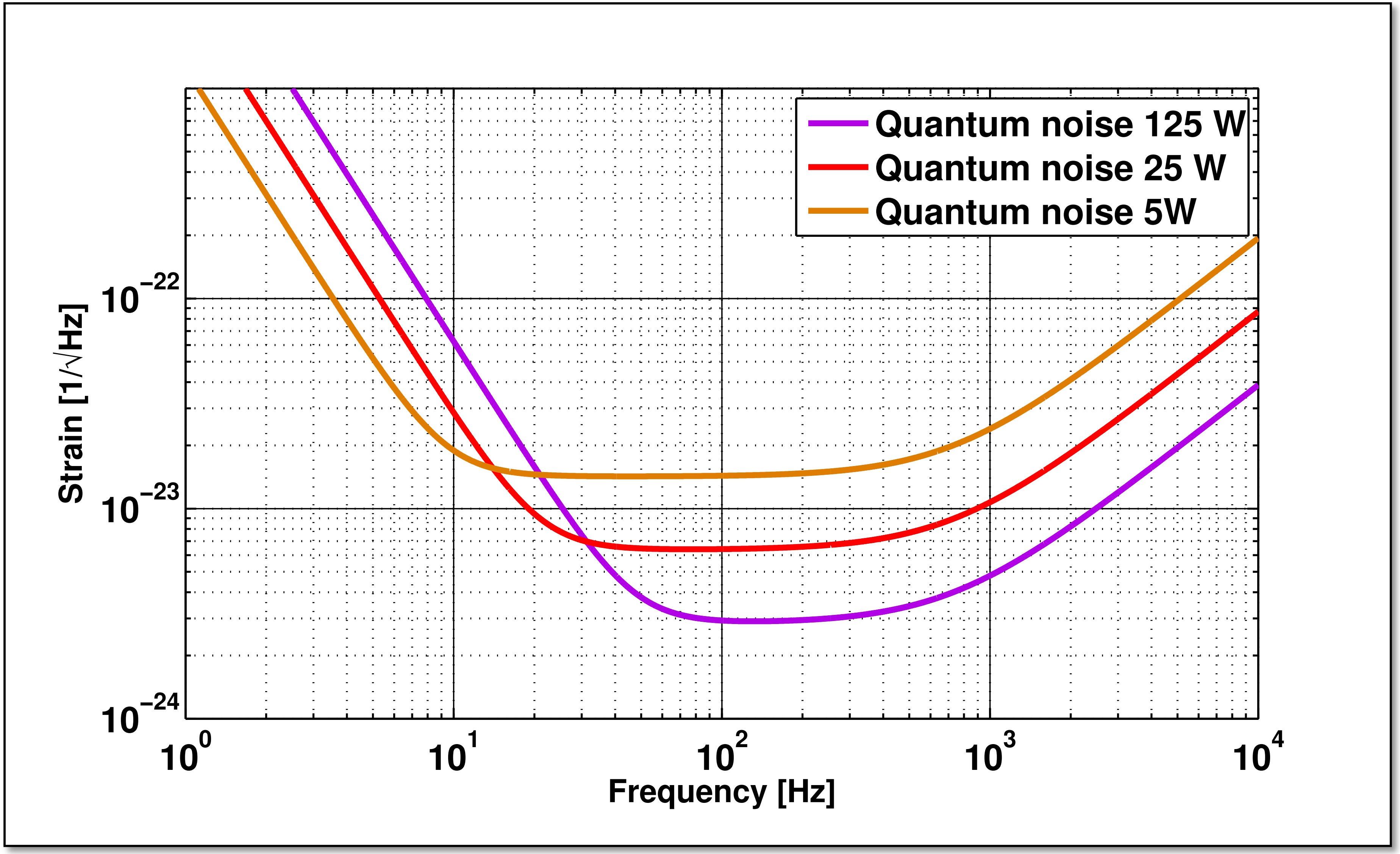
$$h_{\mathrm{rp}}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

Mirror mass



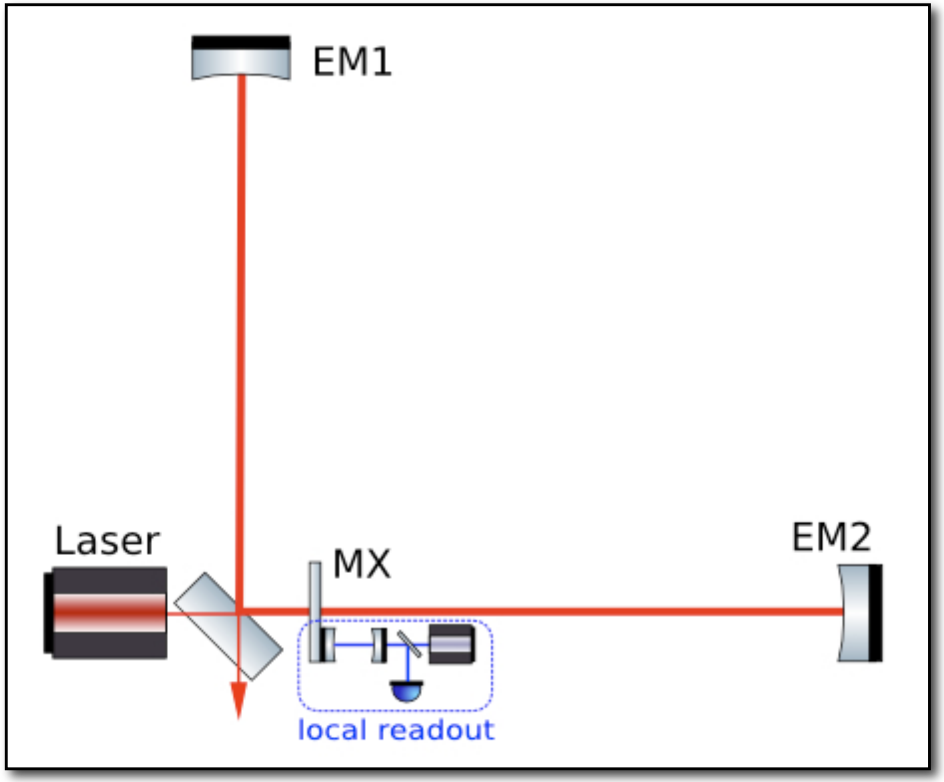
- The SQL is the minimal sum of shot noise and radiation pressure noise.
- Using a classical quantum measurement the SQL represents the lowest achievable noise.

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

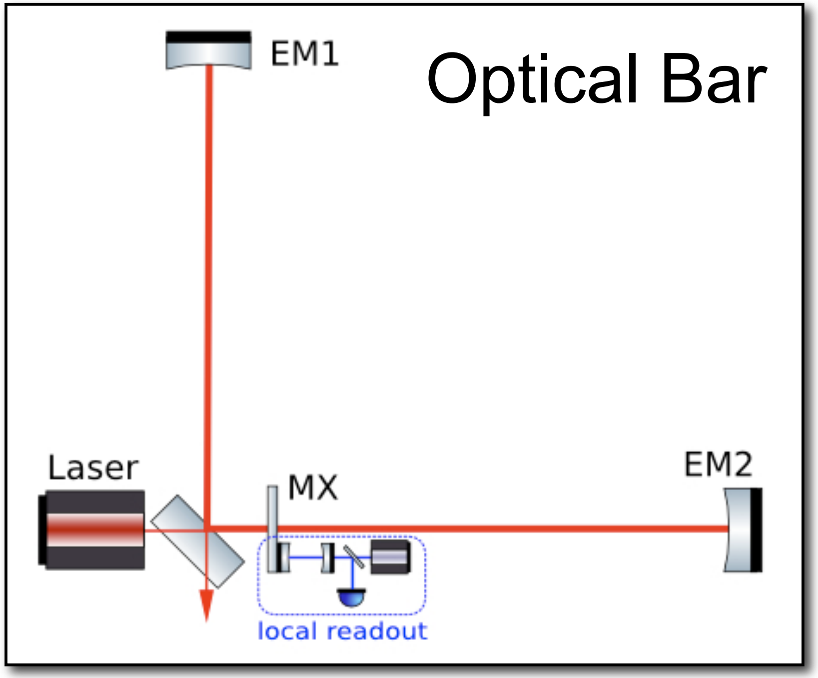

Quantum noise 125 W
Quantum noise 25 W
Quantum noise 5W
Strain [1/√Hz]
10^{-22}
10^{-23}
10^{-24}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

Optical Bar configurations

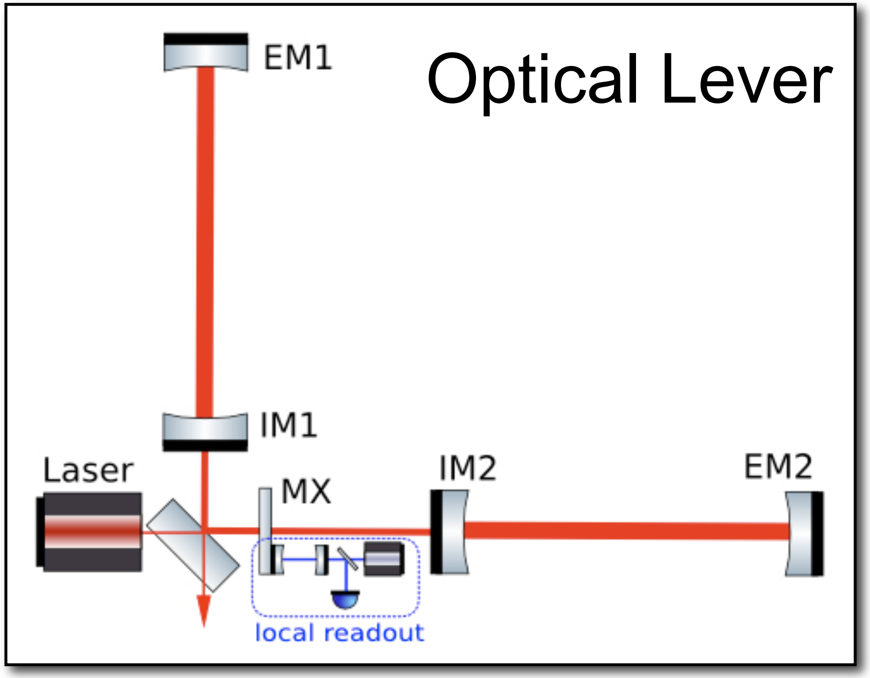
- Very light mirror (MX) is coupled to the movement of EM1 and EM2 via optical springs.
- MX can then locally read out by a small local meter without disturbing the quantum states in the main instrument (QND measurement).
- Split between GW transducer and readout allows separate optimisation of these two systems.



Optical Bars and Optical Levers



V.B. Braginsky and F.Y. Khalili: “Nonlinear meter for the gravitational wave antenna”,Phys. Lett. A 218 (1996).

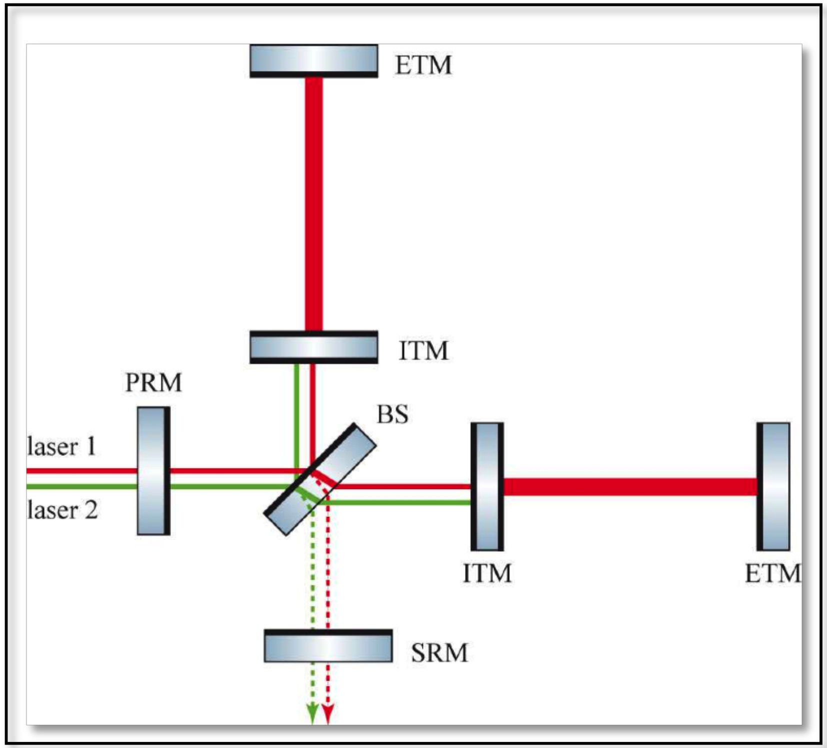


F.Y. Khalili: “The ‘ptical lever’ intracavity readout scheme for gravitational-wave antennae”,Phys. Lett. A 298 (2002).

- Optical lever: introducing arm cavities increases the movement of MX by the Finesse of the arm cavity.

Local Readout for Advanced LIGO

- While optical Bars and levers require a complete redesign of the interferometers, so-called 'local readout' is compatible within advanced LIGO infrastructure
- At low frequencies ITM and ETM are rigidly connected.
- At low frequencies GW signal is not in differential arm length, but in ITM movement (local frame).
- Use a separate laser system to read out the position of the ITM.

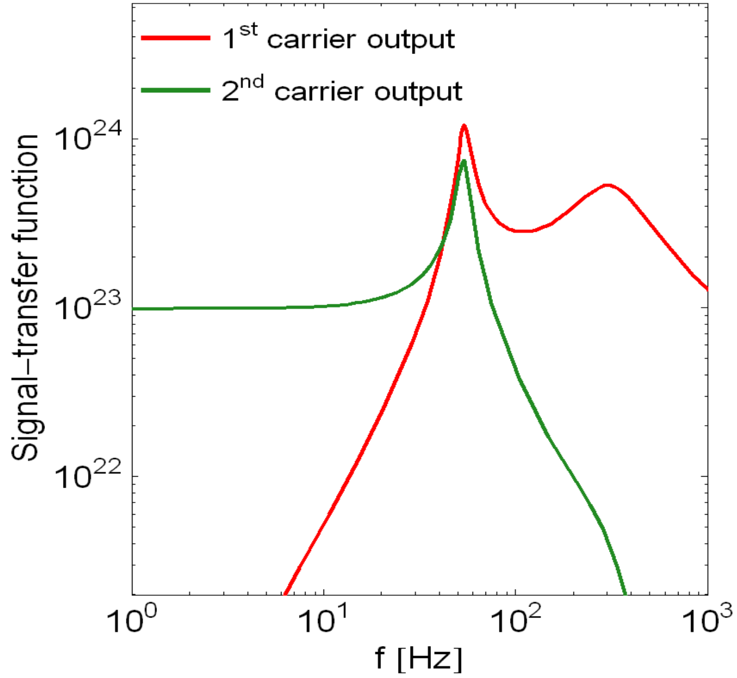


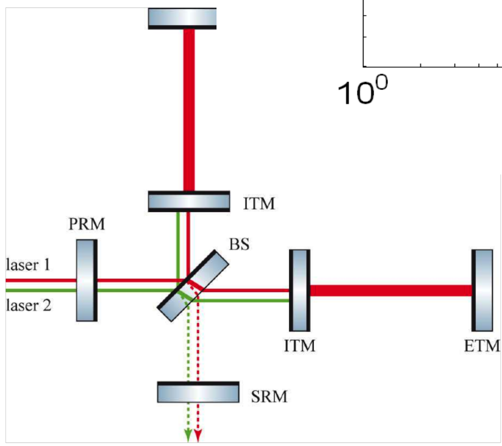
*Rehbein et al: PRD **76, 062002 (2007)***

Local Readout for Advanced LIGO (2)

How does local readout for Advanced LIGO work?

- **At low frequencies:** the arm cavity mirrors are 'rigidly' connected by optical springs => GW does not change the distance between ITM and ETM. However, GW signal is imprinted on ITM movement (in respect to BS), which and can be read out by additional green laser.
- **At high frequencies:** no optical spring present => ITM and ETM can move independently.

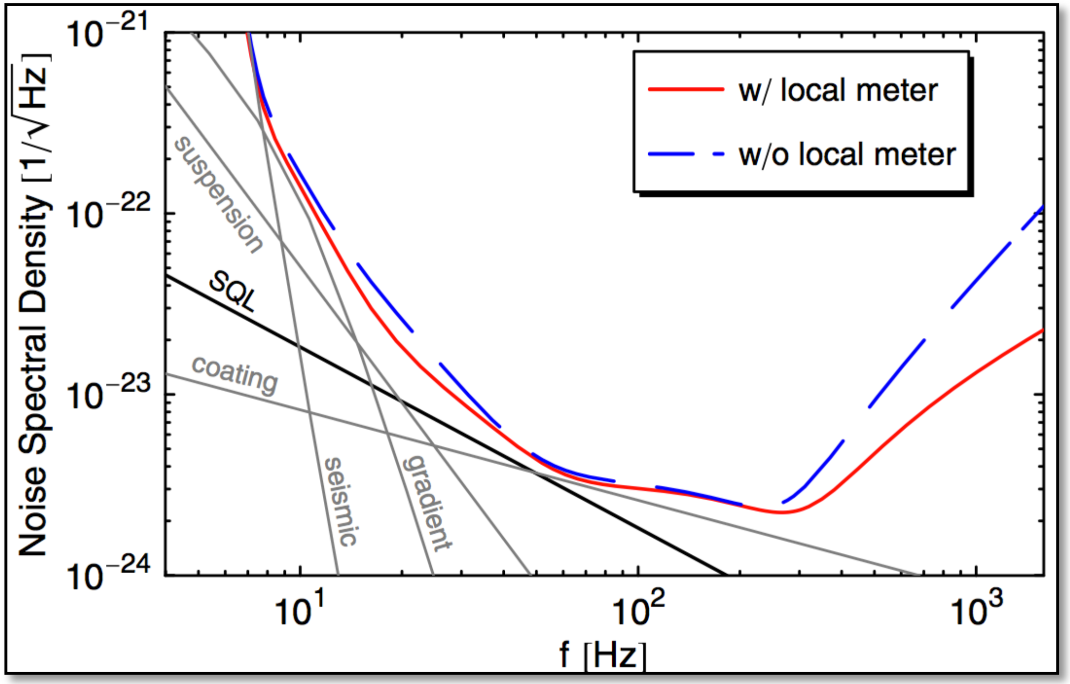




Rehbein et al: PRD ***76, 062002 (2007)***

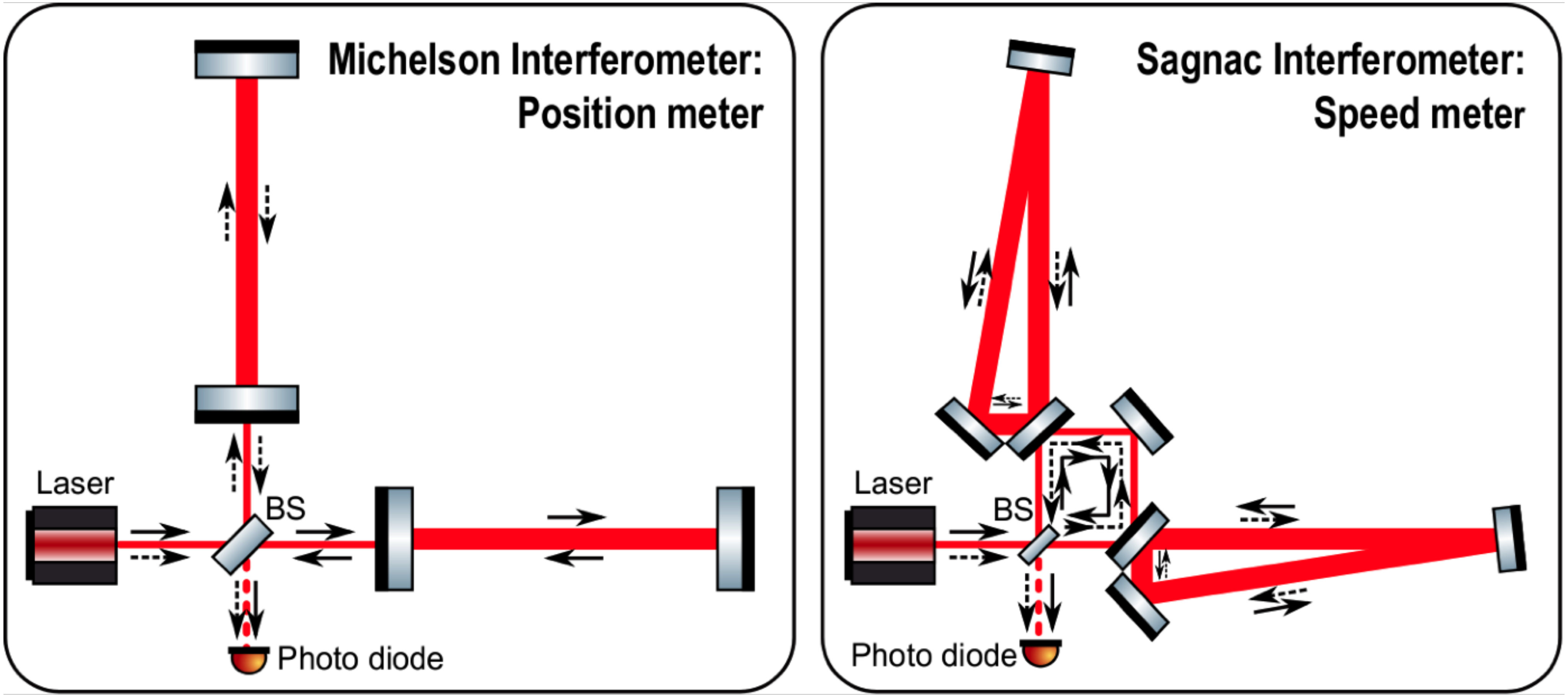
Local Readout for Advanced LIGO (3)

- Technique allows to increase low frequency sensitivity.
- In a second step the Signal-Recycling can then be re-tuned to slightly higher frequency.
- Win at low and high frequencies. =>

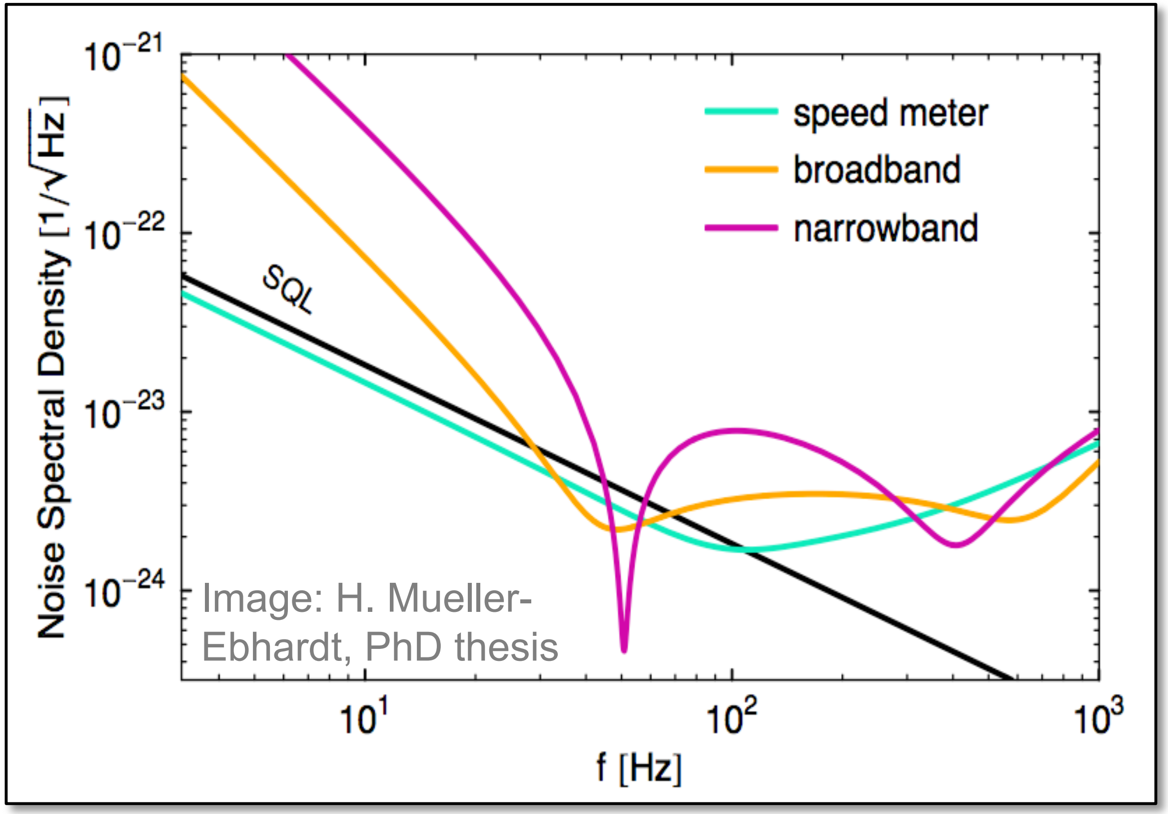


*Rehbein et al: PRD **76, 062002 (2007)***

Speedmeter vs Positionmeter

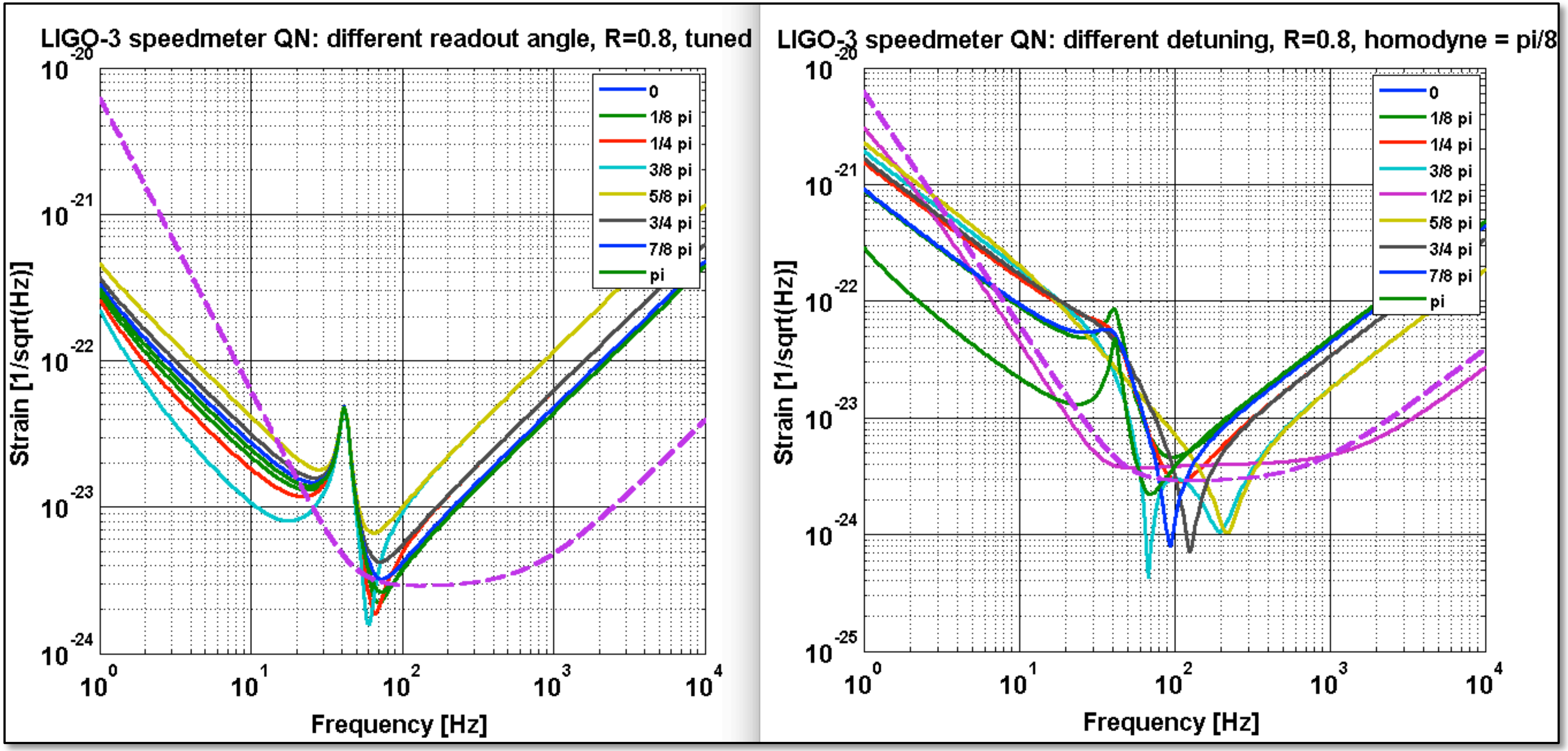


Speed meter 2



➲ Speedmeter can in principles cancel radiation pressure noise to a large extend and surpass the SQL over a wide frequency range

Speedmeter really better than MI ?



Dashed pink curve = ALIGO baseline