Study of a quantum nondemolition interferometer using ponderomotive squeezing

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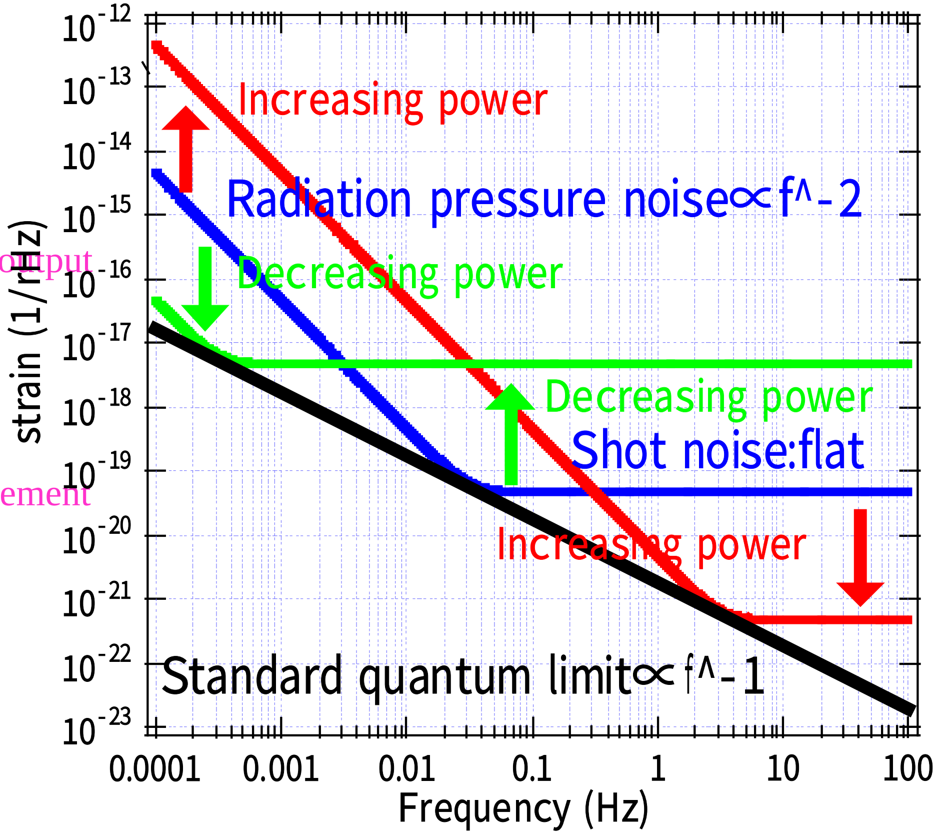
Contents

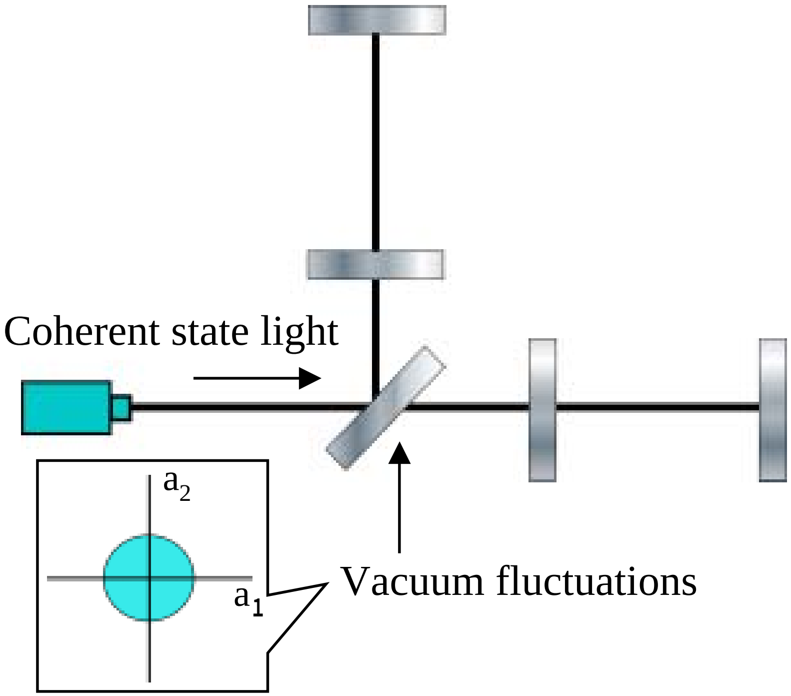
1. Introduction

- Sensitivity of GW detectors will be limited by quantum noise
  - » Shot noise
    - – Spectral density of the shot noise ∝ 1/P,
    - – P: laser power
    - – The shot noise arises from uncertainty due to quantum mechanical fluctuations in the number of photons in the interferometer output
  - » Radiation pressure noise
    - – Spectral density of the radiation pressure noise ∝ P
    - – The radiation pressure arises from displacement Induced by radiation-pressure fluctuations
  - » Standard quantum limit
    - – A point at which the shot noise equals radiation pressure noise



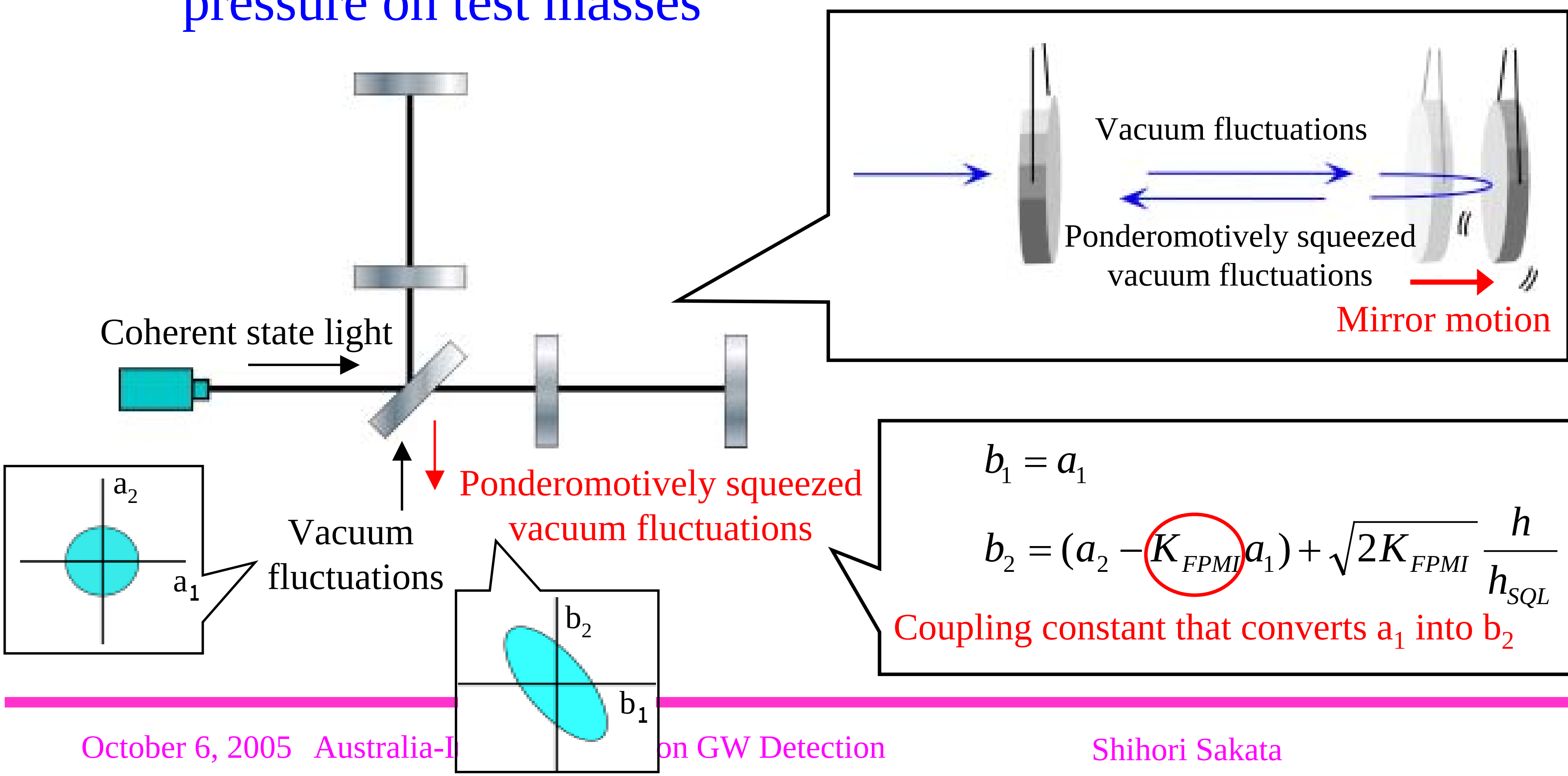
Vacuum fluctuations

- In the next generation, the sensitivity of the interferometer will be limited by the quantum noise at most of frequencies
  - » Vacuum fluctuations entering an anti-symmetric port of conventional interferometer
    - – Expression of the vacuum fluctuations using two quadrature amplitudes $a_1(\boldsymbol{\Omega})$ and $a_2(\boldsymbol{\Omega})$ which are made by the combination of annihilation operators $a_{\pm}(\boldsymbol{\omega}_0 \pm \boldsymbol{\Omega})$



Ponderomotive squeezing

- The vacuum fluctuations is ponderomotively squeezed by back action of mirror motion due to fluctuating radiation pressure on test masses



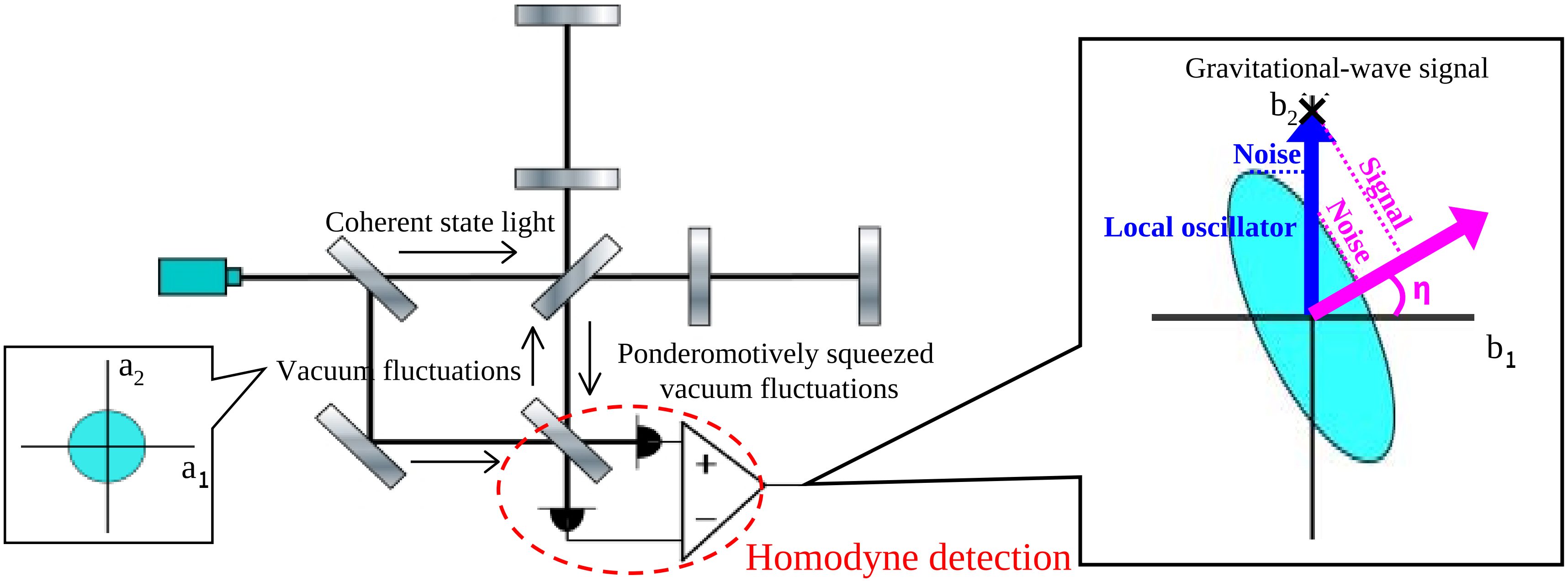
$$b_1 = a_1$$

$$b_2 = (a_2 - K_{FPMI} a_1) + \sqrt{2K_{FPMI}} \frac{h}{h_{SQL}}$$

Coupling constant that converts a_1 into b_2

Homodyne detection

- Using conventional readout scheme, in case of detecting the ponderomotively vacuum fluctuations, the sensitivity is limited by the SQL
- However, by using homodyne detection that is one of the quantum nondemolition devices, the sensitivity will be able to beat the SQL
  - » Optimization of the homodyne phase make it the best signal-to-noise ratio



2. Interferometer to generate ponderomotively squeezed vacuum fluctuations

- We calculate generation of the ponderomotive squeezing using Michelson interferometer and Fabry-Perot Michelson interferometer
  - » In the calculation conditions is that:
    - – Parameters
      - Laser power I_0 =1W
      - **Ω**：Phase modulation frequency due to the mirror motion
      - **Ω**=1kHz
    - – **Ω≪γ**
      - **γ** : cavity pole
      - Arm length=10cm
    - – The sensitivity assumes to be limited by only the quantum noise
    - – Loss is zero
      - End mirror reflectivity: 1
    - – The sensitivity achieves the SQL, then beat the SQL by extracting the ponderomotive squeezing at the SQL
      - The homodyne phase is independent of frequency
  - » Reference: H.J.Kimble et al. Phys.Rev.D **65**, 022002 (2002)

Generation of ponderomotive squeezing using Michelson interferometer

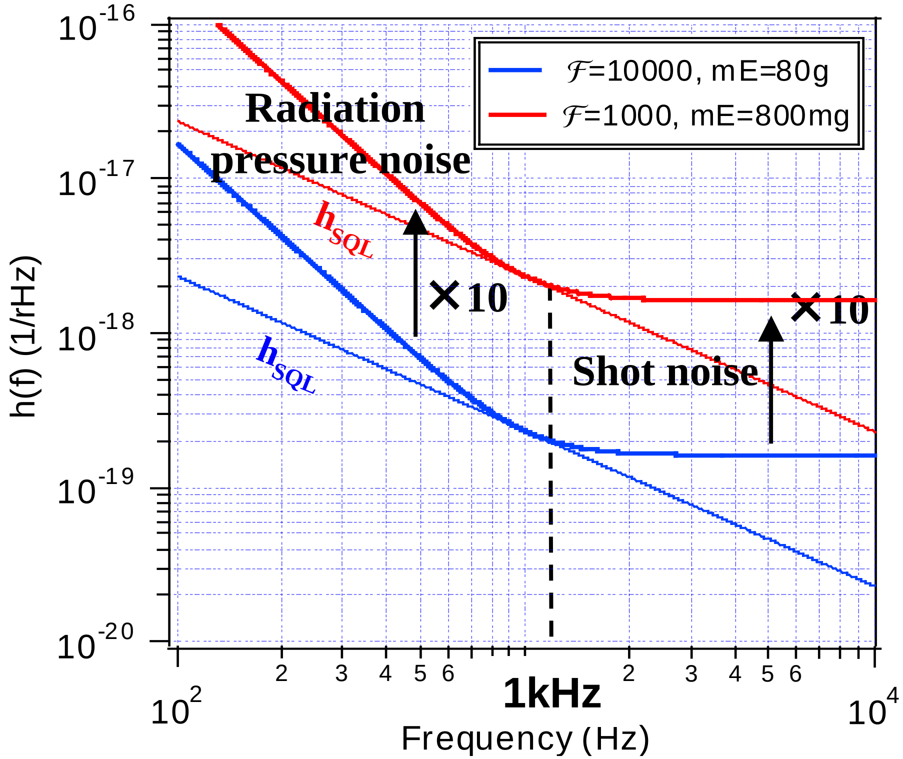
- In case of measuring the output quadrature field by means of the conventional readout scheme,
  - » The noise spectral density: $S_h = \frac{h_{\rm SQL}^2}{2}\left(\frac{1}{\mathcal{K}_{\rm MI}} + \mathcal{K}_{\rm MI}\right)$
  - » where $\mathcal{K}_{\rm MI} = \frac{4 I_0 \omega_0}{m_r c^2 \Omega^2}$, $m_r = \frac{Mm}{M+m}$
    - – The sensitivity achieves the SQL, where $K_{\rm MI} = 1$
      - • m_r : reduced mass, M_{BS}: BS mass, ω_0 : laser angular frequency
- how much mass of the end mirror is needed to achieve the SQL?
  - » The end mirror mass: 1 ng
      - • BS mass: 500 g
  - » The reduced mass: $m_r = \frac{4 I_0 \omega_0}{c^2 \Omega^2}$
    - – Experimentally generation of the ponderomotive squeezing is very difficult
  - » $m_r \propto I_0$

Generation of ponderomotive squeezing using Fabry-Perot Michelson interferometer

- In case of measuring the output quadrature field by means of the conventional readout scheme,
  - » The noise spectral density: $S_h = \frac{h_{\rm SQL}^2}{2}\left(\frac{1}{\mathcal{K}_{\rm FPMI}} + \mathcal{K}_{\rm FPMI}\right)$
  - » where $\mathcal{K}_{\rm FPMI} = \frac{4I_0\omega_0}{m_r r_{\rm F}}\left(\frac{T_{\rm F}\mathcal{F}}{\pi c\Omega(1-r_{\rm F})}\right)^2, \quad m_r = \frac{Mm}{M+m}$
    - – $m_E \propto \mathcal{F}^2$
      - The sensitivity achieves the SQL, where $K_{MI} = 1$
      - m_r : reduced mass, M_F : front mirror mass
      - r_F: amplitude reflectivity of front mirror, T_E : intensity transitivity of end mirror
    - – Making finesses $\mathcal{F}$ ten times is the same effect as making end mass m_E 100 times
      - $\mathcal{F}$:10000→ m_E :500g
      - $\mathcal{F}$:1000→ m_E :5g
      - $\mathcal{F}$:100→ m_E :50mg

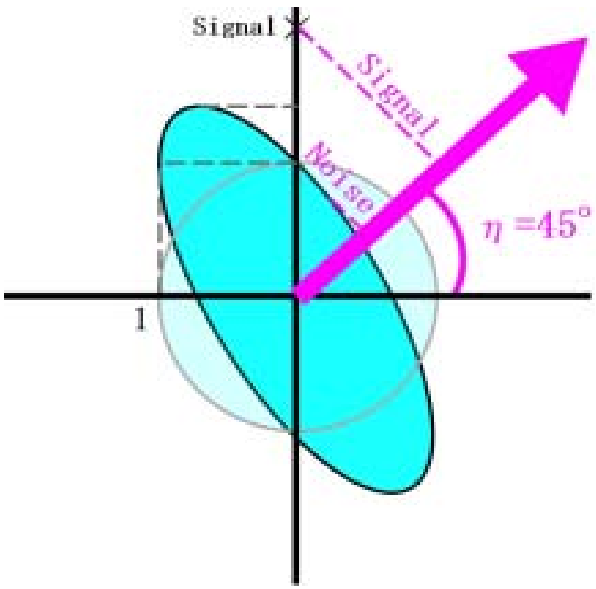
Experimental parameter

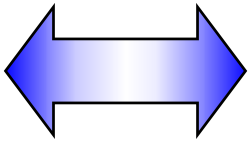
- Discussion of experimental parameter
  - » The sensitivity achieves the SQL at $\boldsymbol{\Omega}_{SQL}$= 1 kHz
  - » The noise spectral density: $S_h = \frac{h_{SQL}^2}{2}\left(\frac{1}{\mathcal{K}_{FPMI}} + \mathcal{K}_{FPMI}\right)$
    - – Finesses $\mathcal{F}$ →1/10 times and mass m→1/100 times does not change the frequency $\boldsymbol{\Omega}$
      - • Radiation pressure noise ∝ 1/m, ∝ $\mathcal{F}$
      - • Shot noise ∝ 1/$\mathcal{F}$
    - – By making the sensitivity worse, achievement of the SQL is more possible
- Noises other than the quantum noise
  - » Suspension thermal noise becomes worse
    - – Roughly ∝ $1/(m)^{1/2}$

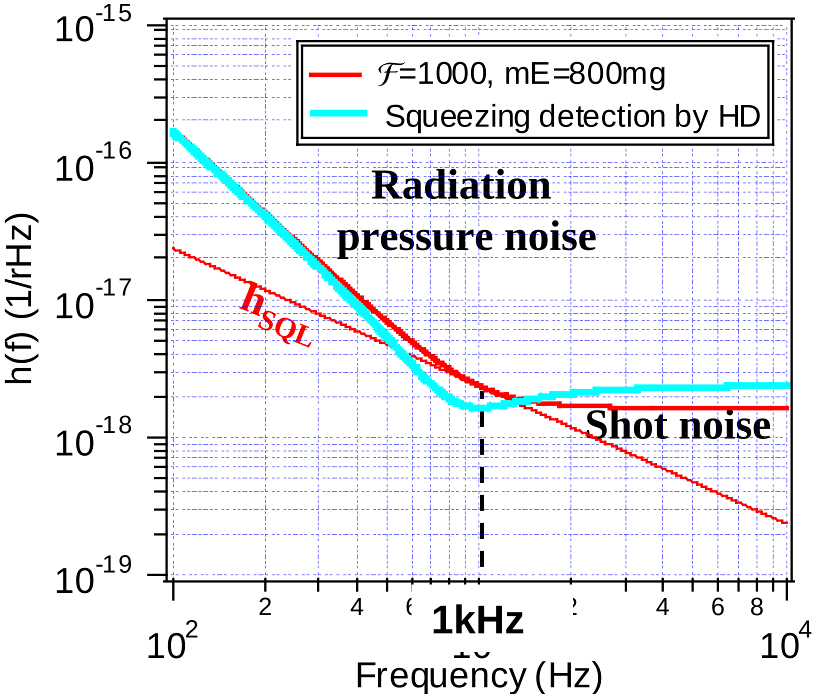


Beat the SQL

- In case of measuring the output quadrature field by homodyne detection,
  - » The sensitivity is obtained by $S_h = \frac{h_{\rm SQL}^2}{2\mathcal{K}_{\rm FPMI}}\left(1 + (\cot\eta - \mathcal{K}_{\rm FPMI})^2\right)$
  - » At the SQL, the homodyne phase is optimized by
    - – Ponderomotive squeezing of 4dB **@ $\Omega_{\rm SQL}$** =1kHz
      - Squeezing factor：arcsinh($K_{\rm FPMI}$ /2)







3. Summary

- By extraction of the ponderomotive squeezing at the SQL, the sensitivity will beat the SQL
  - » Discussion of interferometer to generate the ponderomotive squeezing
    - – Michelson interferometer and Fabry-Perot Michelson interferometer
      - Loss is zero
      - The sensitivity assumes to be limited by only the quantum noise
    - – Finesses $\mathcal{F}$ →10 times is equivalent to the mass m→100 times
  - » Experimental parameter
    - – The sensitivity achieves the SQL at Ω_{SQL}=1kHz
      - Finesses $\mathcal{F}$ →1/10 times and mass m→1/100 times does not change the frequency Ω
      - At the SQL, $K_{FPMI} = 1$
    - – By making the sensitivity worse, achievement of the SQL is more possible
  - » At the SQL, the homodyne phase is optimized by
    - – Ponderomotive squeezing of 4 dB @ Ω_{SQL} =1kHz
    - – Homodyne phase η =45°
      - m_E=800mg, $\mathcal{F}$=1000

4. Future plan

- Design of end mirrors
  - » Design of suspension
  - » Thermal noise
- Photo detection
  - » Homodyne detection or DC readout