Macroscopic Quantum Mechanics in Gravitational-Wave Detectors

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summarizing research done by

Stefan Danilishin, Chao Li, Haixing Miao, Helge Müller-Ebhardt,
Henning Rehbein, Roman Schnabel and Kentaro Somiya

LIGO-VIRGO QND Workshop, 2007

Theme

- Major R&D of **3rd generation detectors** directed toward surpassing the **Standard Quantum Limit**

- Having classical noise below the SQL makes it feasible to study **quantum mechanics** of **macroscopic test masses** (1g to 10 kg)
  - **Prepare** nearly Heisenberg Limited, **test-mass** quantum states
  - Allow them to **evolve** (survive) quantum mechanically
  - Allow **verification** of quantum state with sub-Heisenberg accuracy

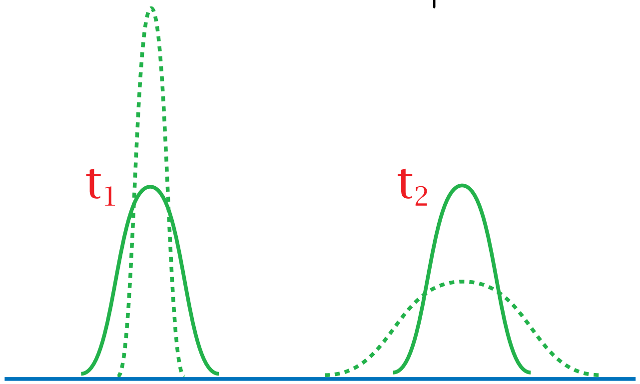
- People (so far) involved in this collaboration
  - **AEI:** Yanbei Chen, Karsten Danzmann, Stefan Danilishin, Helge Müller-Ebhardt, Henning Rehbein, Roman Schnabel, Kentaro Somiya
  - **Caltech:** Chao Li, Yasushi Mino, Sam Waldman, Kip Thorne
  - **MIT:** Thomas Corbitt, Nergis Mavalvala, Chris Wipf
  - **UWA:** Haixing Miao
  - **Moscow ...**

The Standard Quantum Limit

A ***Standard Quantum Limit*** was formulated by Braginsky in the 1960s

Heisenberg Uncertainty Relation

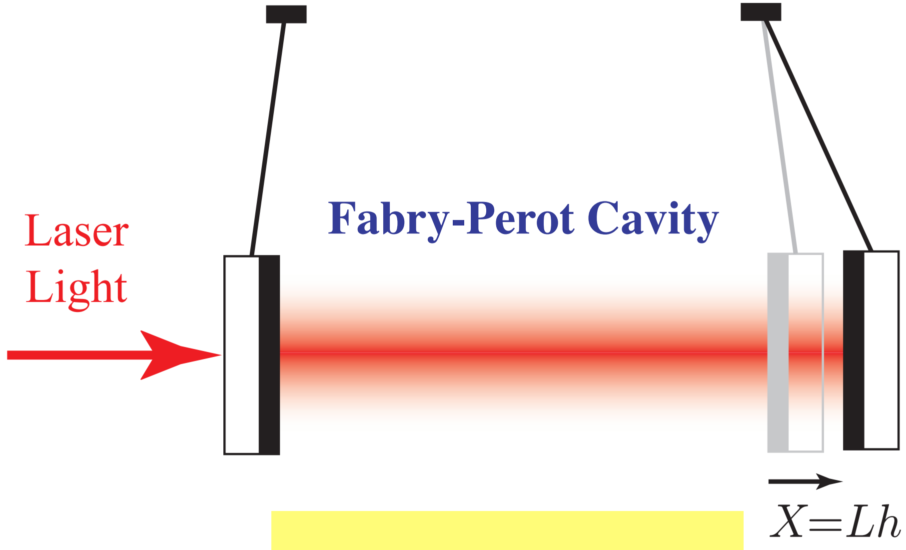
$$[\Delta x(t_1)]\,[\Delta x(t_2)] \geq \left|\frac{\hbar(t_2 - t_1)}{M}\right|$$



wavefunction widths of test mass

t_1: right after 1st measurement

t_2: right before 2nd measurement



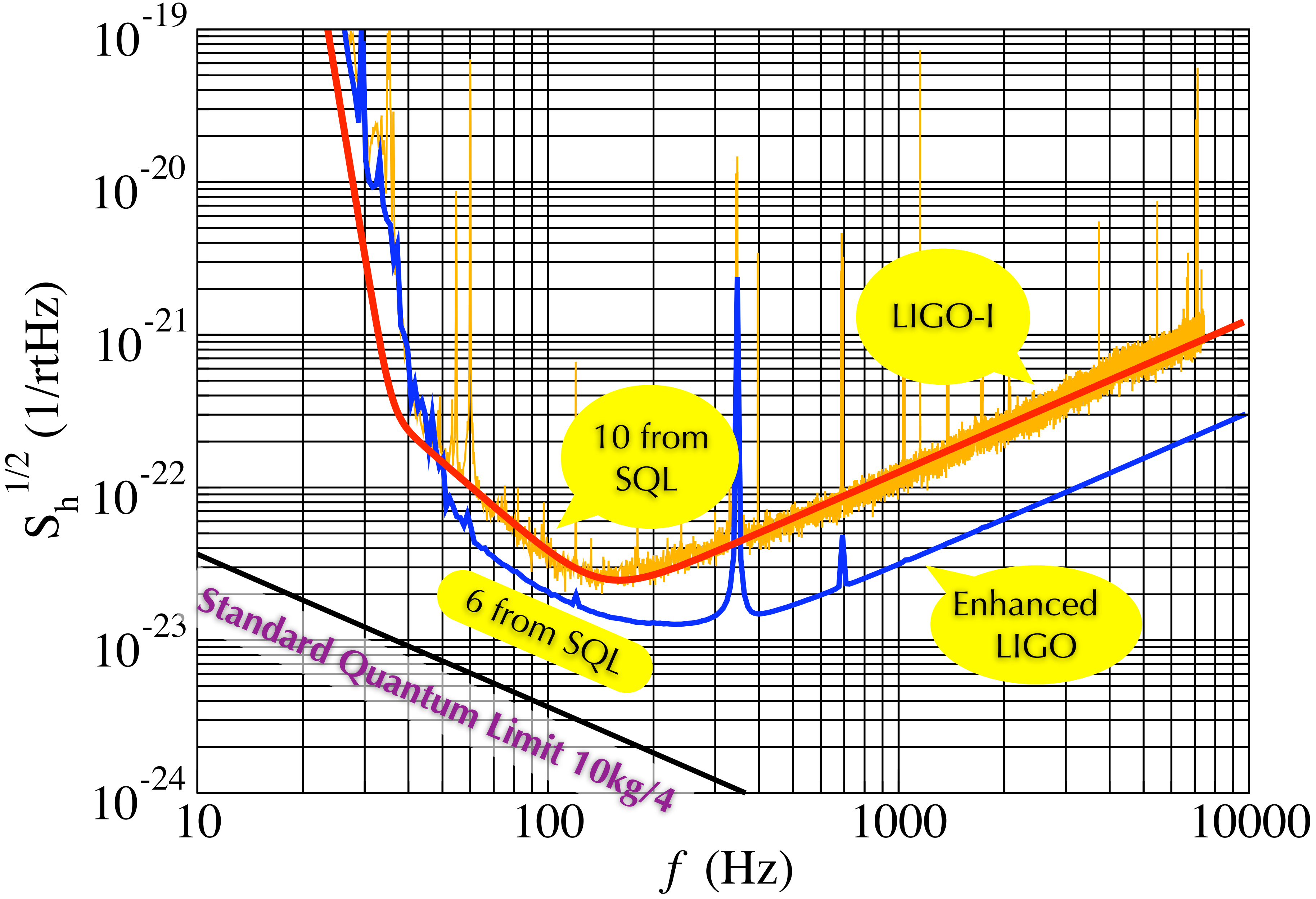
Photon number fluctuation also causing noisy force
Radiation-Pressure Noise

Increasing Photon Number ...
Lowers Shot Noise
Raises Rad. Pres. Noise

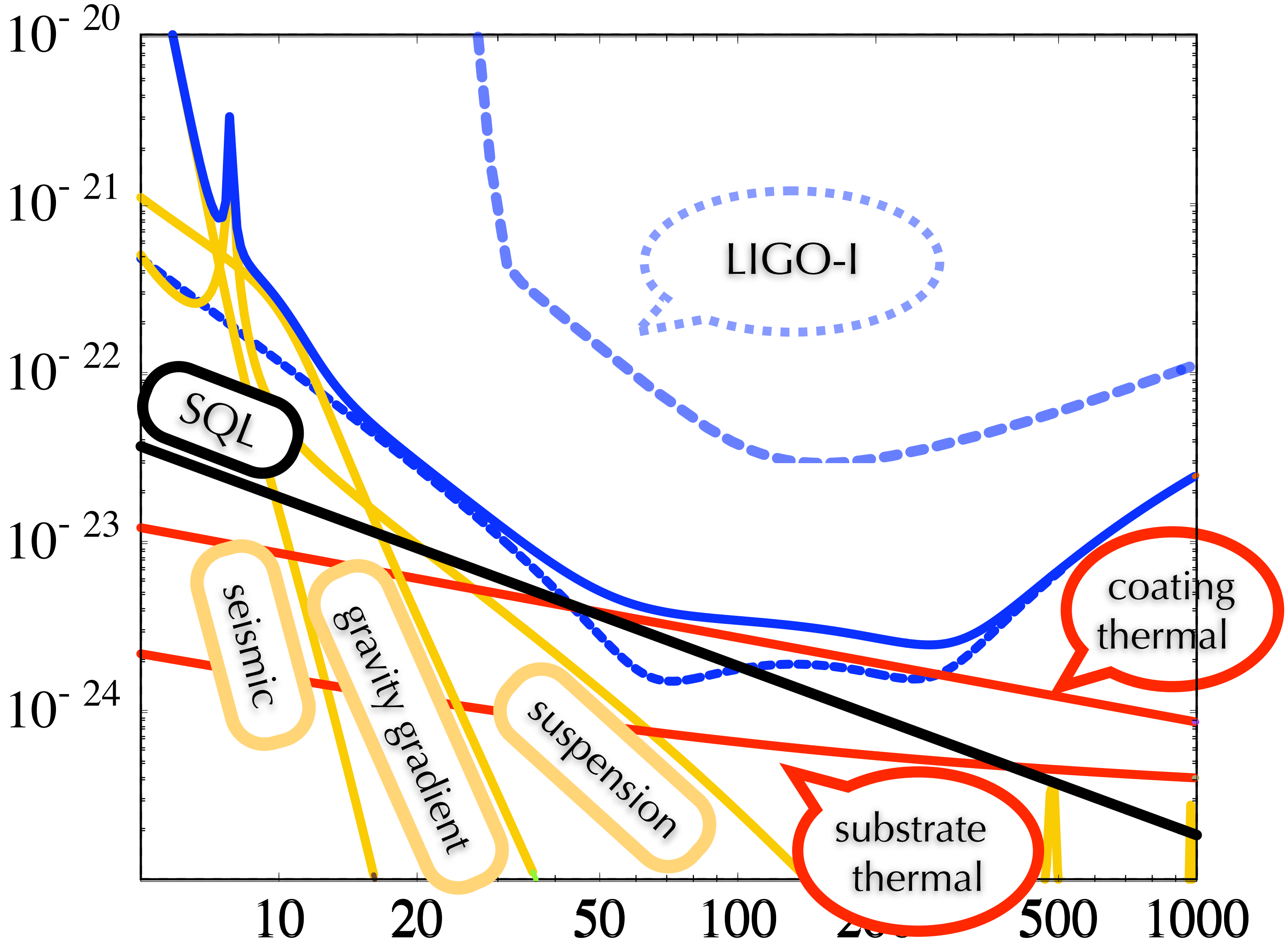
Standard Quantum Limit

$$S_x(\Omega) = \frac{2\hbar}{M\Omega^2}$$

Current Situation



Noise Budget of Advanced LIGO (2014)



Sensitivity improvement by 10, yet mass increase by 4 to 40kg

unless keep increasing mass (SQL~1/$M^{1/2}$), need to surpass SQL in 3rd generation detectors

Mechanical Harmonic Oscillator

- Steady-State **Schrödinger Equation**

$$\left[-\frac{\hbar^2}{2M}\frac{\partial^2}{\partial x^2}+\frac{M\Omega^2 x^2}{2}\right]\psi(x)=E\psi(x)$$

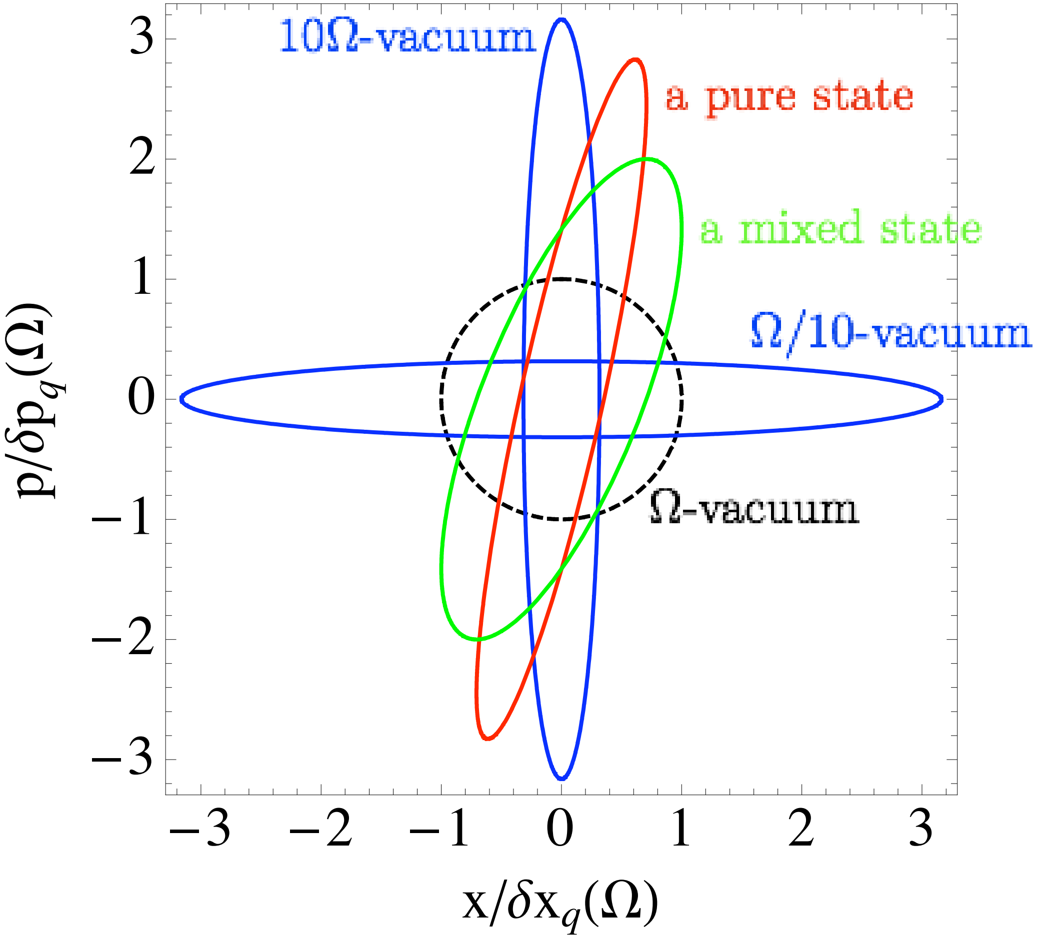
- Ground state

$$E=\frac{\hbar\Omega}{2}$$

$$\begin{aligned}\delta x=\sqrt{V_{xx}} &= \sqrt{\frac{\hbar}{2M\Omega}}\equiv\delta x_q(\Omega)\\ \delta p=\sqrt{V_{pp}} &= \sqrt{\frac{\hbar M\Omega}{2}}=\delta p_q(\Omega)\\ V_{xp} &= 0\end{aligned}$$

- Other Gaussian pure states

$$V_{xx}V_{pp}-V_{xp}^2=\hbar^2/4$$



- The notion of "squeezing" and "anti-squeezing" depends on the **eigenfrequency**, which depends on the **potential well**

Connection between SQL and Ground State

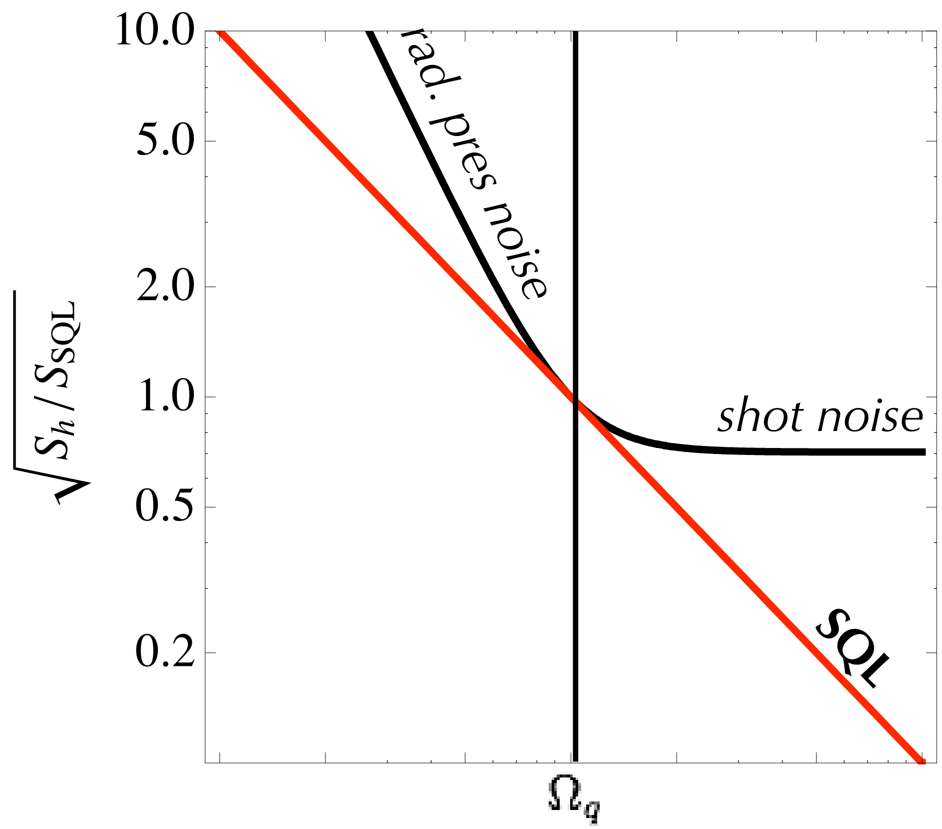
$$S_x(\Omega) = \frac{2\hbar}{M\Omega^2}$$

standard quantum limit

↔

$$\delta x_q(\Omega) = \sqrt{\frac{\hbar}{2M\Omega}}, \quad \delta p_q(\Omega) = \sqrt{\frac{\hbar M\Omega}{2}}$$

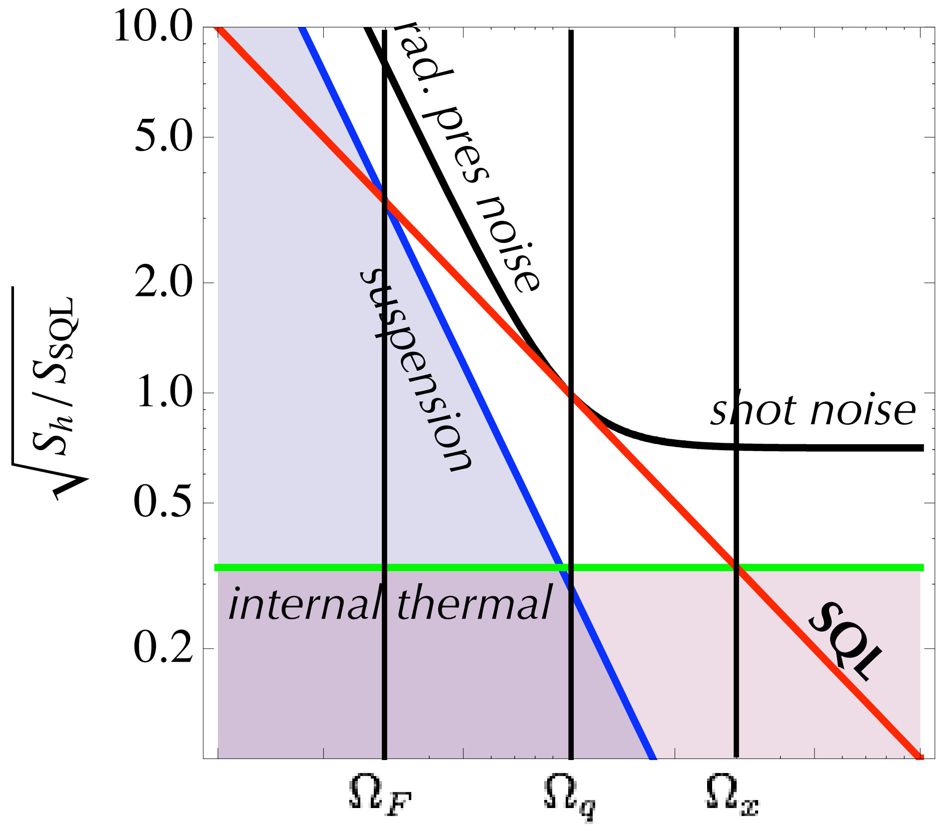
oscillator ground state

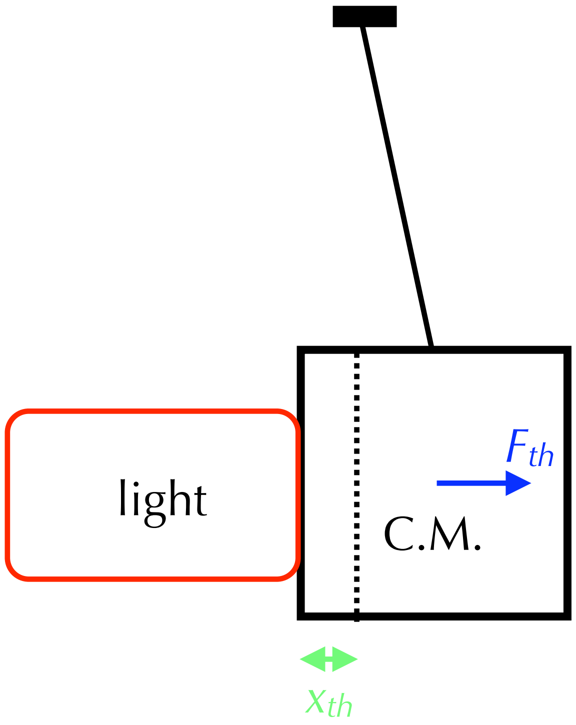


measurement induces quantum state with the scale of Ω_q-vacuum

time-scale of preparation $\tau_q \sim 1/\Omega_q$

Simplified Classical and Quantum Noise Budget





- Two types of classical noise, both white
  - **Force Noise:** force acting on mirror center of mass (e.g., suspension thermal noise)
  - **Sensing Noise:** difference between what is measured and the center of mass (e.g., laser noise, internal thermal noise)
- **Important time scales:**

$$\tau_F \equiv 1/\Omega_F\,, \quad \tau_q \equiv 1/\Omega_q\,, \quad \tau_x \equiv 1/\Omega_x$$

Experimental Scenarios

- **State preparation:**
  - Takes time of $\tau_q \sim 1/\Omega_q$ to reach nearly pure state, if $\Omega_F < \Omega_q < \Omega_x$
  - **Quantum entanglement between test masses *[Talk by Helge Müller-Ebhardt]***
- **State survival under decoherence:**
  - Lifetime given by $\tau_F \sim 1/\Omega_F$
  - allows
    - **quantum evolution *[Talk by Yanbei Chen]***
    - **state verification *[Talks by Stefan Danilishin and Kentaro Somiya]***
  - demonstrates that quantum entanglement can exist for a finite amount of time ***[Talk by Helge Müller-Ebhardt]***
- Alternatively, pure **quantum state via feedback control**
  - steady-state entanglement ***[Talk by Helge Müller-Ebhardt]***

- **Before reaching sub-SQL classical noise**
  - quantum optics/optical entanglement through ponderomotive squeezing ***[Talk by Henning Rehbein]***