Direct Measurement of Mirror Thermal Noise

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Abstract

- First & clear measurement of mirror thermal noise
  - » Wide band measurement (100Hz-100kHz)
  - » High sensitivity (10^{-18} m/rtHz @100kHz)
    - – Including mirror resonance & off-resonance
    - – Direct validation of Fluctuation-Dissipation Theorem(FDT)
  - » Established system for direct evaluation of mirror TN

Brownian Noise

✓Optical glass: BK7

- – Structural loss
- – $f^{-1/2}$ dependence

Thermoelastic Noise

✓Calcium Fluoride(CaF_2)

- – Large thermal expansion
- – $f^{-1/4} \sim f^{-1}$ dependence

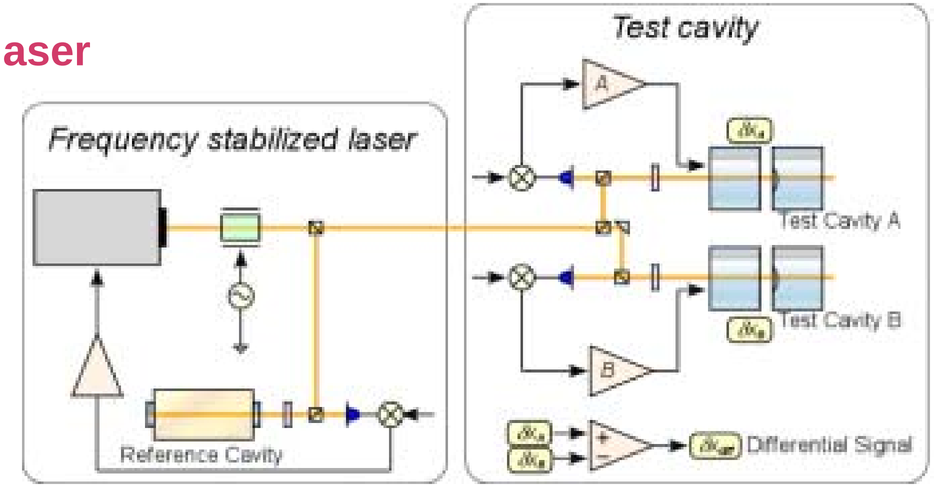
Contents

1.Introduction

- **Thermal noise in GW detector**
  - » **Limiting factor of detector’s sensitivity**
  - » **Has to be reduced**
- **Recent topics**
  - » **Theoretical**
    - – **“New” thermal noise**
    - – **“New” calculation method**
  - » **Experimental**
    - – **Direct evaluation of intrinsic loss**
- **Experimental test**
  - » **Ultimate goal of prototype interferometers**
  - » **Progress in Univ. of Tokyo**

Methods for Direct Measurement

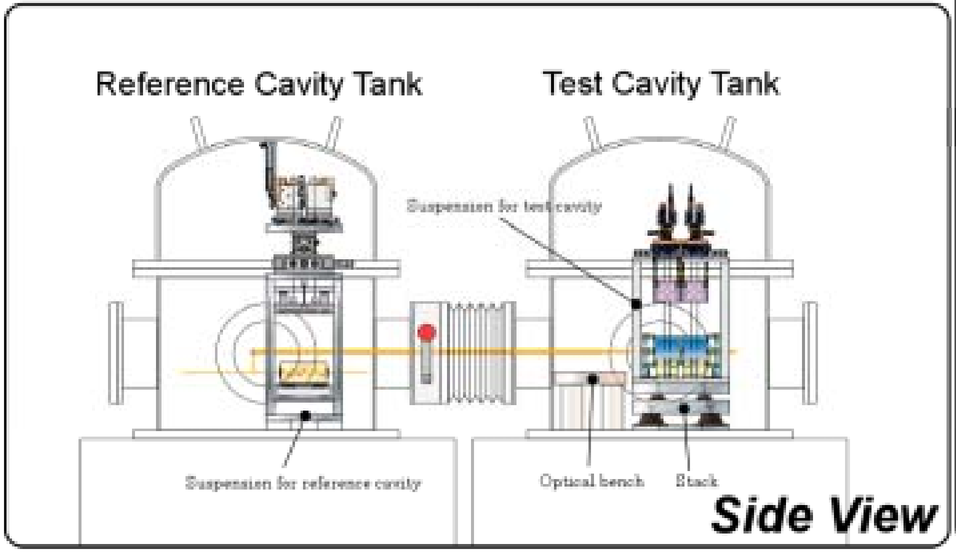
- **Conceptual design**
  - » **Simplest setup**
    - – Test cavity locked to stabilized laser
  - » **Reference cavity**
    - – Frequency stabilization
  - » **Test cavity**
    - – TN in a realistic system

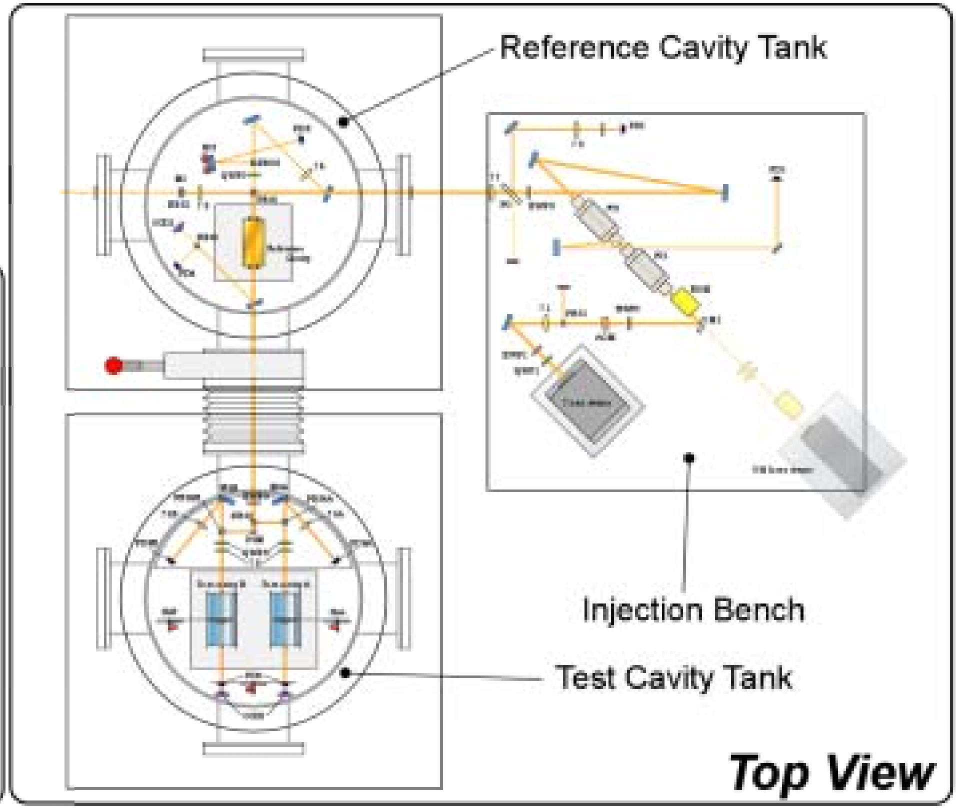


- **This talk**
  - » **Brownian noise & thermoelastic noise measured**
    - – Wide band observation : 3decades
    - – Good agreement with theoretical predictions
  - » **First clear observation of mirror TN**
    - – Including mirror resonance

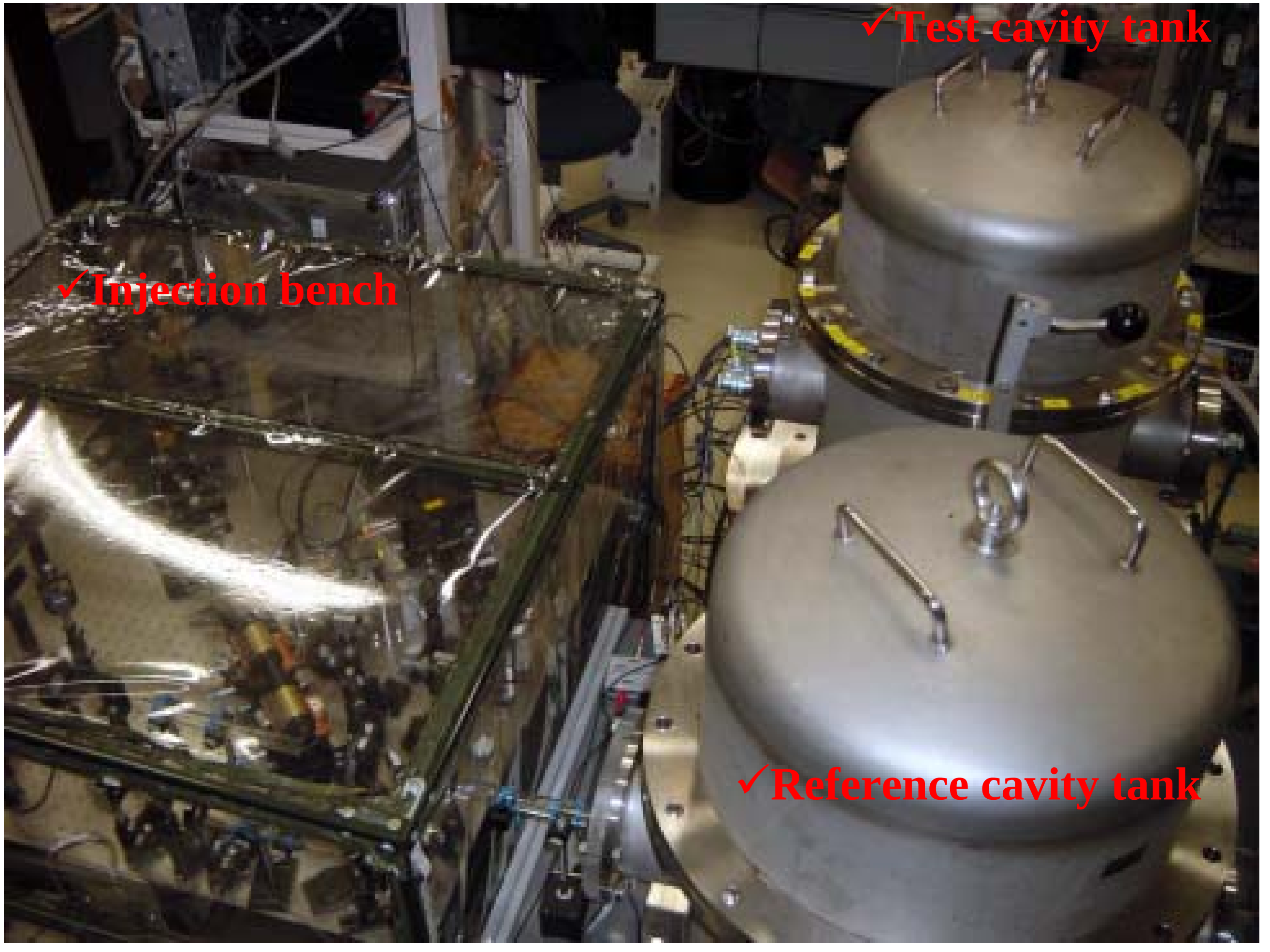
2.Experimental Setup

- **Optical setup**
  - » **Compact scale**
    - – **Vacuum system**
      - **Reduction of air motion**
      - **Internal diameter: 50cm**



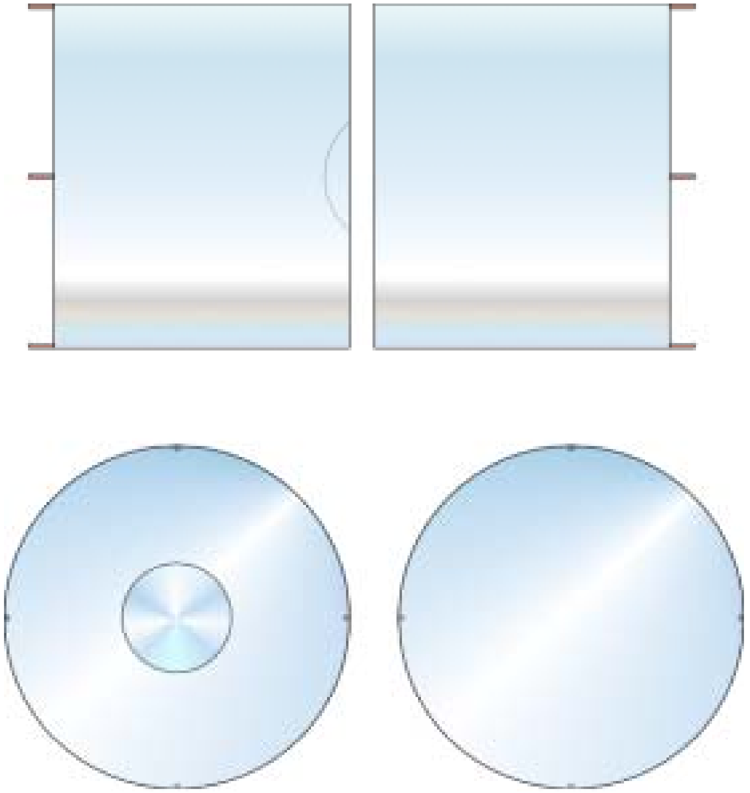


Photograph



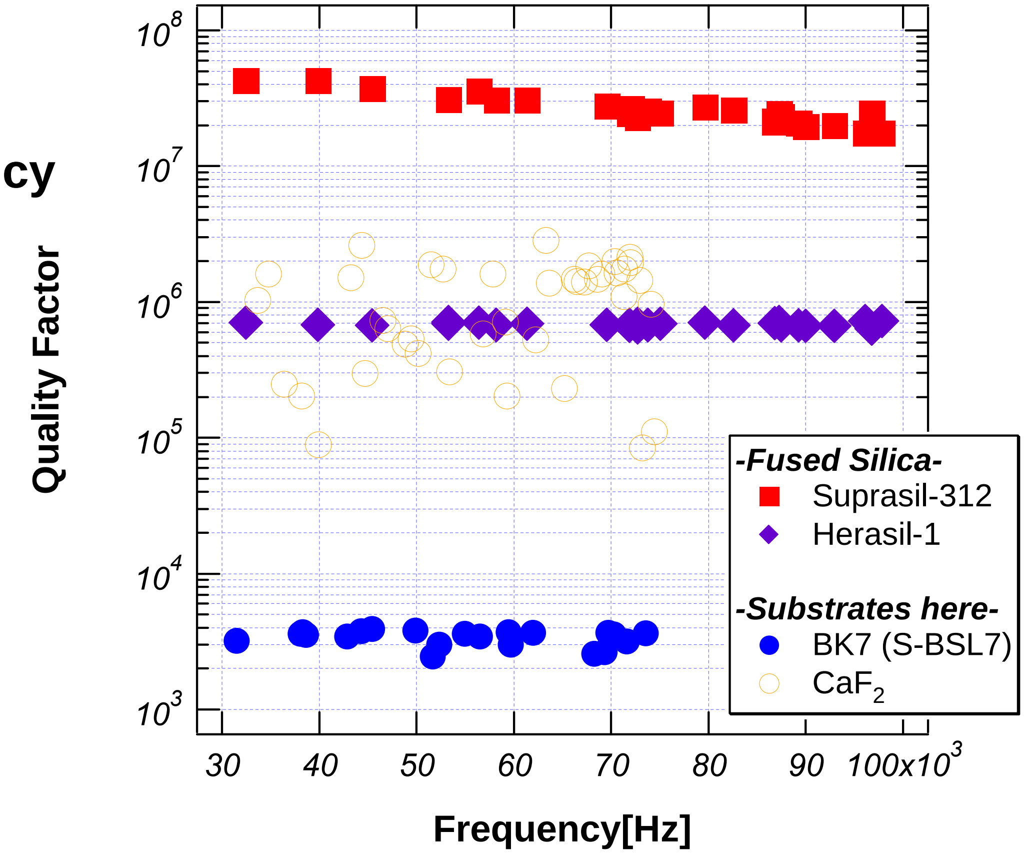
Mirror for Test Cavity

- **Monolithic mirror**
  - » **Short length Fabry-Perot cavity**
    - – **Diameter: 70mm, Height: 60mm**
    - – **Baseline: 1cm**
    - – **Flat-concave cavity: *g*=1/3**
    - – **Finesse: ~500**
  - » **Beam spot size**
    - – **48.9um(Flat), 84.8um(Concave)**



Selection of Substrate Material

- **BK7**
  - » **OHARA S-BSL7**
    - – **General optical glass**
    - – **70%: SiO_2**
  - » **Constant loss against frequency**
    - – **Intrinsic Q : 3600**
- **CaF_2**
  - » **Cubic crystal**
    - – **Apochromat**
  - » **Relatively small loss**
    - – **Intrinsic Q~$3x10^6$**



Properties of Substrates

- **Properties related to TN**
  - » **Alternative substrates at low cost**

	Silica	BK7	Sapphire	CaF_2
$Q(=1/\phi)$	$10^5 \sim 10^7$ Constant	3.6×10^3 Constant	$10^6 \sim 10^8$	3×10^6
α [1/K]	5.5×10^{-7}	7.2×10^{-6}	5.0×10^{-6}	1.8×10^{-5}
κ [J/m/s/K]	1.4	1.13	40	9.71

$$\sqrt{G} \propto \sqrt{1/Q}$$

✓**Brownian**

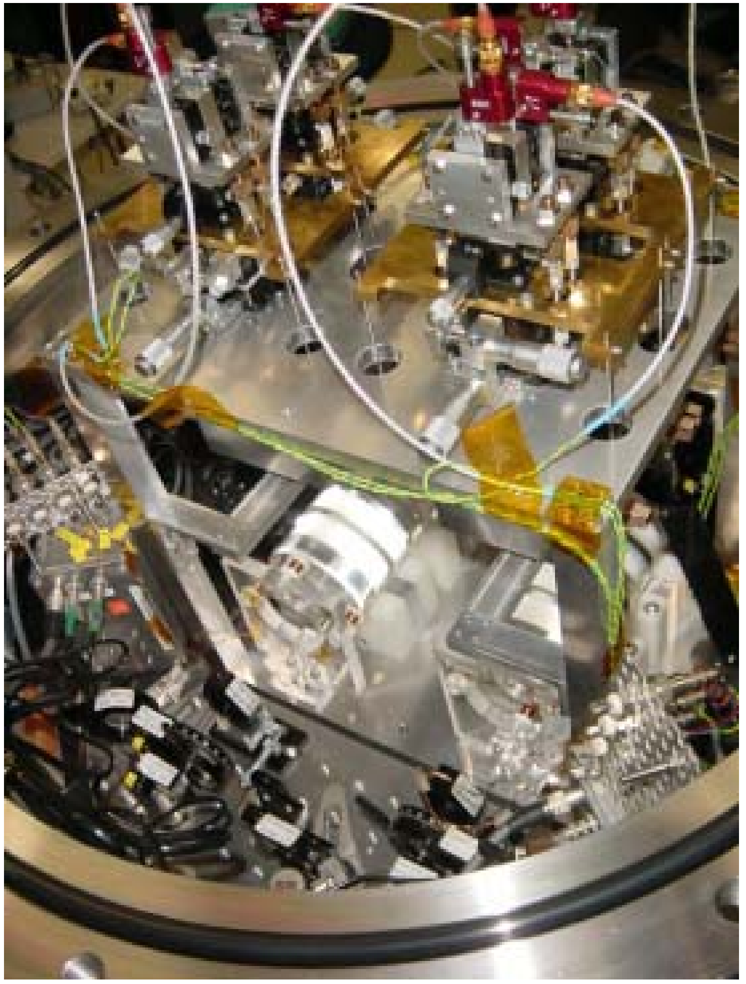
$$\sqrt{G} \propto \alpha \times \sqrt{\kappa}$$

✓**Thermoelastic**

(adiabatic limit)

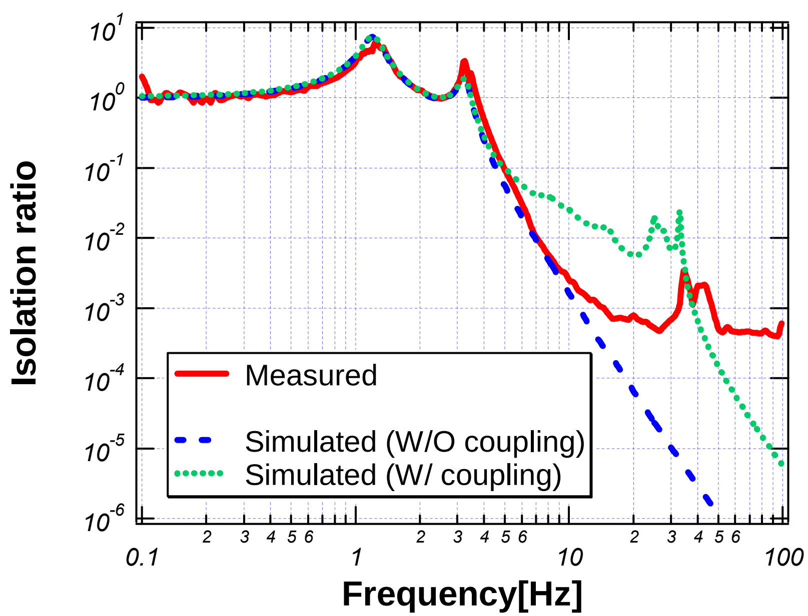
Vibration Isolation System

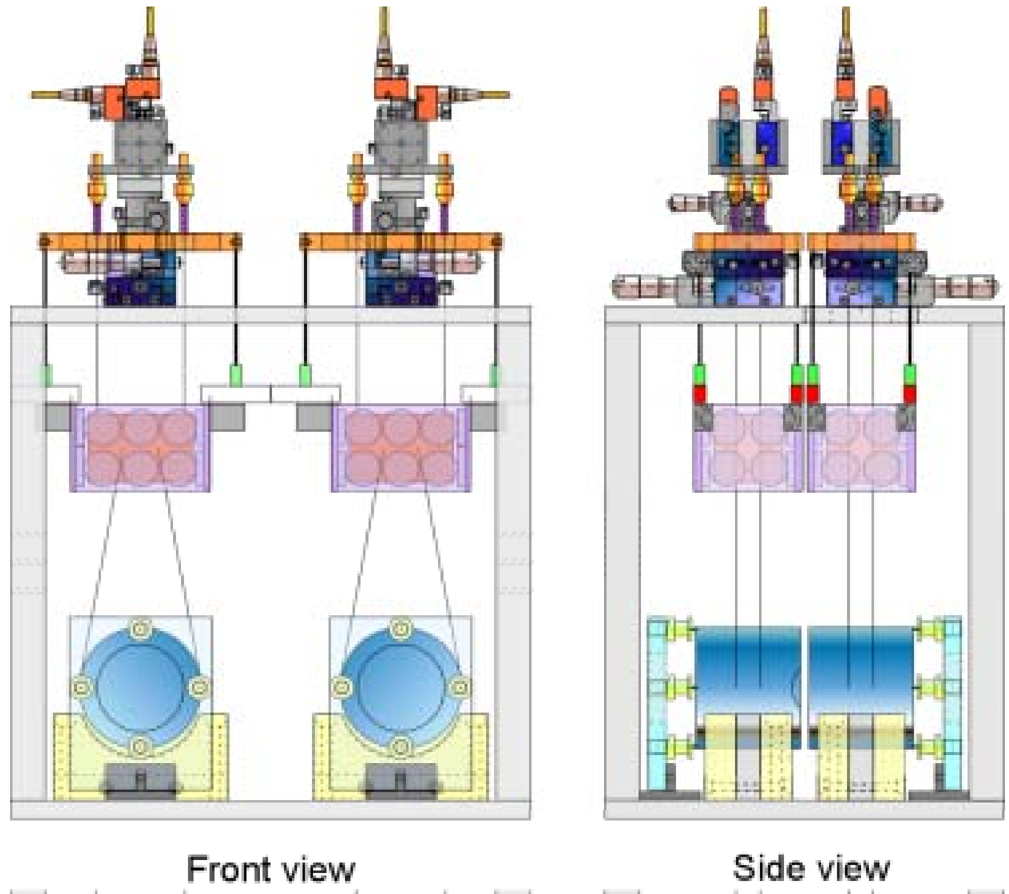
- **Vibration isolation system**
  - Seismic noise level: *~10^{-11}* m/rtHz@100Hz
  - Mirror TN level: *~10^{-16}* m/rtHz@100Hz
    - Requirement: *$1/10^5$* (translation)
    - Isolation of other DOFs
- **Two stages of isolation system**
  - » Suspension
    - Provided isolation ratio: *~$1/10^5$*
  - » Stack
    - Provided isolation ratio: *~$1/10^4$*



Test Cavity Suspension

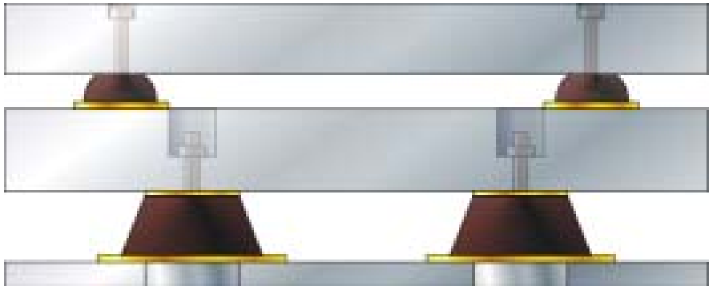
- Double pendulums
  - » TAMA type
    - – Magnet damping
  - » Identical platform
    - – CMR for seismic motion

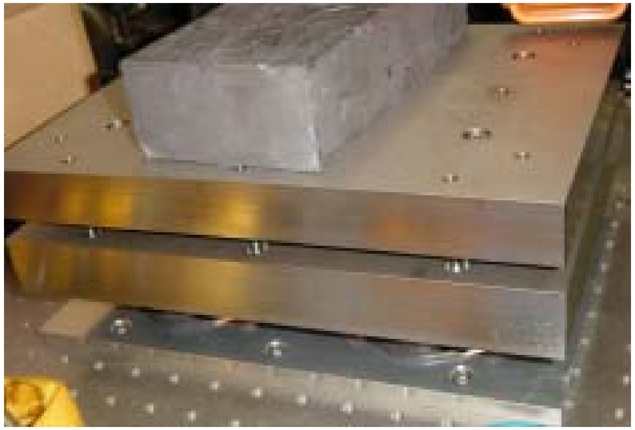


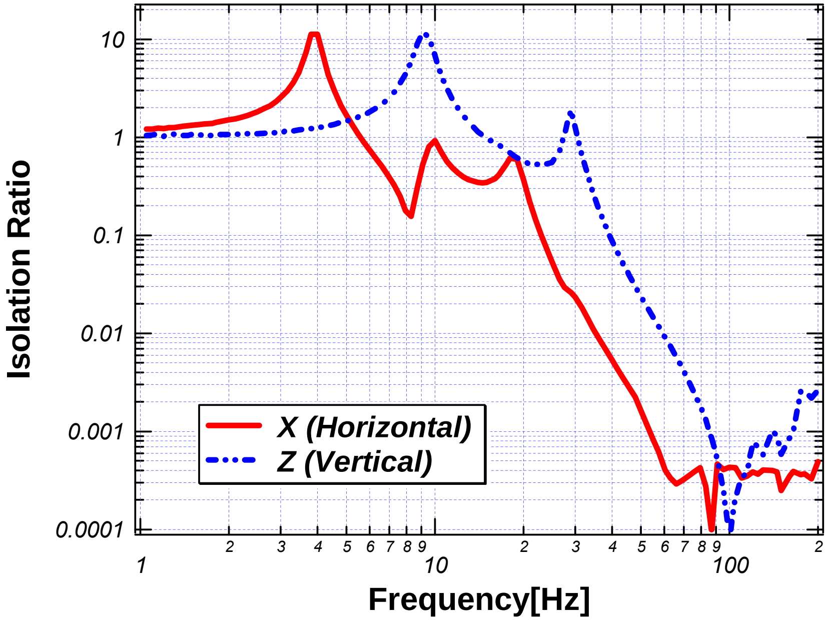


Test Cavity Stack

- **Double stages**
  - » **Isolation rubber**
    - – Vertical & horizontal
    - – Isolation ratio: *1/10*^{4}
  - » **Used with suspension**
    - – Requirement achieved

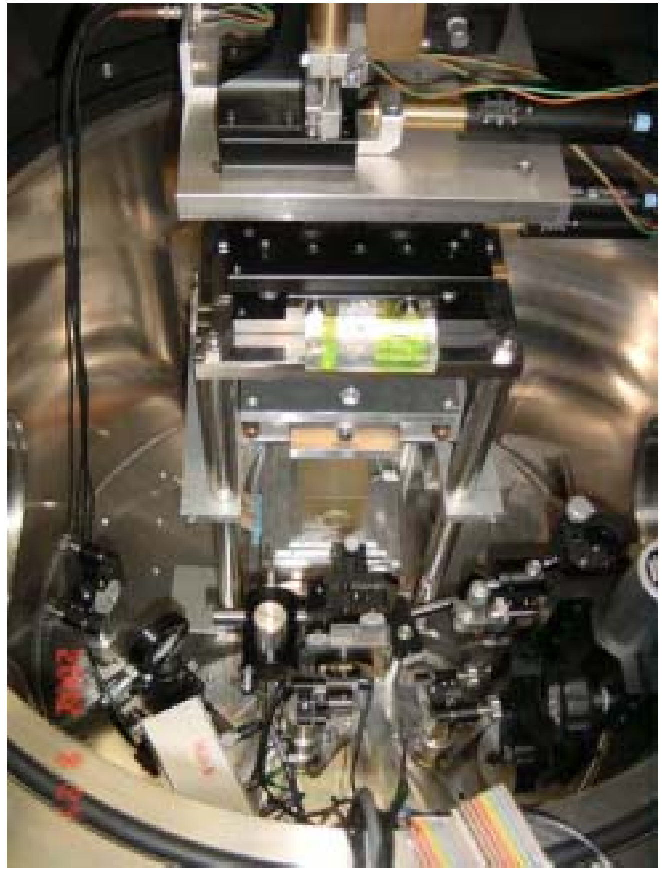


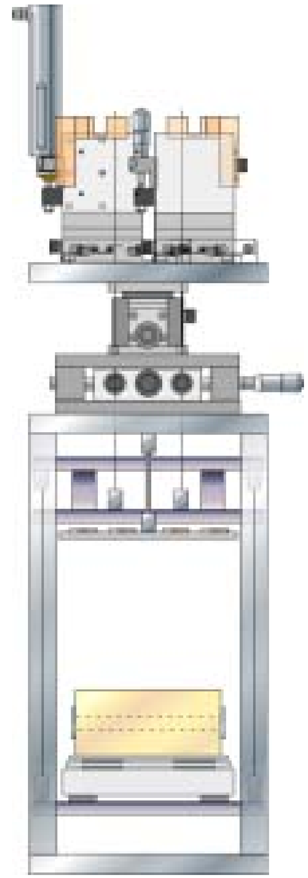




Reference Cavity

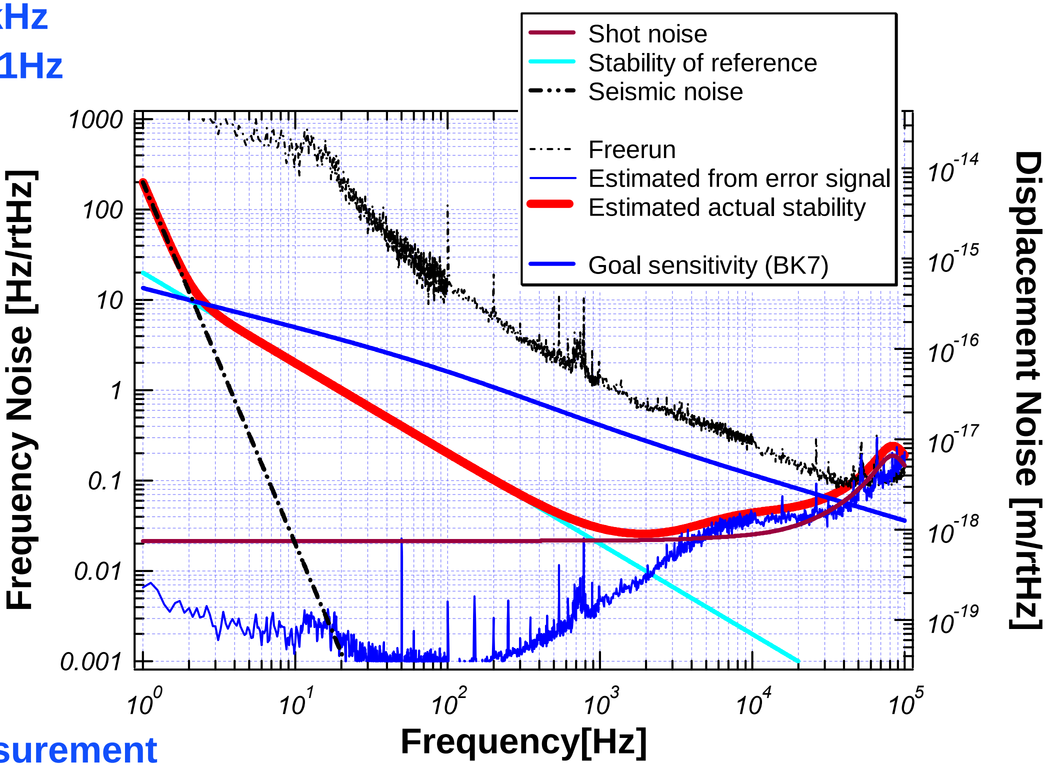
- **Rigid FP cavity**
  - » **Length**
    - – **110mm**
  - » **Spacer**
    - – **Low expansion glass**
    - – **Clearceram Z**
  - » **Finesse**
    - – **36000 (measured value)**
- **Suspension**
  - » **Double pendulum**





Stabilization Servo System

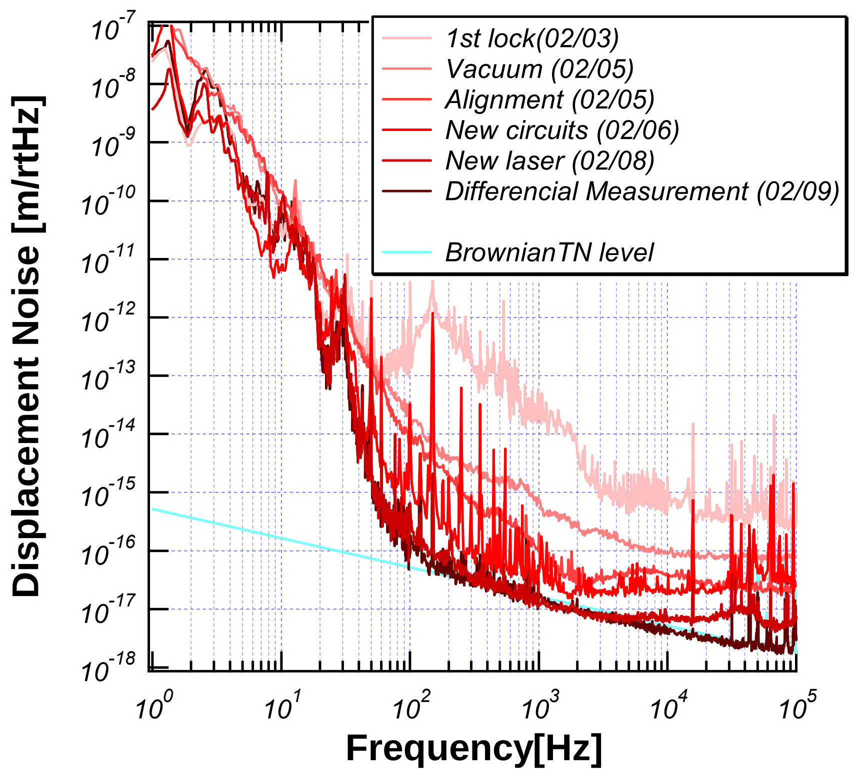
- **Servo system**
  - » **Fed back to a laser connectors**
    - – **PZT/Thermal**
      - **Unity gain frequency: ~80kHz**
      - **Crossover frequency: ~0.01Hz**



- **Achieved stability**
  - » **Shot noise**
    - – **~0.02Hz/rtHz**
  - » **Stability of reference cavity**
    - – **~1kHz**
  - » **Comparison with TN level**
    - – **Below 30kHz: satisfied**
    - – **Over 30kHz: not satisfied**
      - **Solved by differential measurement**

3.Experimental Result

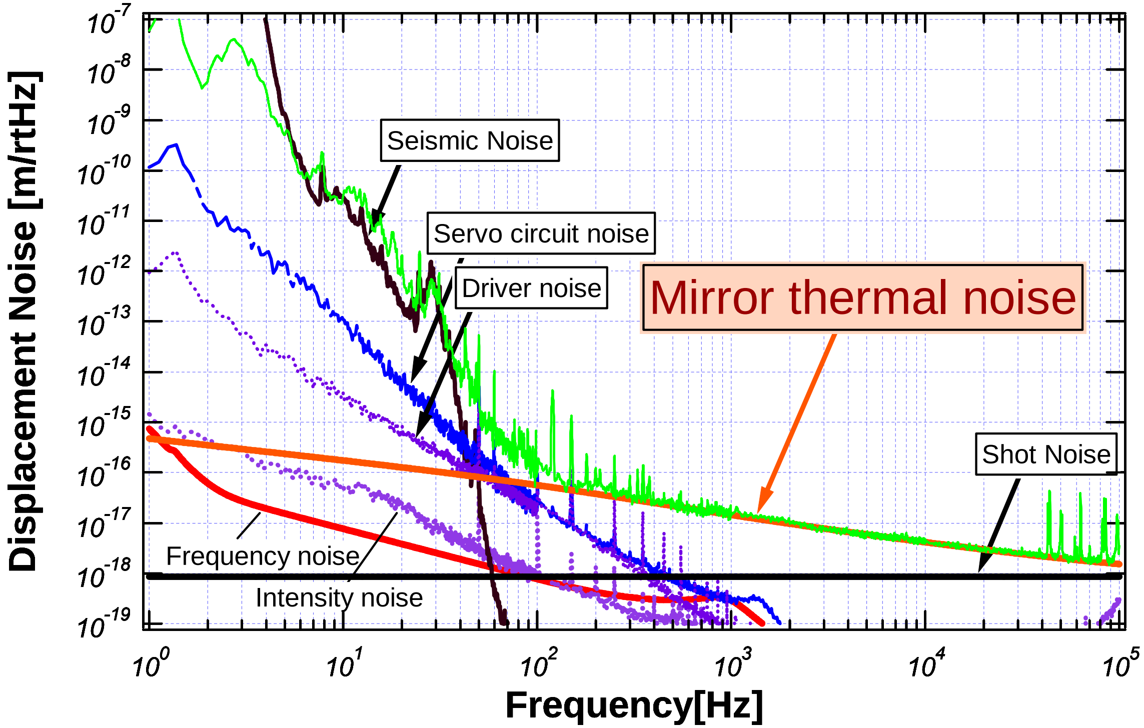
- Noise suppression
  - » Seismic noise
    - – Stiff optical bench
    - – Improvement of SUS
  - » Shot noise
    - – Laser replacement
    - – Alignment
    - – Matching
  - » Electric circuit noise
    - – Optimization
  - » Frequency noise
    - – Servo improvement
    - – Differential measurement



Reached to TN level between wide frequency range

Noise Sources of IFO

- **Freq./Intensity noise**
  - » **Neglected**
- **Seismic/Electric noise**
  - » **Limiting factor ~100Hz**
- **Shot noise**
  - » **~40kHz**

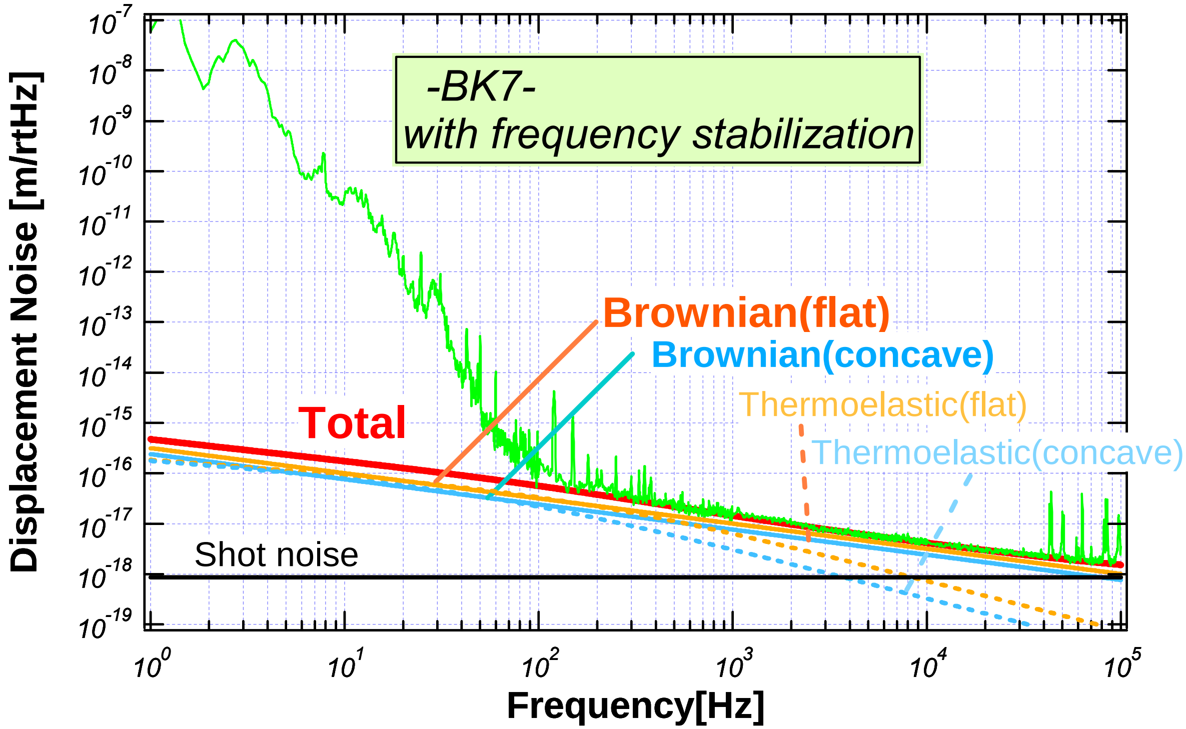


●Only mirror TN can explain measured spectrum.

●Measurement system was established.

Result in BK7 Cavity

- **Coincided with theoretical Brownian noise**
  - » **Theoretical curve: calculated with intrinsic loss**

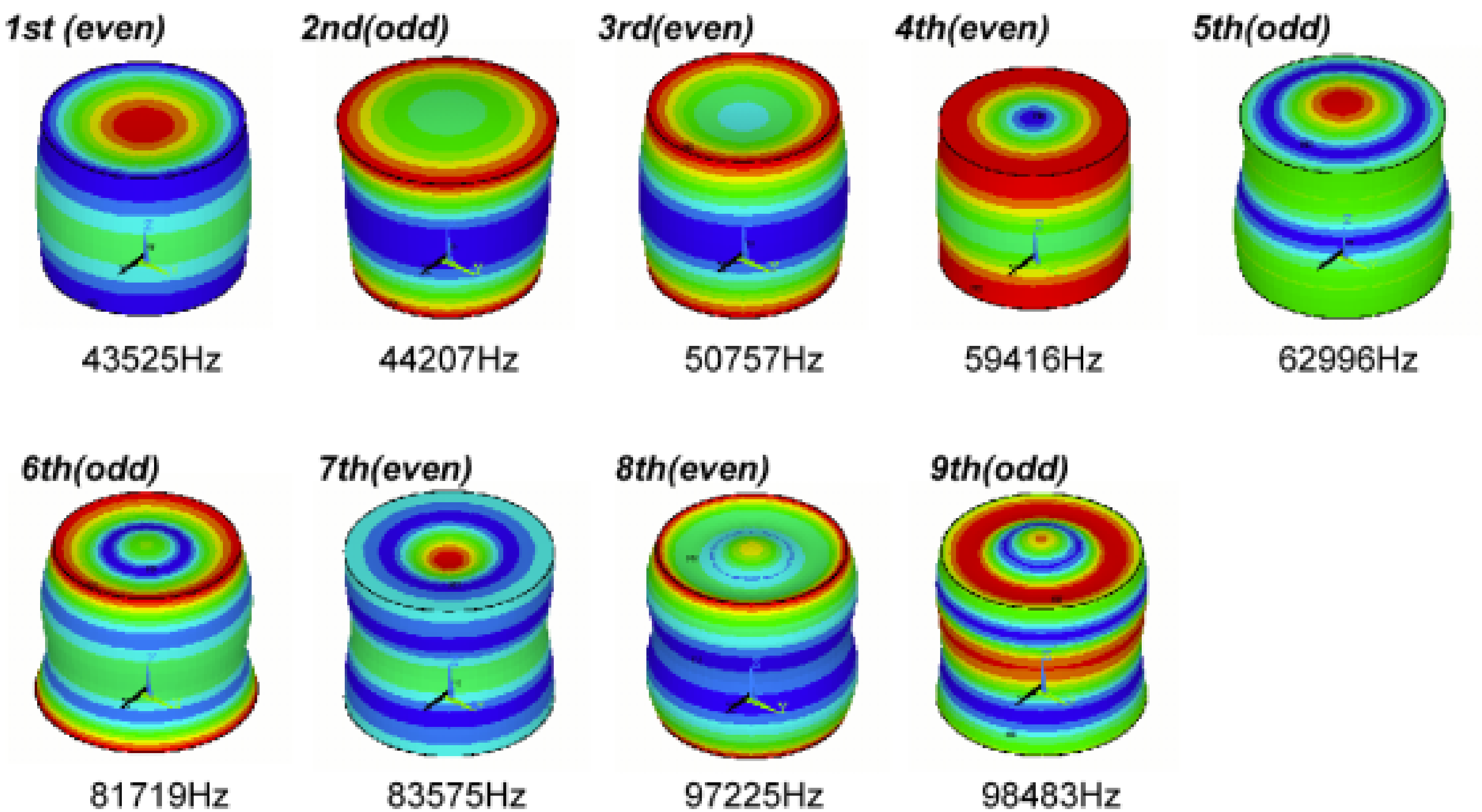


●First clear measurement of Brownian noise ($f^{-1/2}$)

●Wide-band & off-resonant thermal noise measurement

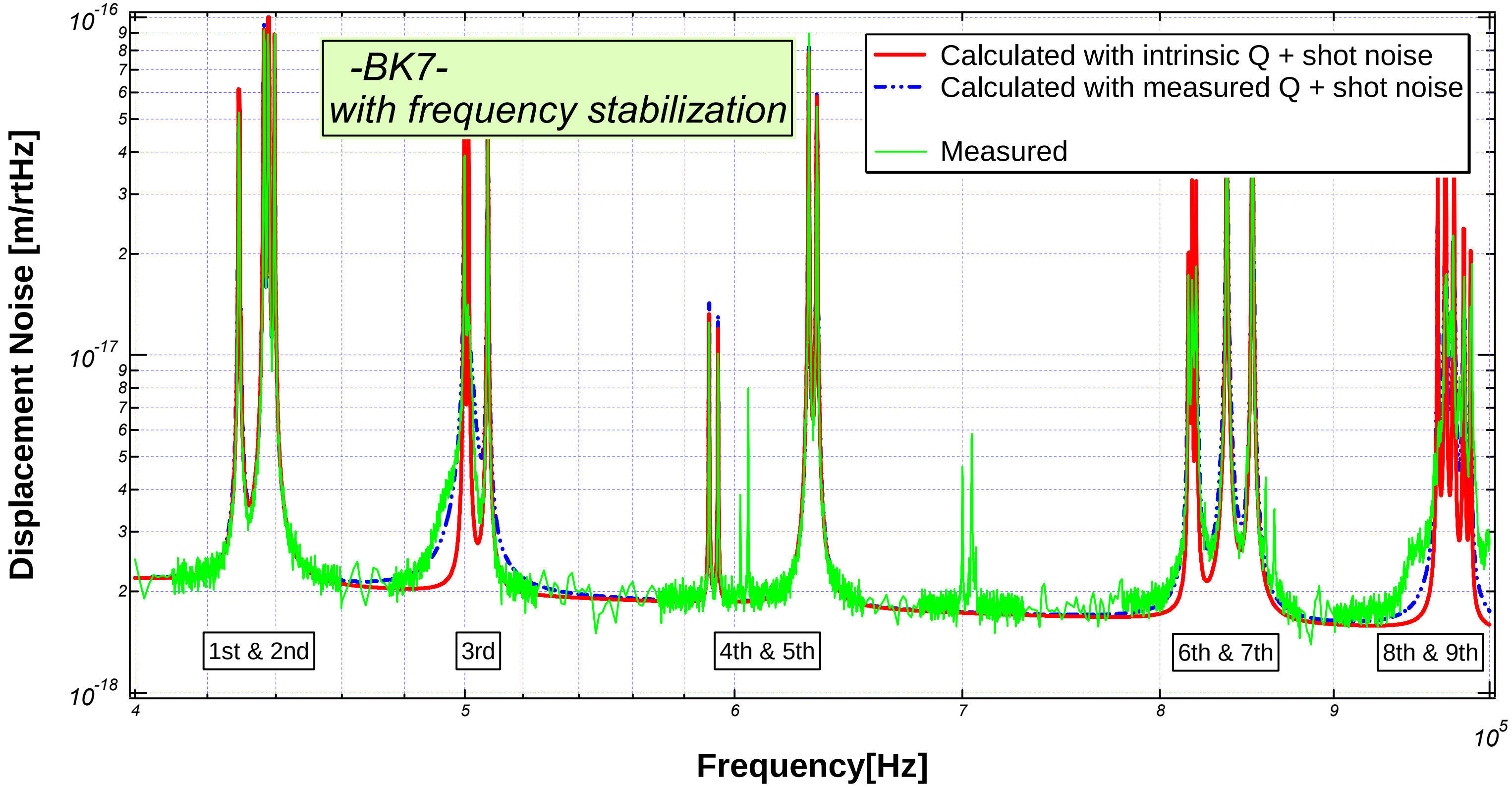
Longitudinal Mode

- **9 vibrational modes**



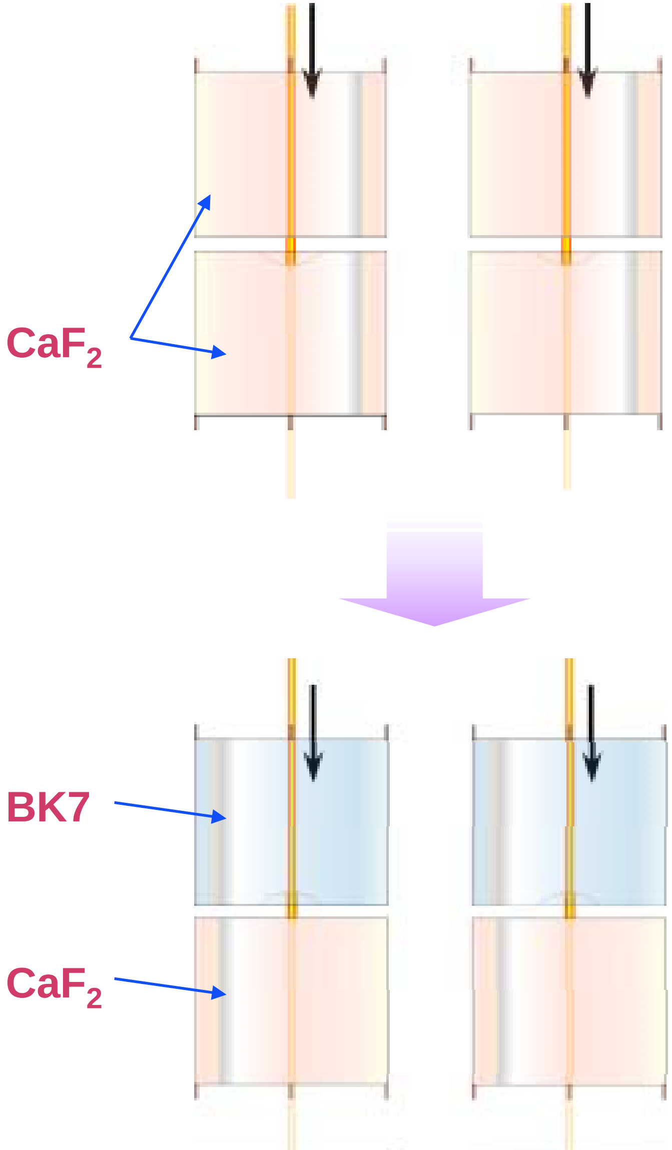
Around Resonance

- **Comparison with calculated curve**
  - » **Very similar spectrums**
    - – **Mirror TN around resonance was also measured**



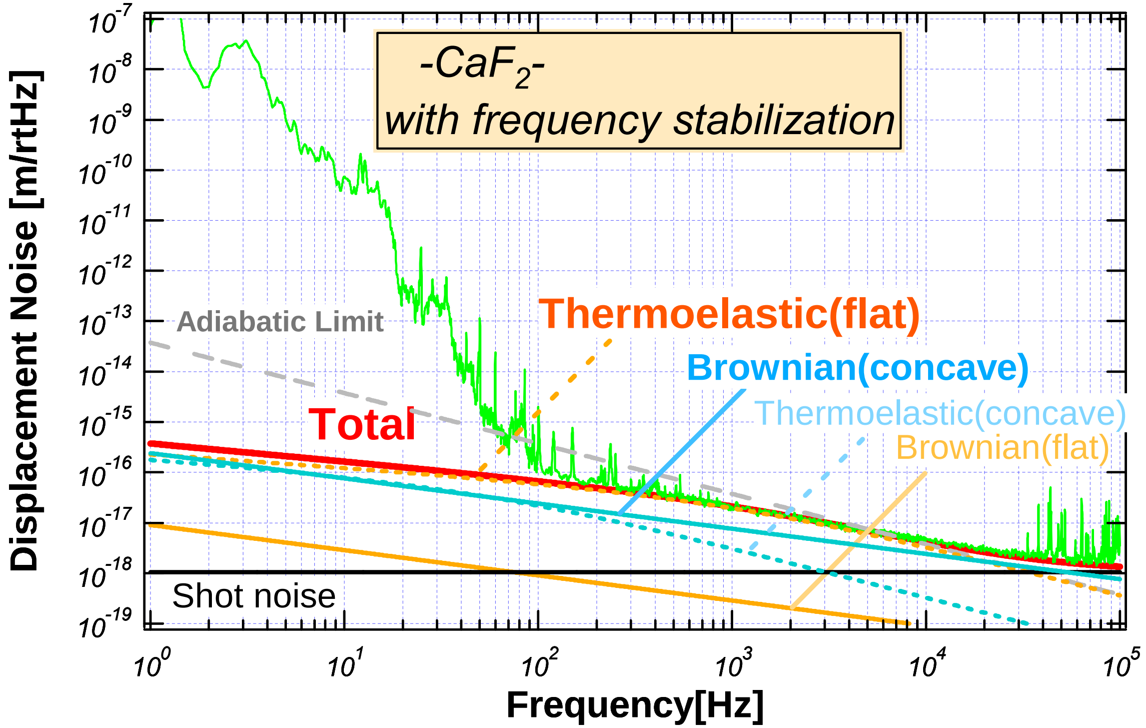
Experiment on CaF_2

- **Setup modification**
  - » **Problem in CaF_2 coating**
    - – Low transmissivity (~0.1%)
    - – Cannot be used for front mirror
  - » **Solution here**
    - – Combination with BK7
    - – Flat CaF_2 as end mirror
      - • TN of CaF_2 emphasized
  - » **Dominant TN**
    - – Low freq. range: CaF_2's thermoelastic
    - – High freq. range: BK7's Brownian



Result in CaF_2 Cavity

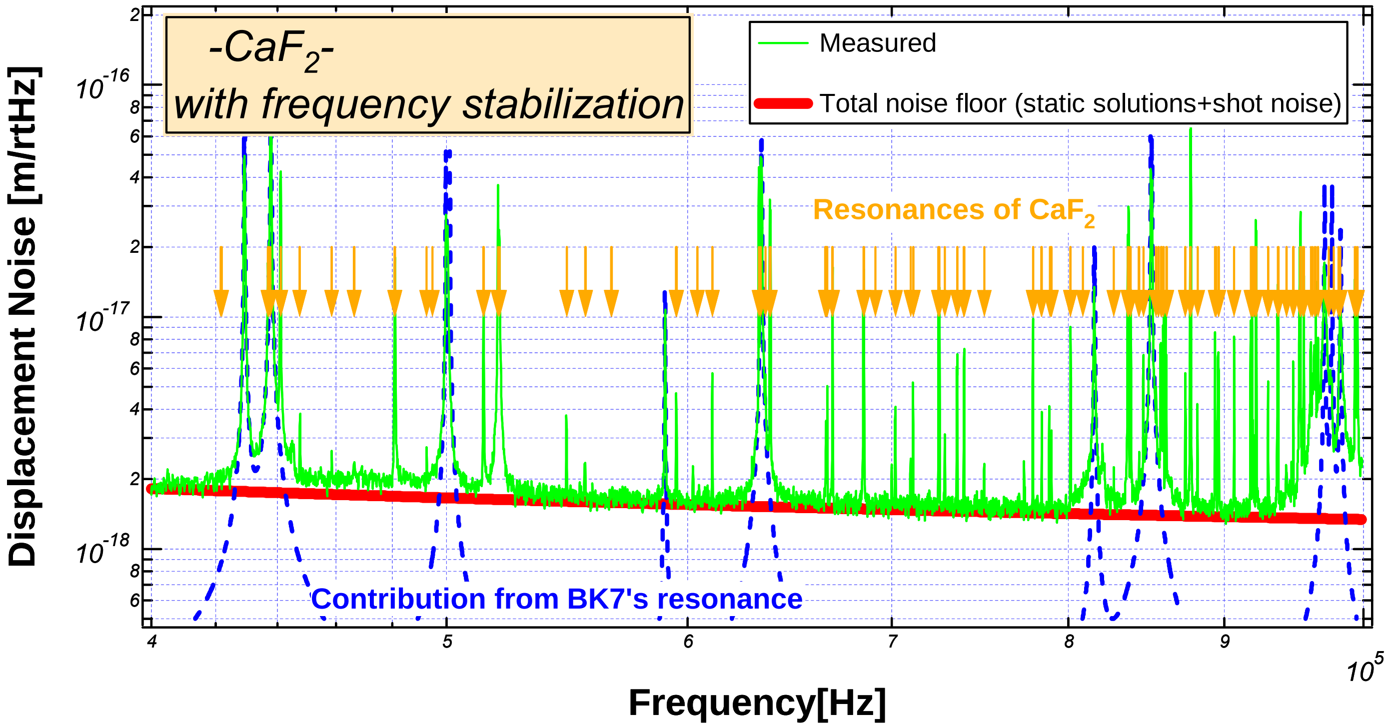
- **Coincided with theoretical thermoelastic noise**
  - » **Calculated only by substrate's properties & beam radius**



●First measurement on thermoelastic noise

Around Resonance

- **Many peaks**
  - » **Originated in CaF_2**
    - – **Properties of modal shape in anisotropic crystal**



●World-highest level sensitivity

4.Summary

- **Mirror TN successfully measured**
  - » On-resonant & off-resonant measurement
    - – 100Hz~100kHz
    - – Confirmation of theories
      - Widest verification of FDT in mechanics
      - Existence of Brownian noise & thermoelastic noise
    - – Unified analysis
      - Direct measurement of intrinsic loss / numerical calculation

→ **Milestone for GW detector development**

- **Established system for TN measurement**
  - » Virtually unique IFO that achieved goal sensitivity

→ **Roles as test bench for GW detector**

Future Works

- **Improvement for better sensitivity**
  - » **Minimum components at this stage**
    - – **Plentiful room to install advanced technique**
  - » **Expansion of observation band for lower frequency**
    - – **Pendulum thermal noise**

- **Measurement of important mirror TN**
  - » **Ex.1 Sapphire**
    - – **Next generation IFO**
  - » **Ex.2 Coating(Fused silica)**
    - – **Importance realized recently**
    - – **Process choice by direct meas.**