Breaking the quantum barrier

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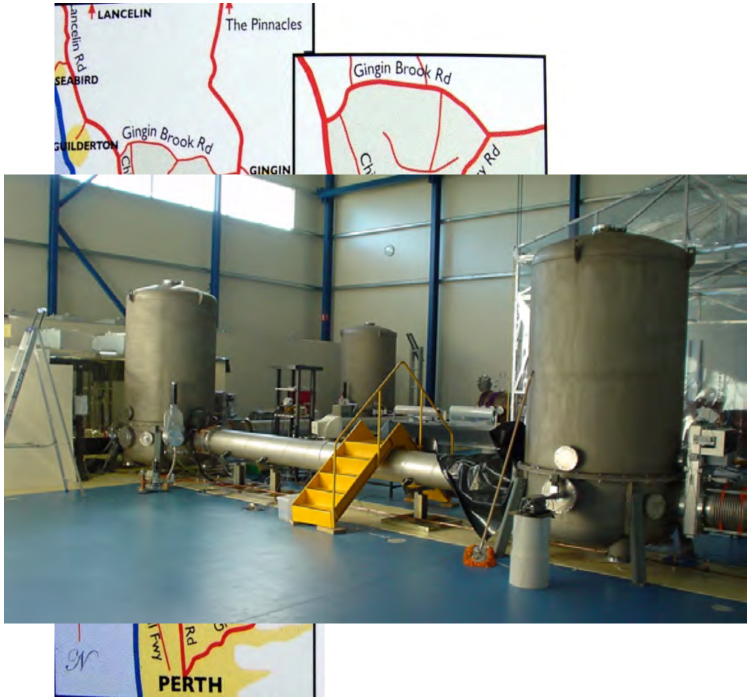
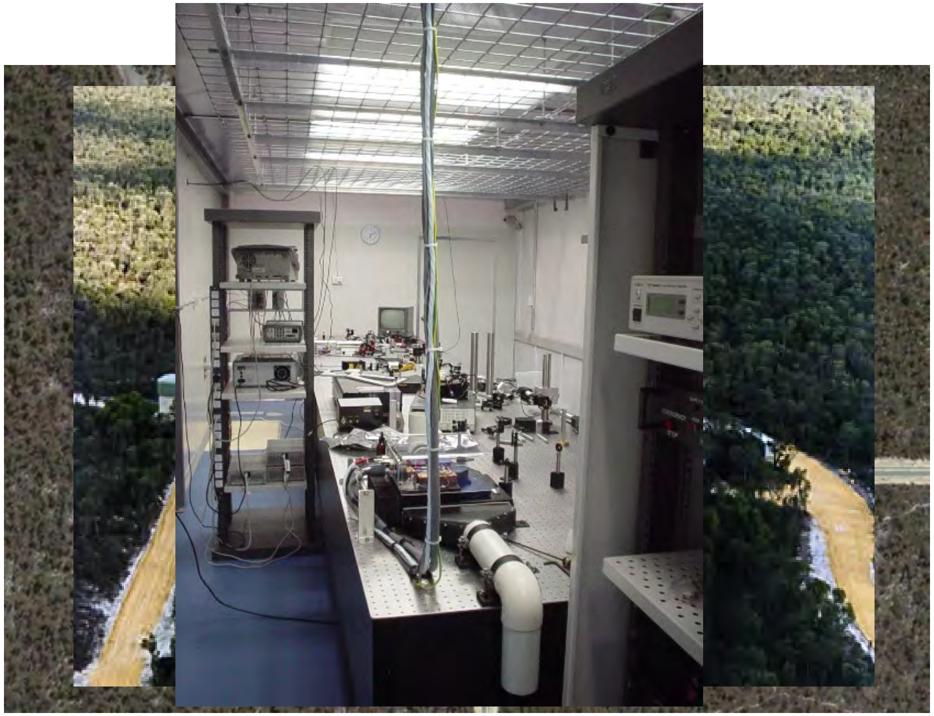
- Squeezed vacuum injection and variational readout
- Optical spring modified test mass dynamics
- Experiments on Gingin facility

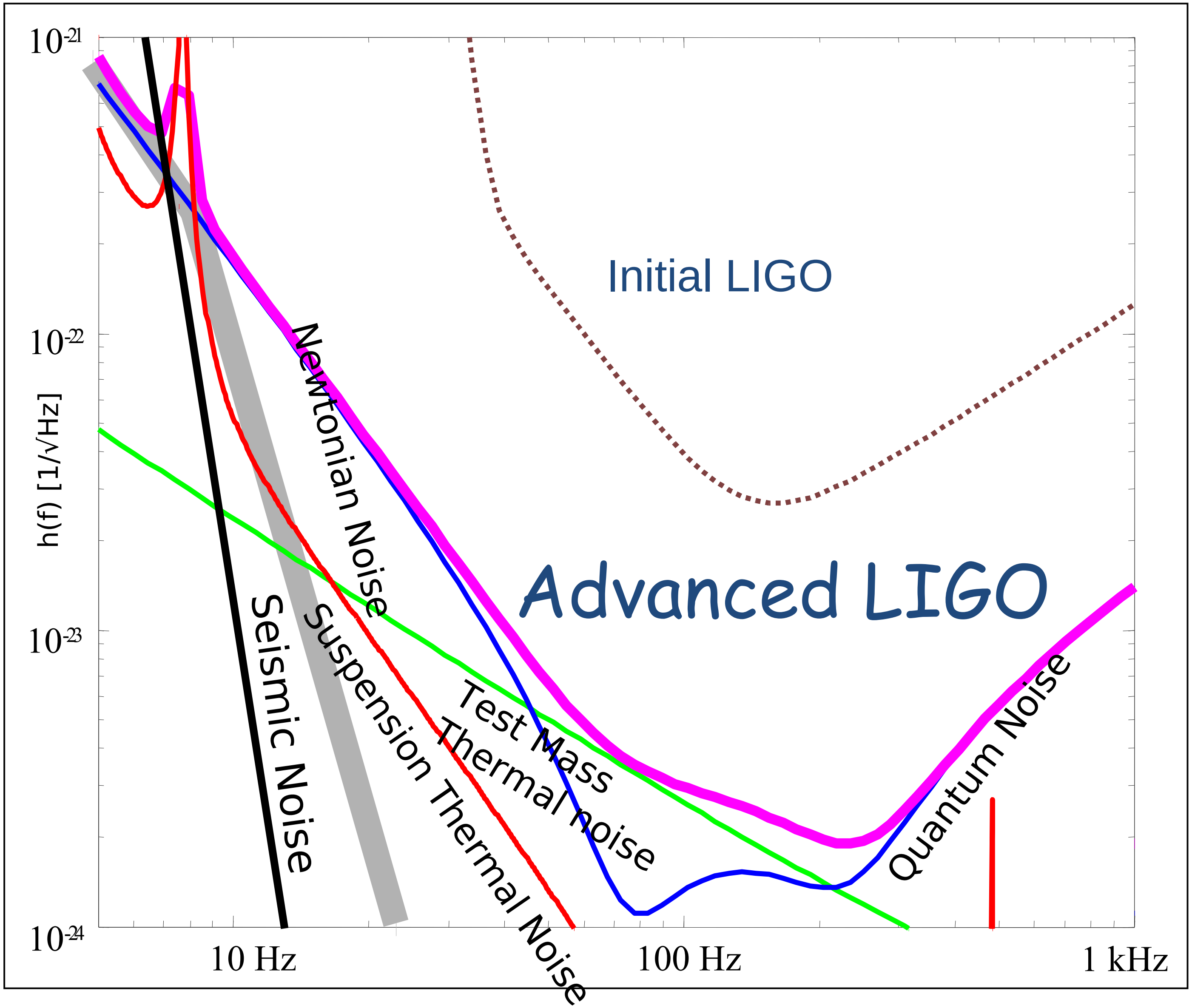
Gingin high optical power test facility

The facility was built by UWA ANU and Adelaide in collaboration with LIGO to investigate high optical power effects in advanced interferometers

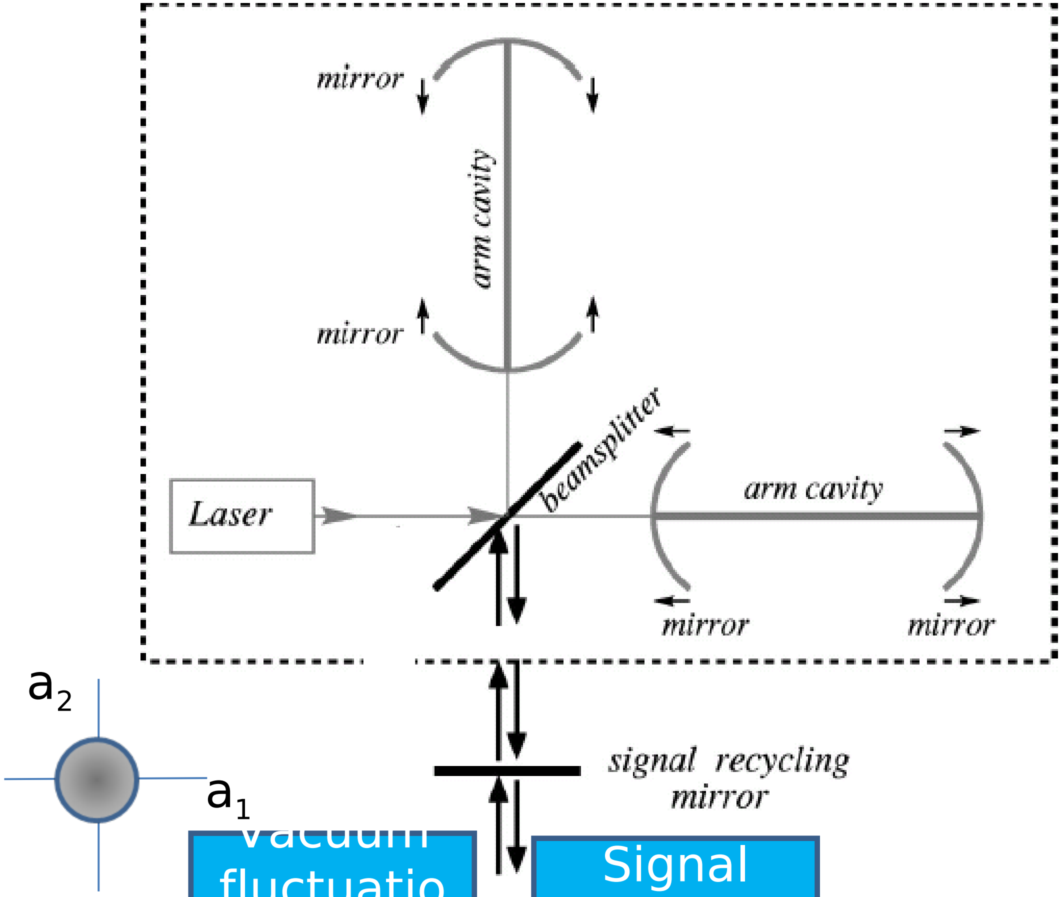




Introduction



Laser interferometer



Vacuum fluctuation a_i (a_1, a_2)

Signal fields b_i (b_1, b_2)

- GW induced mirror movement creates output signal b_i

- Vacuum fluctuation a_i injected from the output port couples noise to b_i

Quantum noise

- The fluctuation of photon arriving time at the photodiode create shot noise
- The photon number fluctuation induced the radiation pressure noise drives the test masse.

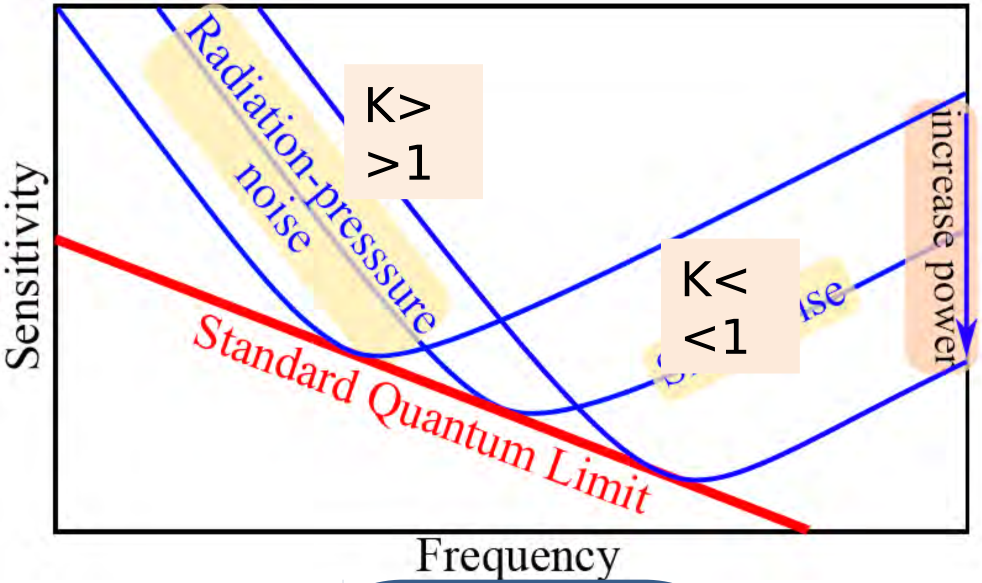
$$b_1 = e^{2i\beta} a_1$$

$$b_2 = e^{2i\beta}(a_2 - \mathcal{K} a_1) + e^{i\beta}\sqrt{2\mathcal{K}}\frac{h}{h_{\rm SQL}}$$

Shot noise

Radiation pressure noise

GW signal



K> >1

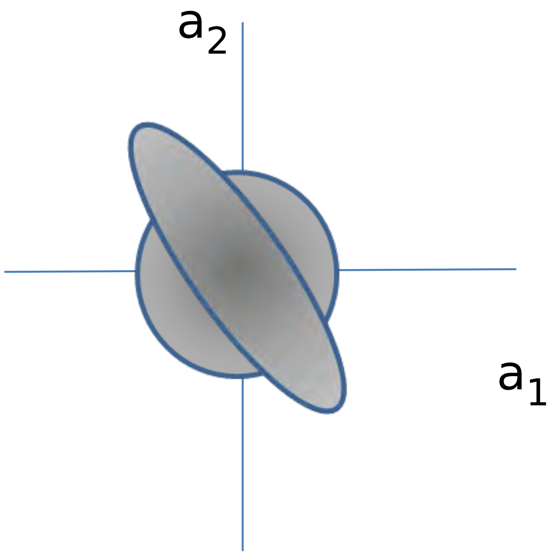
K< <1

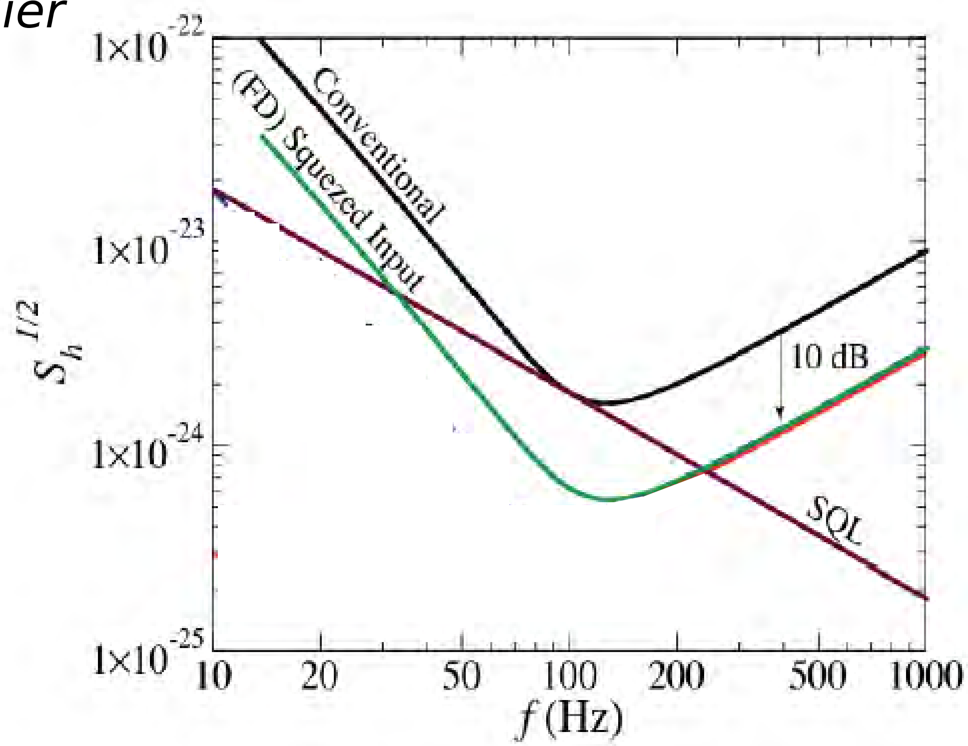
Measurement strength

$$\mathcal{K} = \frac{2\gamma\Theta^3}{\Omega^2(\Omega^2+\gamma^2)}, \quad \Theta^3 = \frac{8\omega_0 I_0/T_i}{mLc}$$

Squeezed vacuum injection

A *squeezed-input interferometer conceived by Unruh based on earlier work of Caves in early 80s*





Variational output interferometer

- A *variational-output interferometer conceived by Vyatchanin, Matsko and Zubova in 90s*
- H. J. Kimble, etc. designed the practical scheme to implement the variational-output in 2002

Correlated

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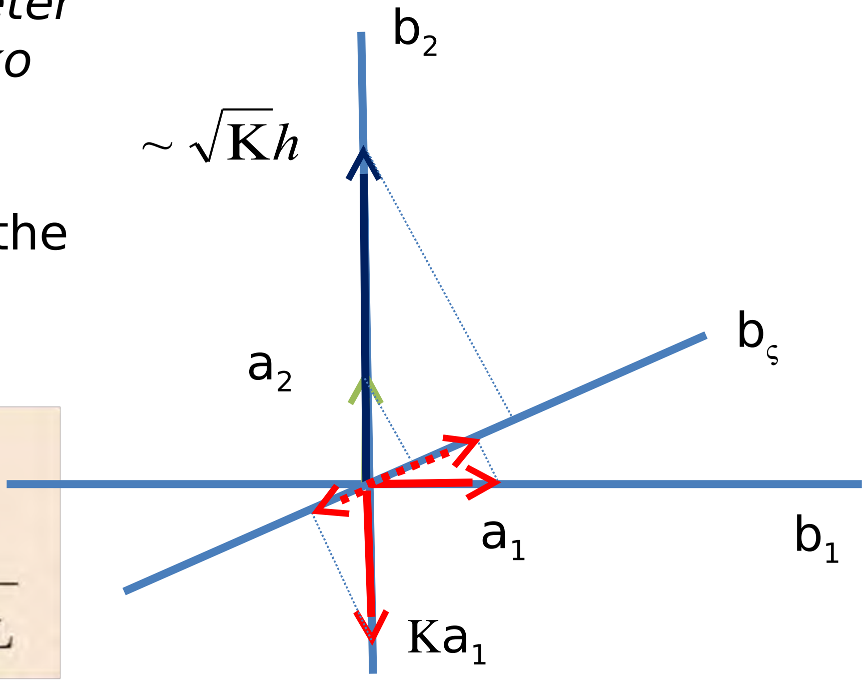

$$b_\zeta = b_1 \cos\zeta + b_2 \sin\zeta$$

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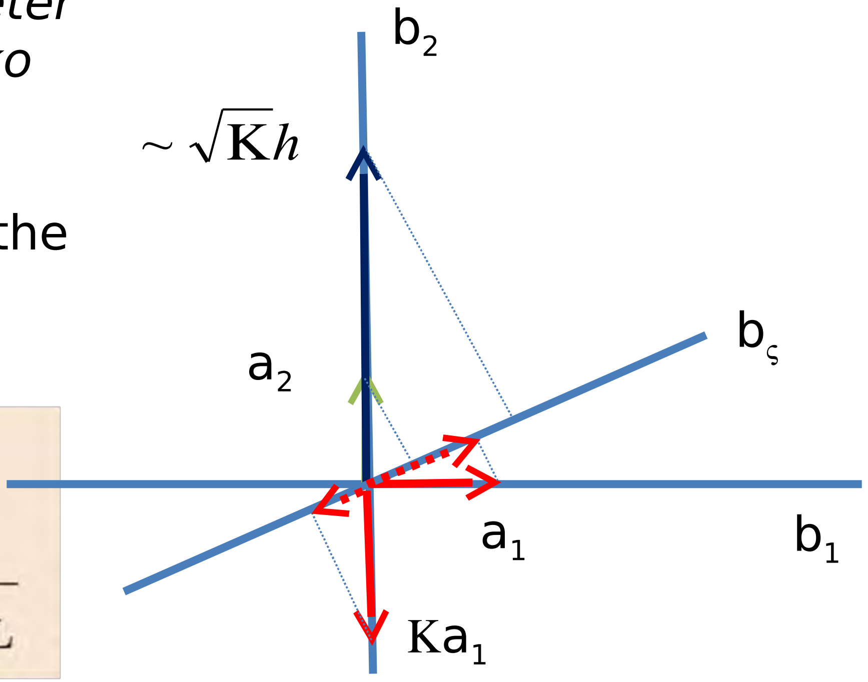

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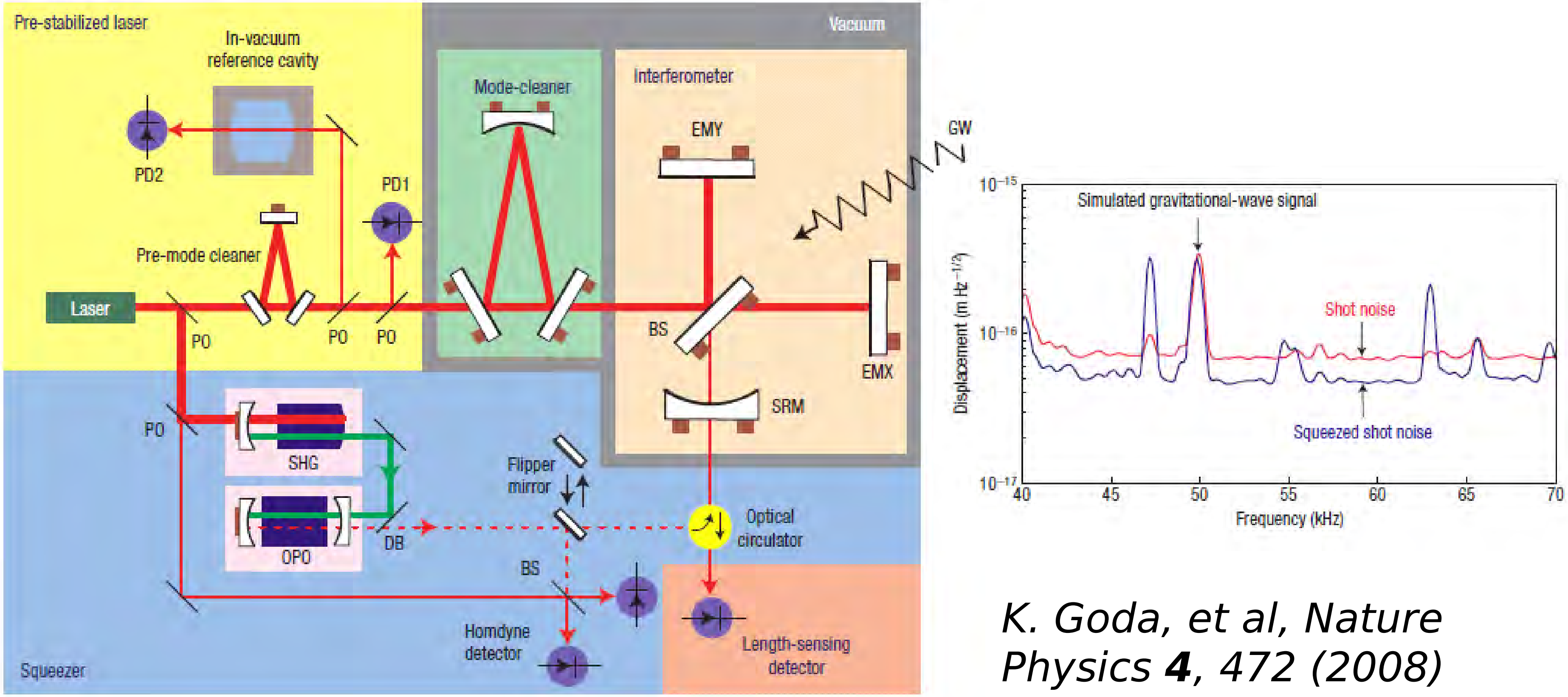
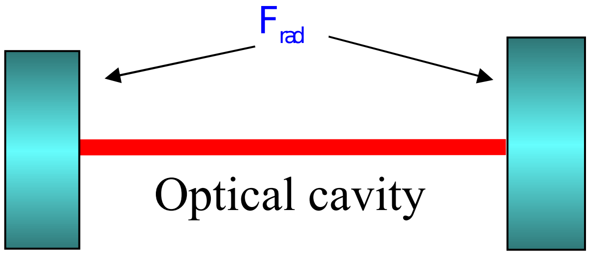
Experimental demonstration at LIGO 40 meter

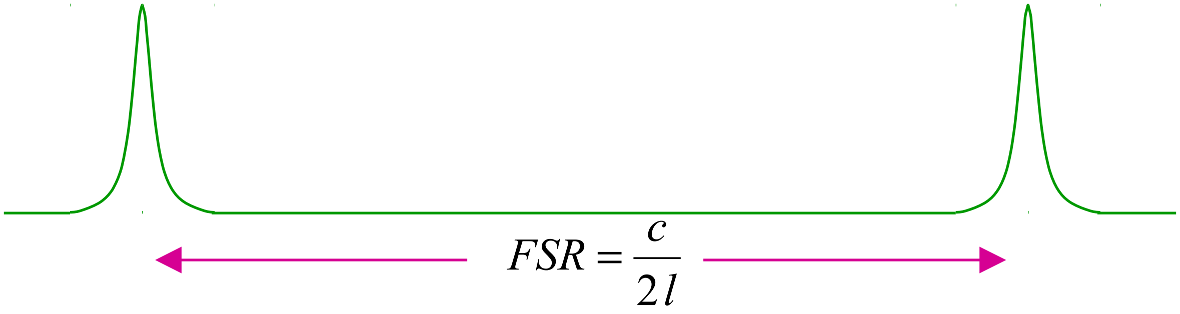


*K. Goda, et al, Nature Physics **4**, 472 (2008)*

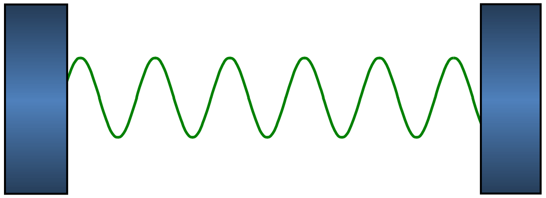
Optical Springs

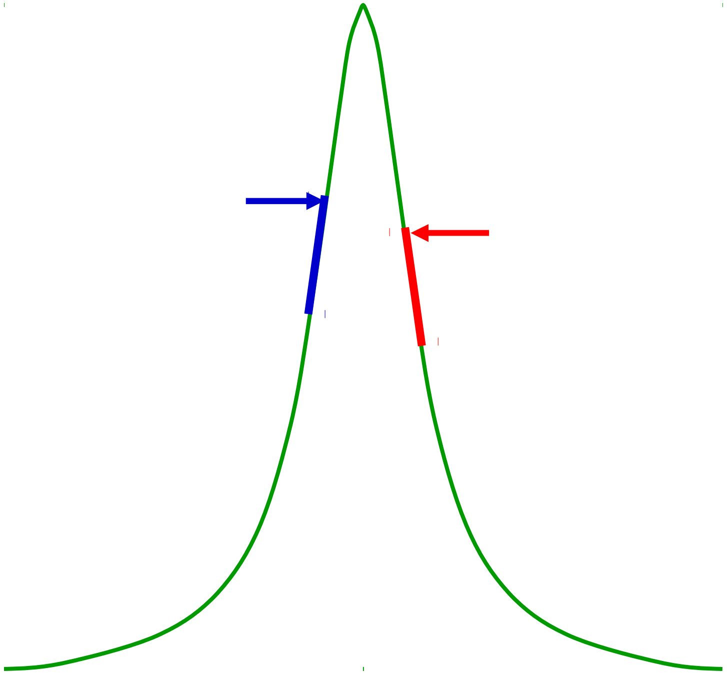
a simplified version





$FSR = \frac{c}{2l}$





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Properties of optical springs

tical spring is frequency dependent and in a particular narrow frequency
spring constant can be expressed as:

$$K(\Omega) \approx m_{opt}\Omega^2$$

SQL for force measurement depends on test mass dynamics:

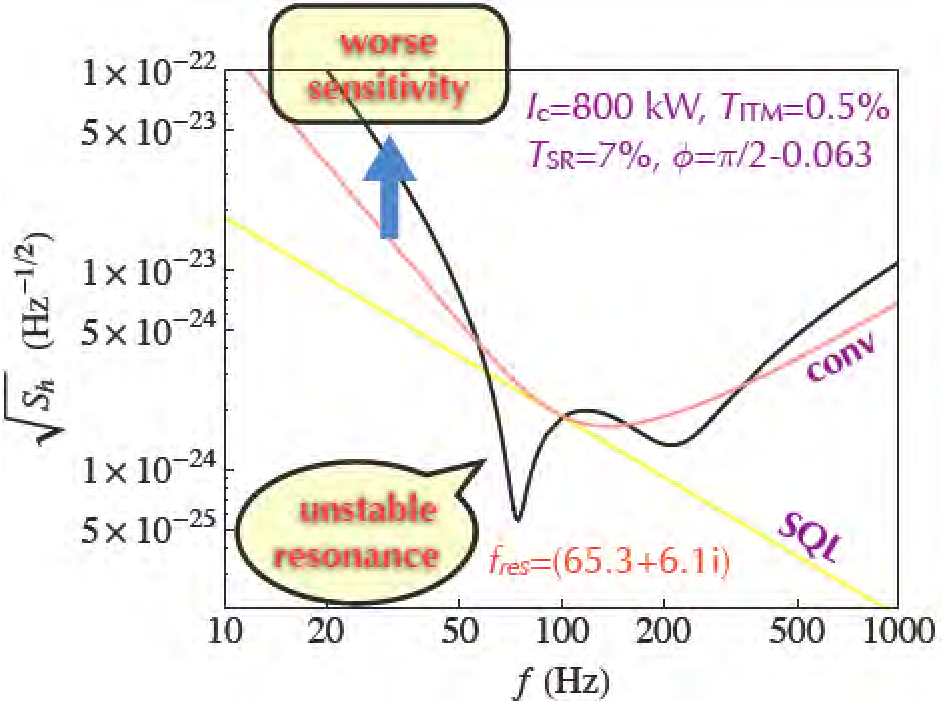
$$S_F^{\mathrm{SQL}}(\Omega) = 2\hbar|\chi^{-1}(\Omega)|\,,$$

χ is the mechanical force to displacement response

$$\chi(\Omega) = [-m\Omega^2 + K(\Omega)]^{-1}$$

The optical spring modifies the test mass dynamics and therefore the quantum noise limit.

Optical spring modified test mass dynamics



Y. Chen: Parametric Instability Workshop, July 17, 2007

Buonanno & Chen: PRD, VOLUME 65, 042001
PRD, VOLUME 64, 042006

- The sensitive improved at optical spring resonance, and the cavity resonance.

- Around the optical resonance, the free mass Standard Quantum Limit is surpassed.

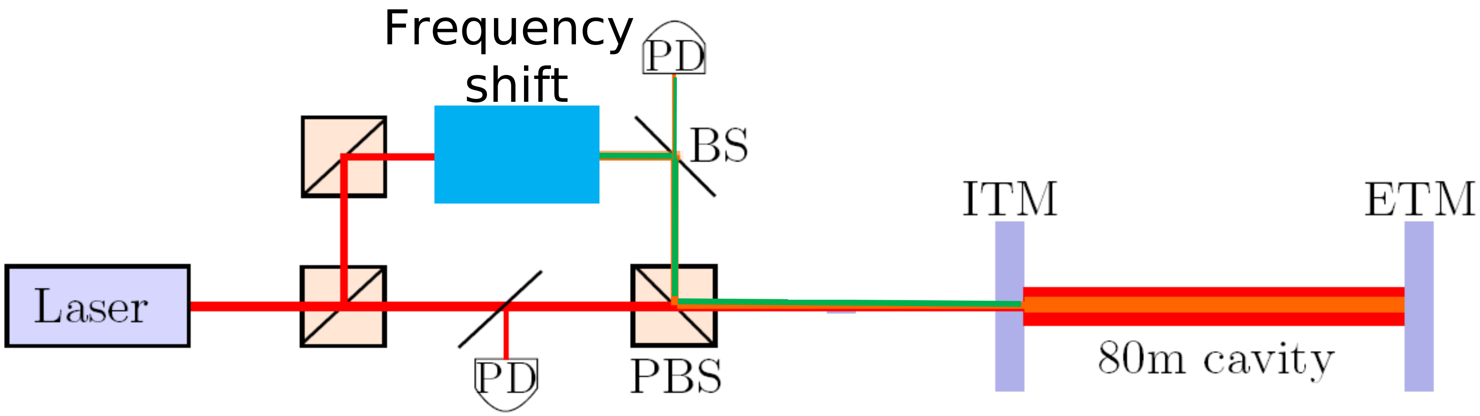
Can we surpass the free mass SQL in broadband?

For double optical springs,

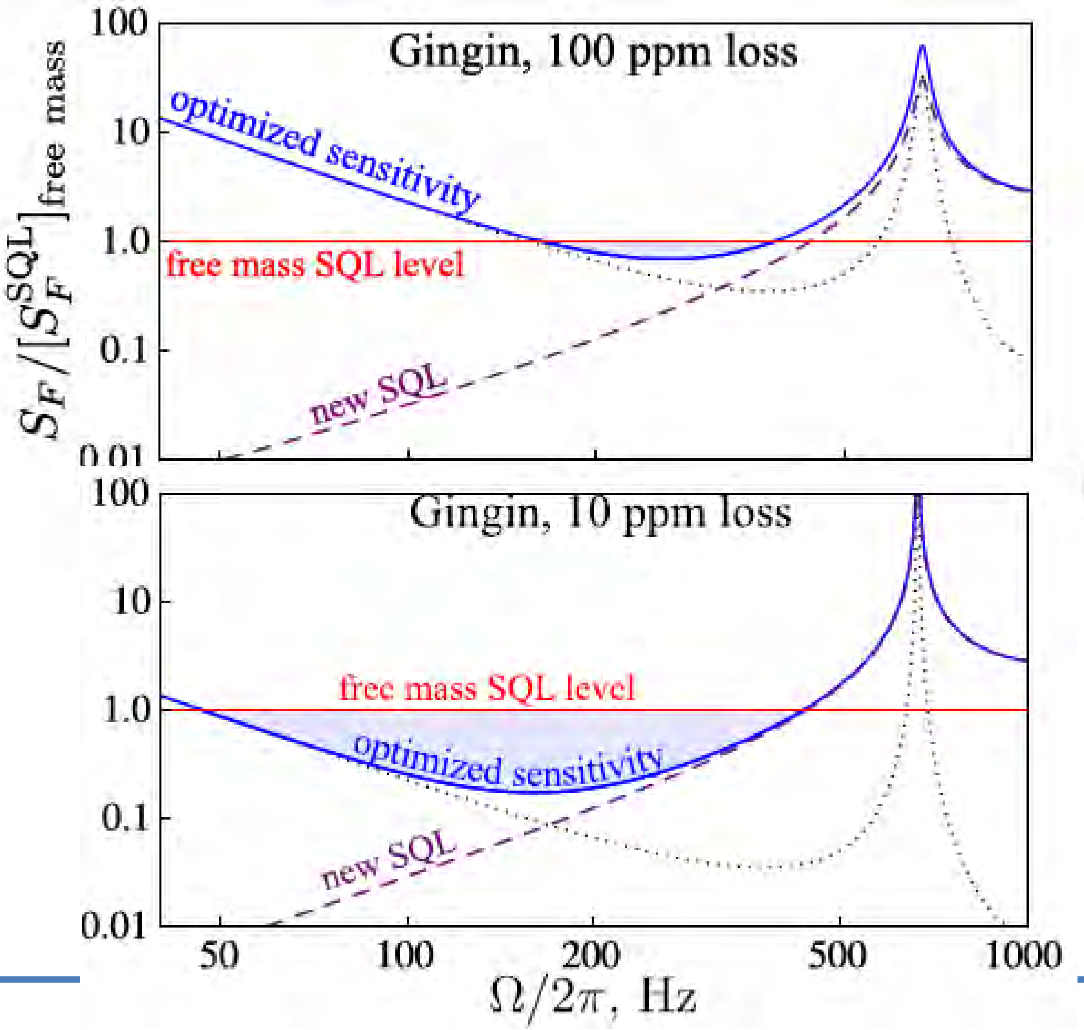
$$K(\Omega) = K_1(\Omega) + K_2(\Omega) \approx m'_{opt}\,\Omega^2$$

in a broad band frequency range, to surpass the free mass SQL

Double optical springs

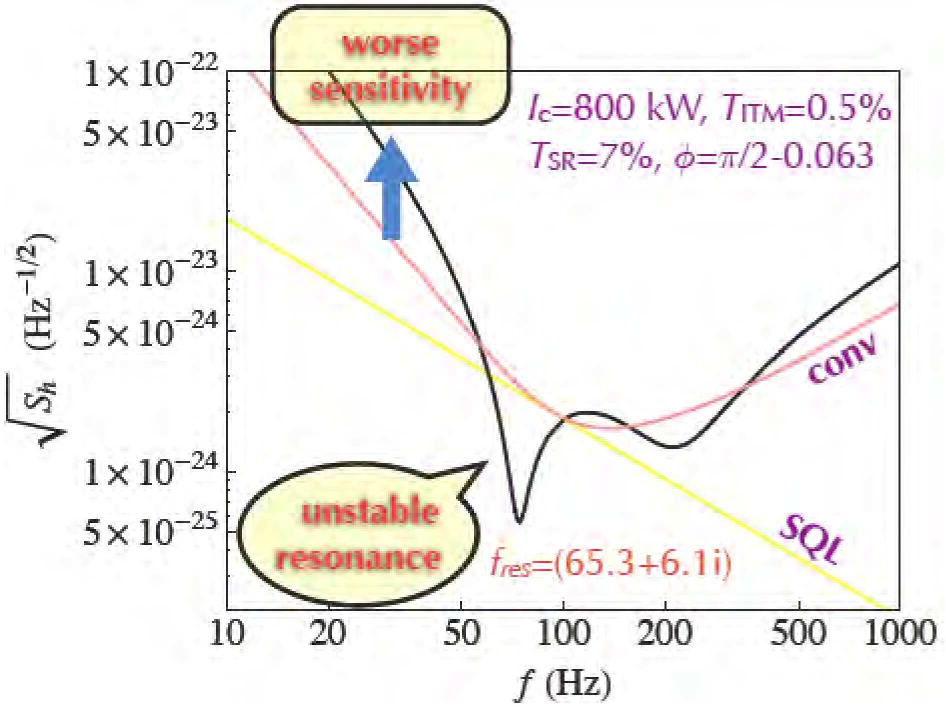


Predicted sensitivity at Gingin with double optical springs



With 100 kW intracavity power, surpassing free mass SQL is achievable assuming all other noises can be reduced to below SQL.

Local readout



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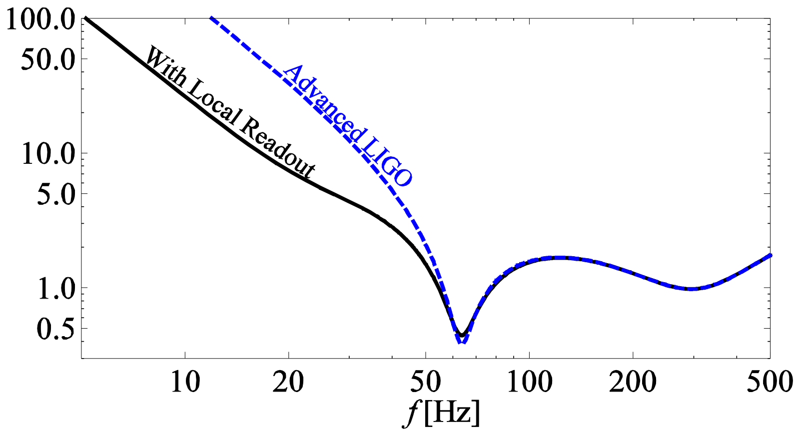
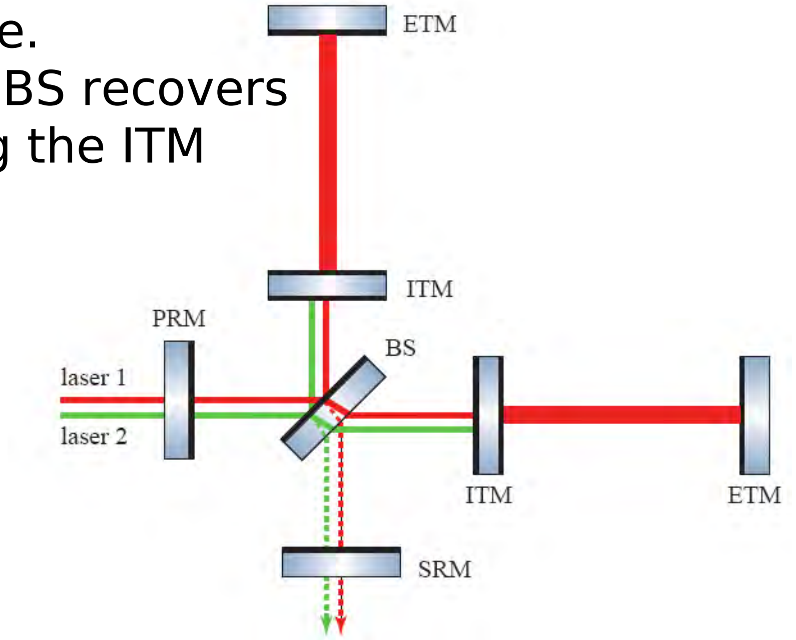
Local readout

- Because of the very stiff optical springs, the ITM and ETM move in-phase below the resonance frequency, the low frequency sensitivity become worse.
- The second interferometer (green) around BS recovers the low frequency sensitivity by monitoring the ITM position.



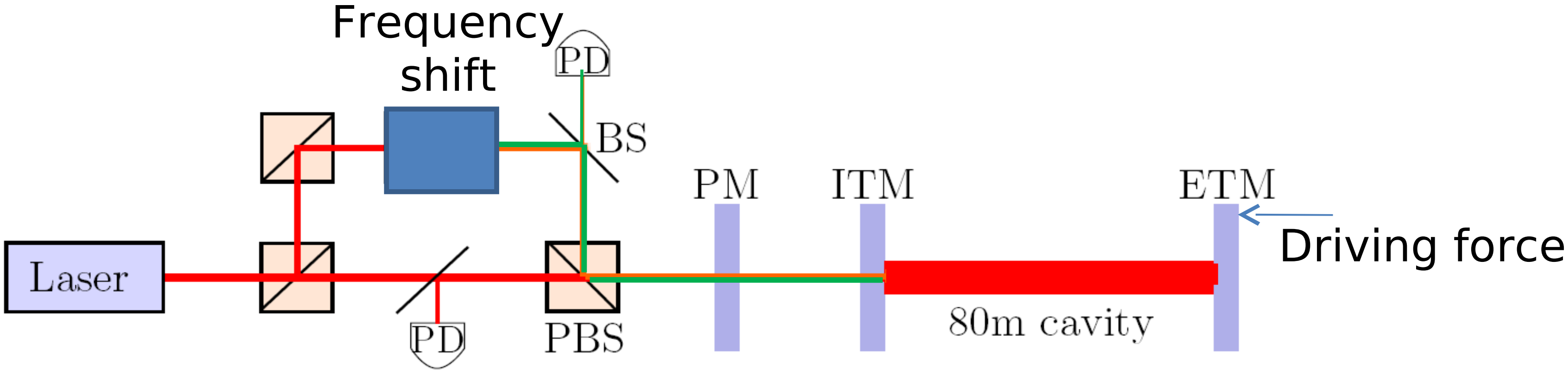


Henning Rehbein, etc. Phys. Rev. D **76**, 062002 (20

Sensitivity divided by SQL of detuned AdvLIGO with and without local readout

Experimental demonstration of local readout

Using the same configuration as previous with additional power recycling mirror, PRM.



Summary

1. At Gingin, we will aim for proof-of-principle experiments, but not the quantum noise limited measurement at the first stage;
2. We have started injection of two light beams of specific frequencies to the 80 m cavity;
3. A 50w Nd:YAG laser developed by University of Adelaide (Jesper Much) is being installed at Gingin;
4. The same facility will be used for experiments of investigating parametric instability.

Acknowledgement

1. The Gingin facility was built by UWA, ANU and Adelaide in collaboration with LIGO.
2. ACIGA consortium members and LIGO people (Mark Barton GariLynn Billingsley, Phil Willems, Stan Whitcomb, and etc.) provided great help.
3. The Gingin advisory committee advices on experiments through regular teleconference, that led by David Reitz, Phil Willems, Gregg Harry and Stefan Goßler in turn.
4. Most experimental ideas talked here come from Yanbei Chen, Farid Khalili, Stefan Danilishin, Haixing Miao, and Helge Müller-Ebhardt.