LIGO-G070197-00-Z

Squeezed light and radiation pressure effects in suspended interferometers

Thomas Corbitt

MIT
Sarah Ackley, Tim Bodiya, Keisuke Goda, David Ottaway, Eugeniy Mihkailov, Daniel Sigg, Nicolas, Smith, Chris Wipf, Nergis Mavalvala

Caltech
Jay Heefner, Rolf Bork

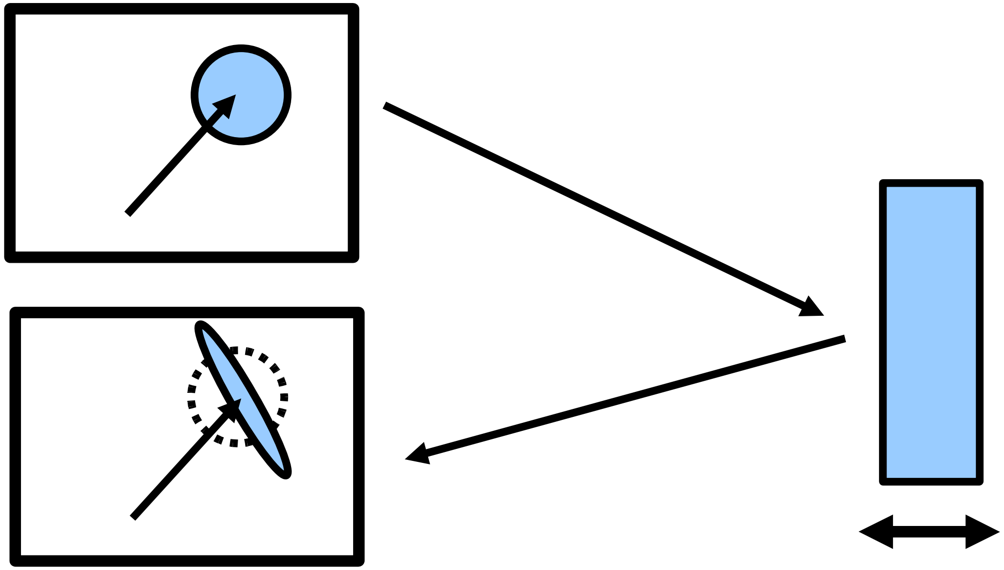
Rencontres de Moriond
March, 2007

Outline

- Radiation pressure effects in optical systems
  - Changes in dynamics
    - Optical spring
    - Parametric instability
  - Noise
    - QND techniques
    - Squeezing
- Tests of quantum mechanics on gram objects.

Reduce quantum noise by squeezing

- Radiation pressure squeezes light:
  - Intensity fluctuations (shot noise) of laser field cause test mass motion
  - Test mass motion creates phase shift of reflected light
  - Phase shift is proportional to intensity fluctuations – this correlation gives the squeezing effect.
- It's not just additional noise – if used properly, it can reduce the noise! Squeezing can be produced by interferometer itself.

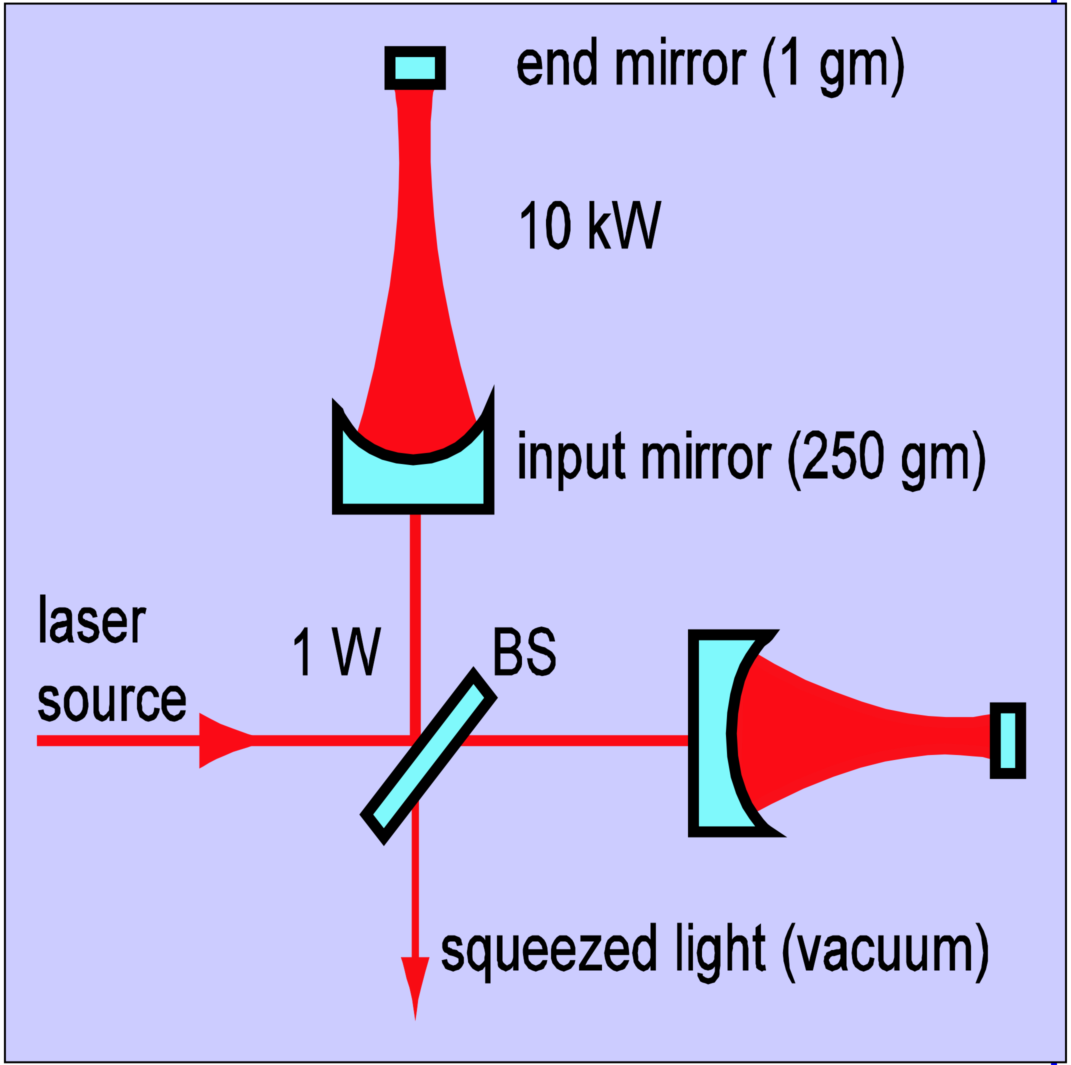


EM fluctuations (ball) on top of laser field (stick) are squeezed by the movable mirror.

The ponderomotive interferometer

Key ingredients:

- "Table-top experiment"
- Low mass, low noise mechanical oscillator mirror – 1 g with 6 Hz resonant frequency
- High circulating power – 10 kW
- High finesse cavities - 8000
- Differential measurement – common-mode rejection to cancel classical noise
- Optical spring – noise suppression and frequency independent squeezing

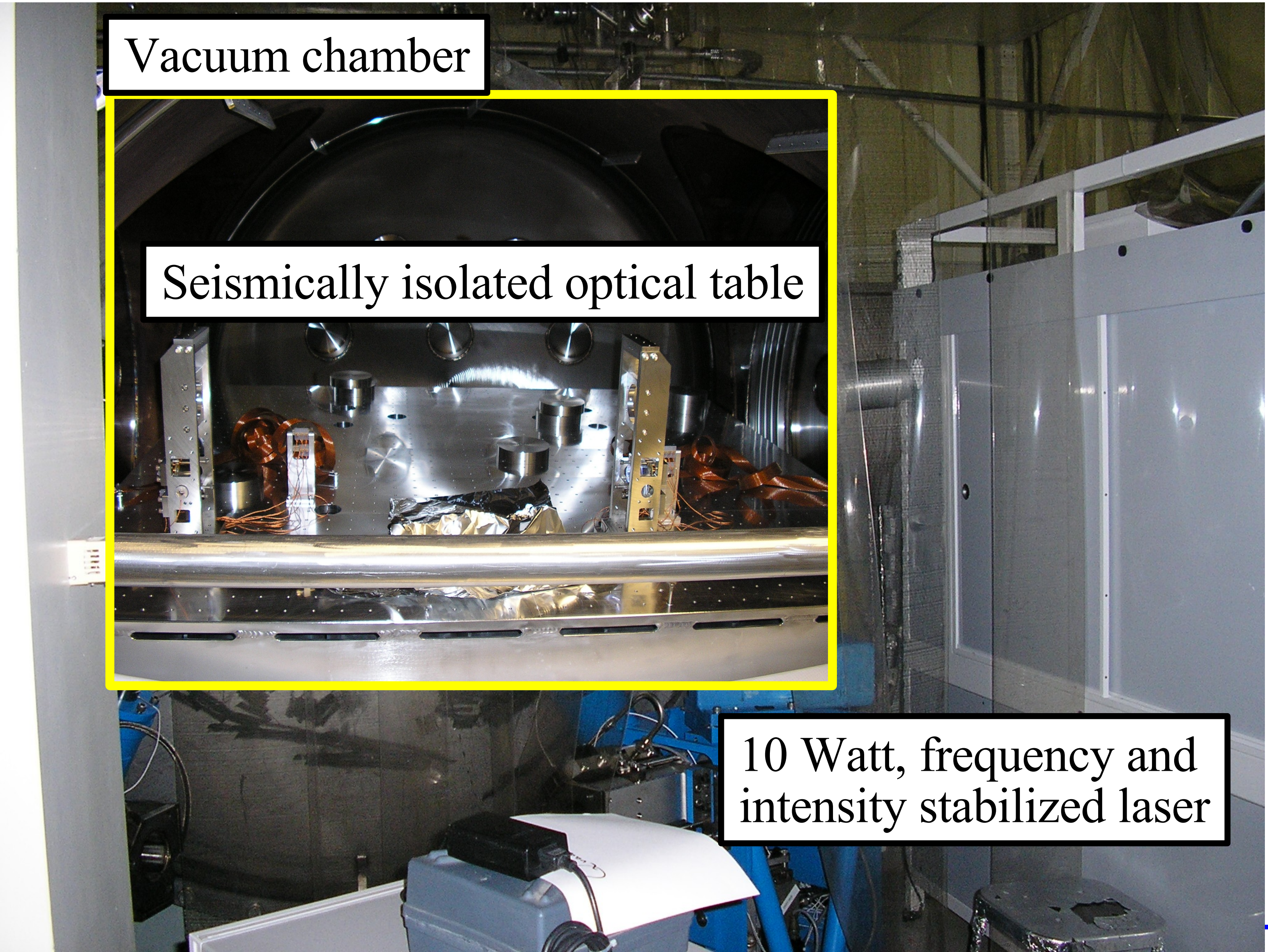


Phys. Rev A **73**, 023801 (2006)

Scale comparison

	PDE	LIGO	Adv. LIGO	40m
Mass	1 gram	10 kg	40 kg	0.25 kg
Power	10 kW	10kW	1MW	~1 kW
P/M	**10 MW/kg**	**1 kW/kg**	**25 kW/kg**	**4 kW/kg**

Experimental Platform



Vacuum chamber

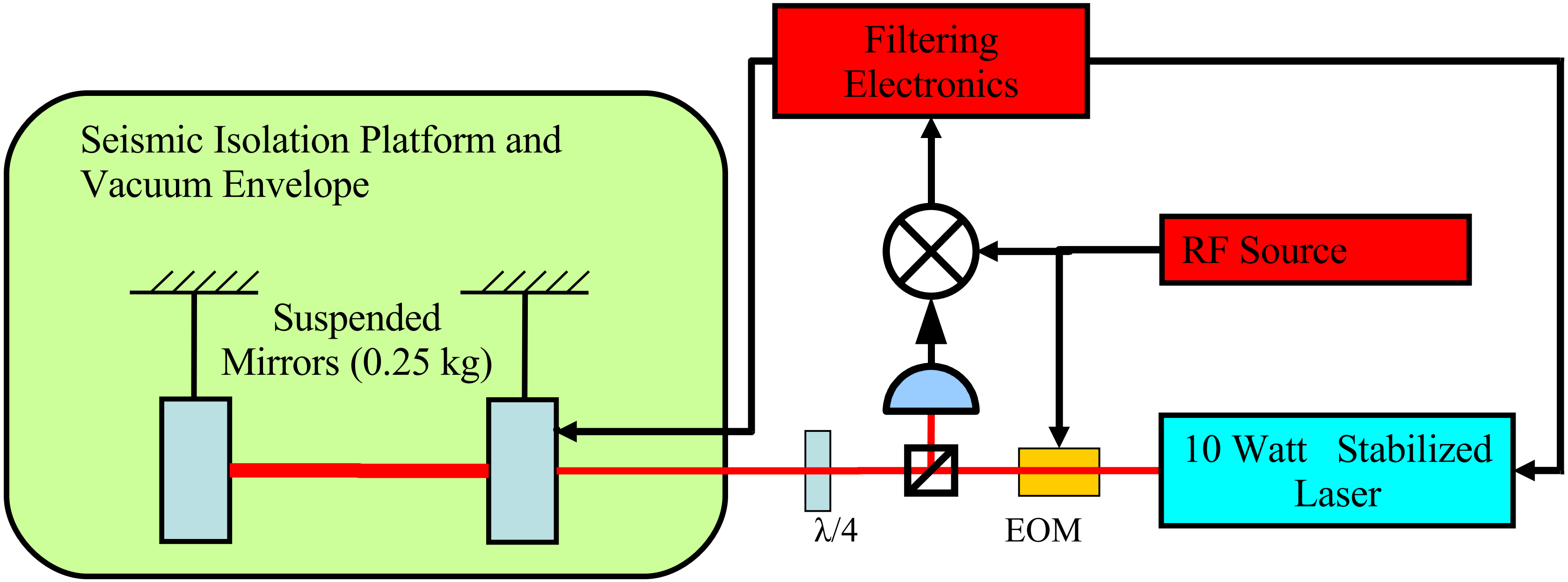
Seismically isolated optical table

10 Watt, frequency and intensity stabilized laser

Experimental progress

- Experiment carried out in three phases
  - Phase I → linear cavity with two 250 g suspended mirrors, finesse of 1000, ~5 W of input power – dynamics test
  - Phase II → cavity with one 250 g and one 1 g suspended mirror, finesse of 8000, ~5 W of input power – dynamics test
  - Phase III → two identical cavities and Michelson interferometer – low noise
- Ultimate goal – quantum-limited radiation pressure and ponderomotive squeezing

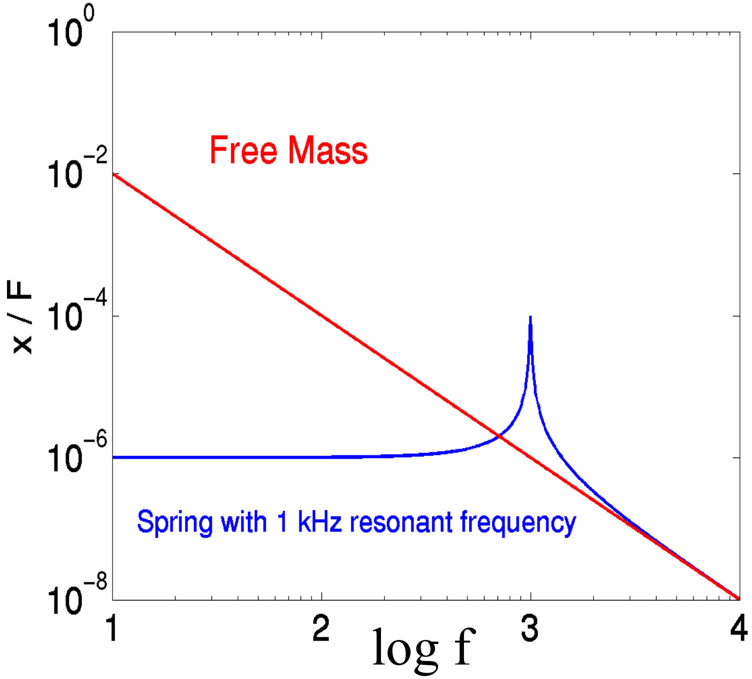
Phase I Experiment



Detuned by inserting offset into PDH error signal, limited to detunings ~ half linewidth.

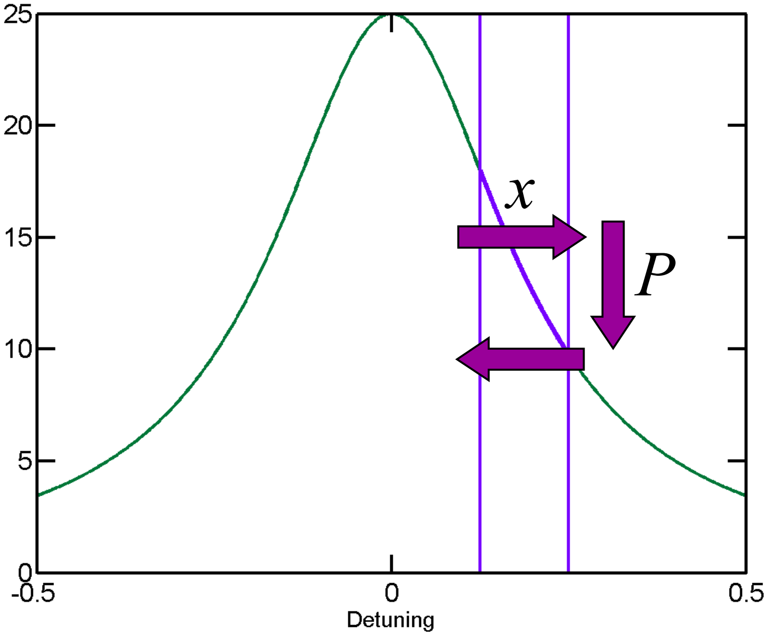
Optical Springs

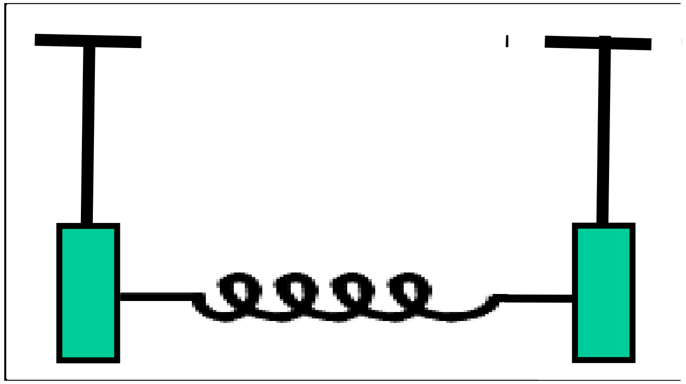
- Modify test mass dynamics
- Potentially circumvent the free mass SQL
- Suppress displacement noise
- Why not use a mechanical spring?
  - Large thermal noise
- Connect low-frequency mechanical oscillator to (nearly) noiseless optical spring
- An optical spring with a high resonant frequency will not change the thermal force spectrum of the mechanical pendulum
  - Use a low resonant frequency mechanical pendulum to minimize thermal noise



How to make an optical spring?

- Detune a resonant cavity to higher frequency (blueshift)
  - DC radiation pressure balanced by control system
  - Detuning increases
  - Cavity becomes longer
  - Power in cavity decreases
  - Radiation-pressure force decreases
  - Mirror ‘restored’ to original position
  - Cavity becomes shorter
  - Power in cavity increases
  - Mirror still ‘restored’ to original position





Optical rigidity model

- Power inside cavity in steady state is
  - δ is detuning
  - γ is linewidth

$$P = \frac{4P_0 / T_i}{1 + (\delta / \gamma)^2}$$

- Radiation pressure force is 2P/c, so optical spring constant is:

$$k_{opt,0} = \frac{2}{c}\frac{dP}{dx} = \frac{128\pi P_0}{c T_i^2 \lambda_0} \frac{(\delta/\gamma)}{[1+(\delta/\gamma)^2]^2}$$

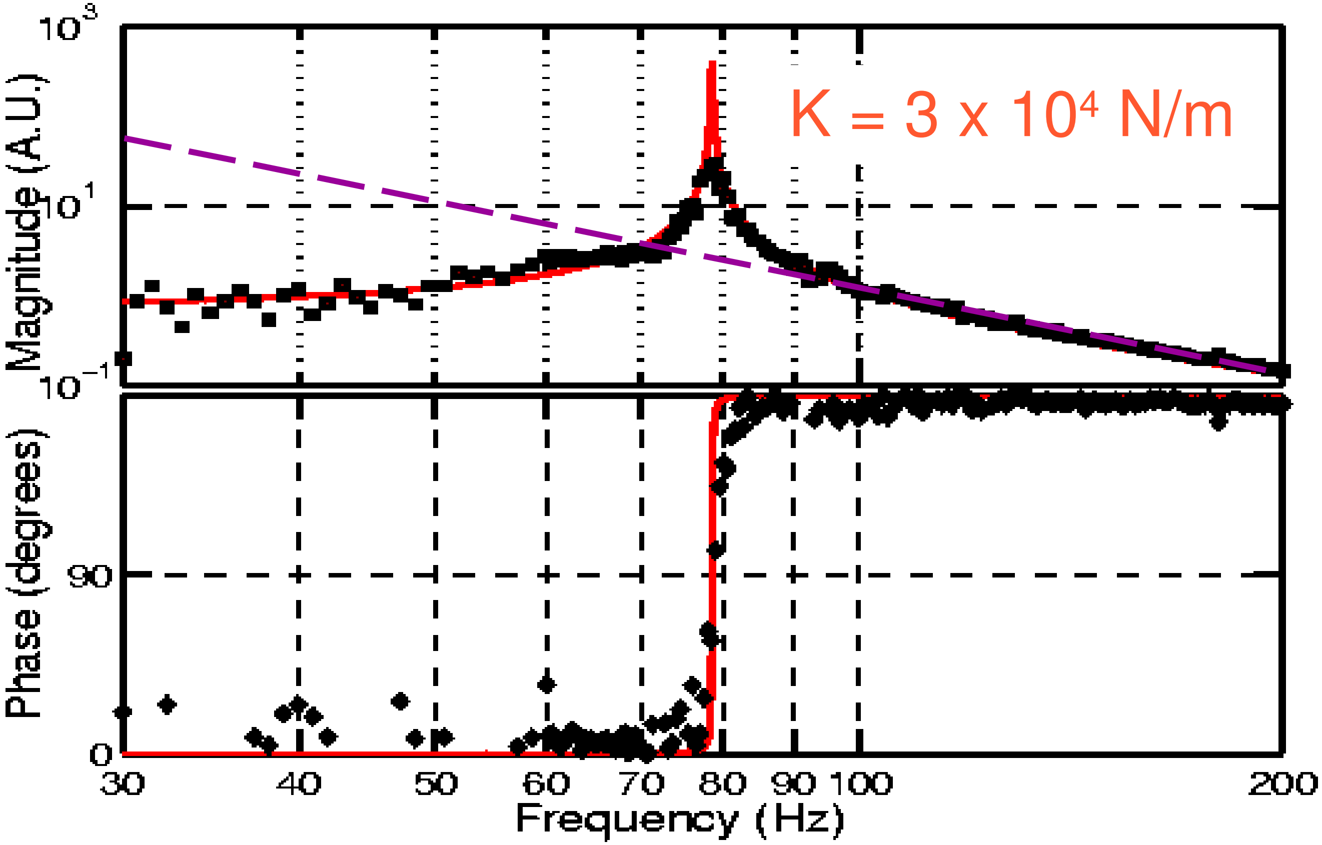
- This determines the frequency shift of mechanical modes.
- When the finite response time of the cavity is included:

$$k_{opt} = k_{opt,0} \frac{1+(\delta/\gamma)^2}{(1+i\Omega/\gamma)^2 + (\delta/\gamma)^2}$$

Imaginary spring constant gives viscous forces, leading to unstable optical spring, as well as PI and cold damping effects.

Optical Spring Measured

- Phase increases by 180˚, so resonance is unstable!
- But there is a lot of gain in our servo at this frequency, so it doesn't destabilize the system.
- Stiffness is approximately the same as if the two mirrors were connected by a wood beam with same dimensions as the optical field.
- About 6,000 times stiffer than the mechanical suspension.



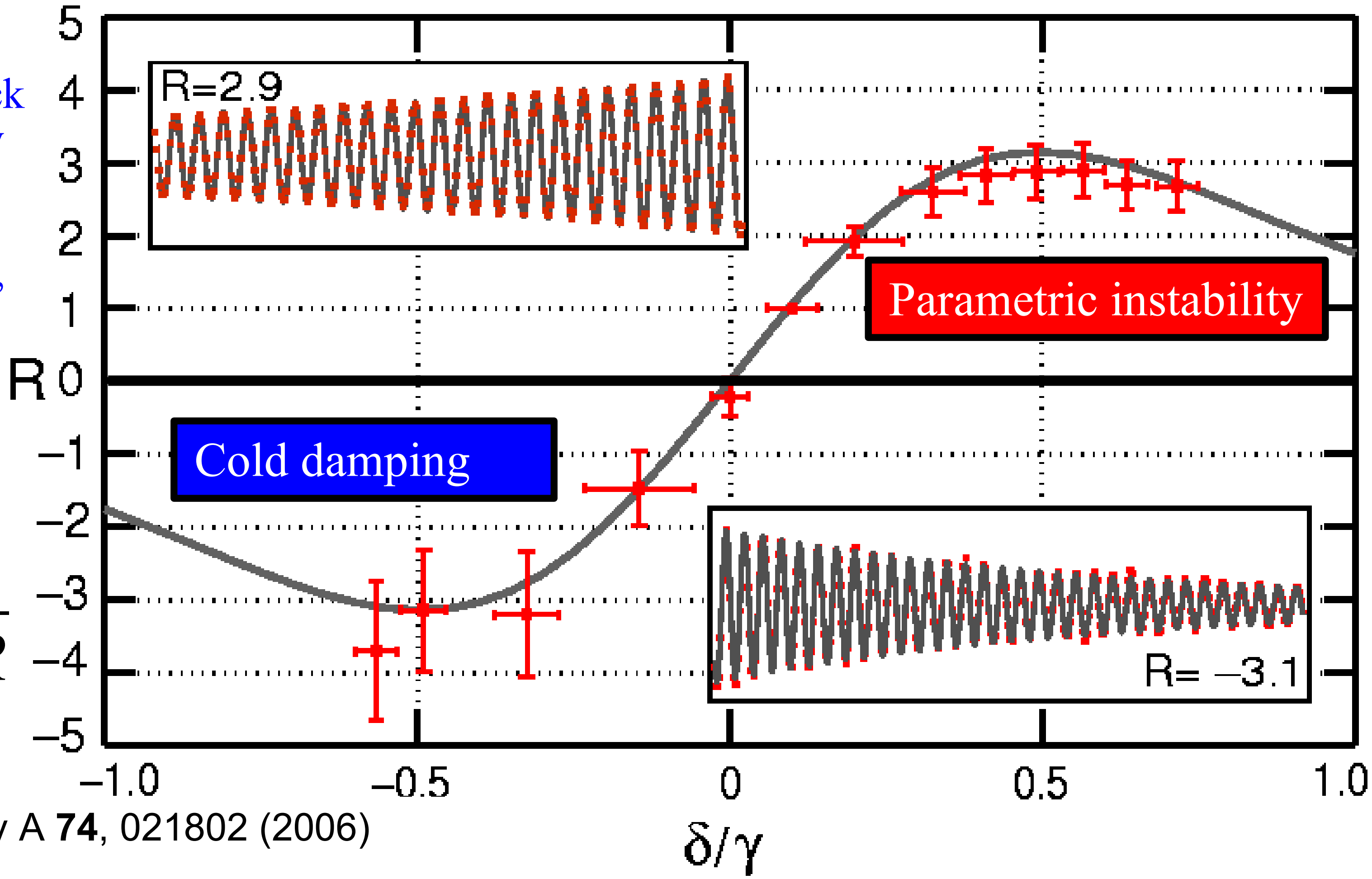
Parametric instability observed and damped!

Acoustic drumhead mode of one mirror became unstable when detuned at high power. The viscous radiation pressure force drives the mode to become unstable – PI! Also when detuned to opposite direction, the Q of the mode is decreased – cold damping!

The mode was stabilized through feedback to the frequency of the laser.

If not stabilized, the mode rings up until cavity loses lock.

$$\tau_{eff} = \frac{\tau}{1-R}$$



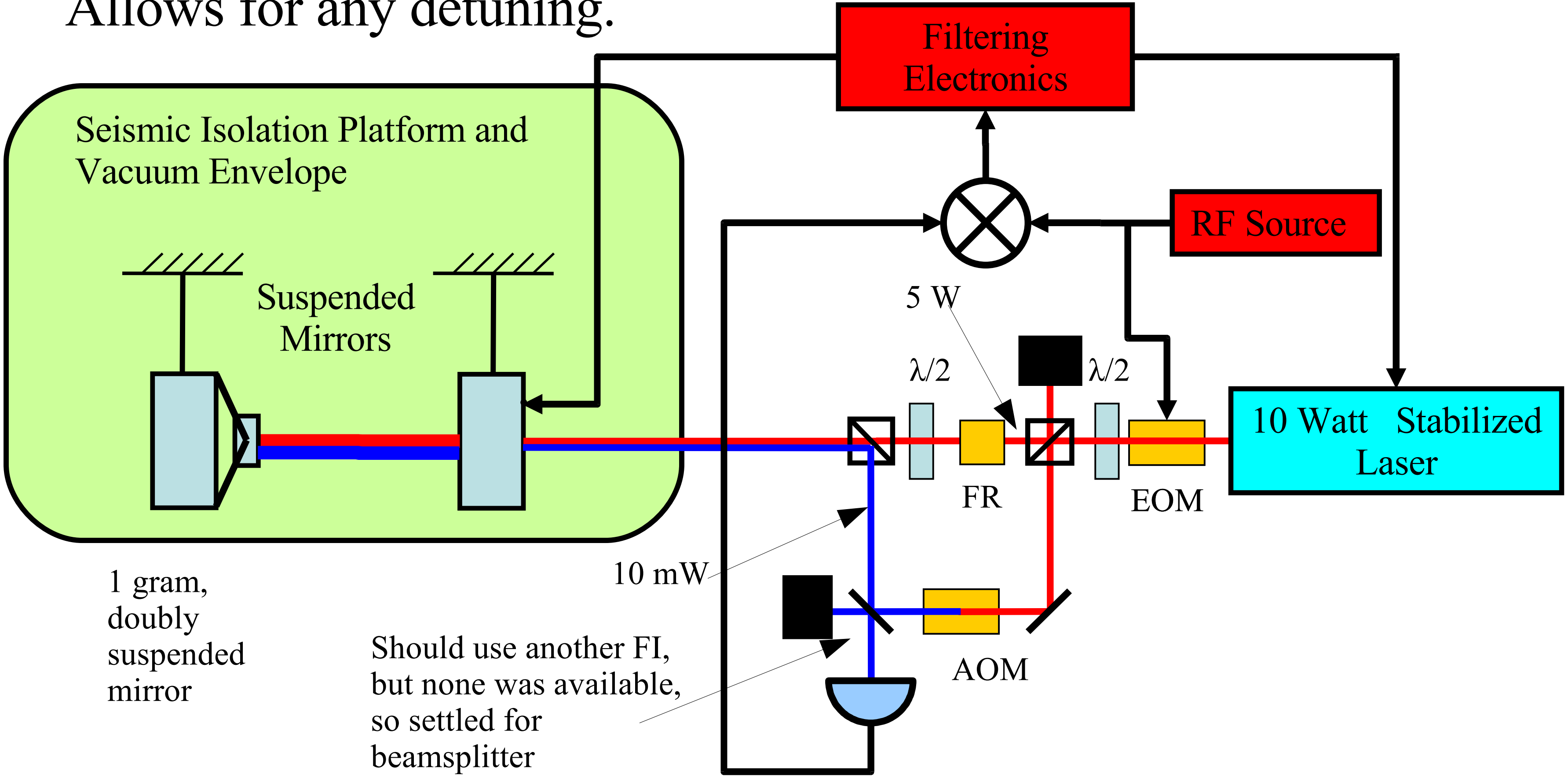
Phys. Rev A **74**, 021802 (2006)

Phase II Cavity

- Use 250 g input and 1 g end mirror (same mirrors to be used in Phase III) in a suspended 1 m long cavity of finesse 8,000 with goal of
  - PI R < 100 at full power
  - <1 MW/cm^2 power density
  - Optical spring resonance at > 1 kHz
  - Same performance as single cavity of Phase III
- Double suspension for 1 gram mirror
- Goals for this stage
  - See noise reduction effects
  - Get optical spring out of the servo bandwidth
  - See instability directly and damp it

Phase II Experiment

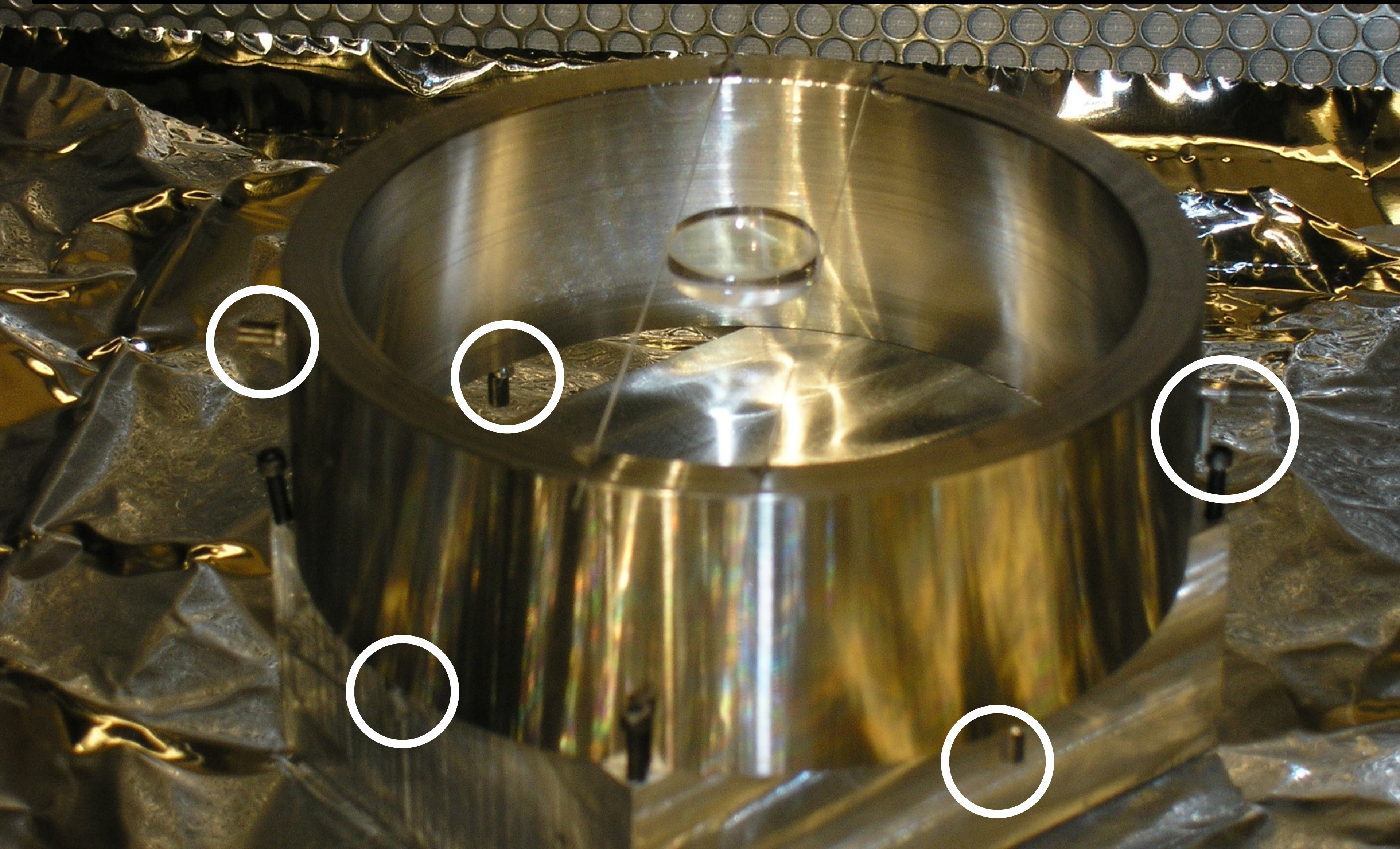
Frequency shifted light (by 1 FSR) is always locked on resonance. By controlling the frequency shift, we detune the pump beam, but frequency shifted light stays on resonance! Allows for any detuning.



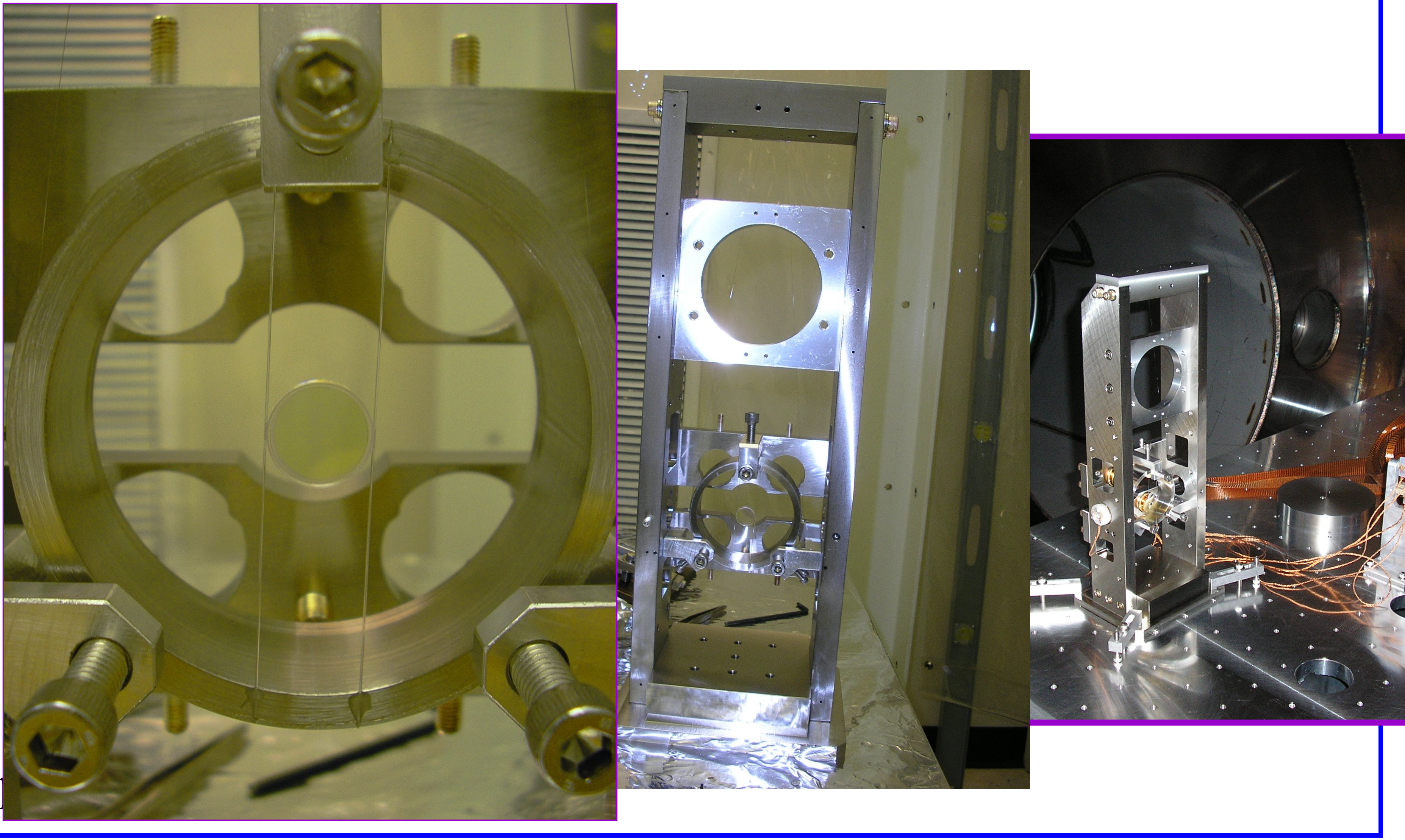
1 gram, doubly suspended mirror

Should use another FI, but none was available, so settled for beamsplitter

Steel shell with same diameter as small optics. Suspended as a small optic with magnets, wire standoffs, etc. Little mirror attached by two 300 micron fused silica fibers. All glued together.



Double suspension for mini mirror

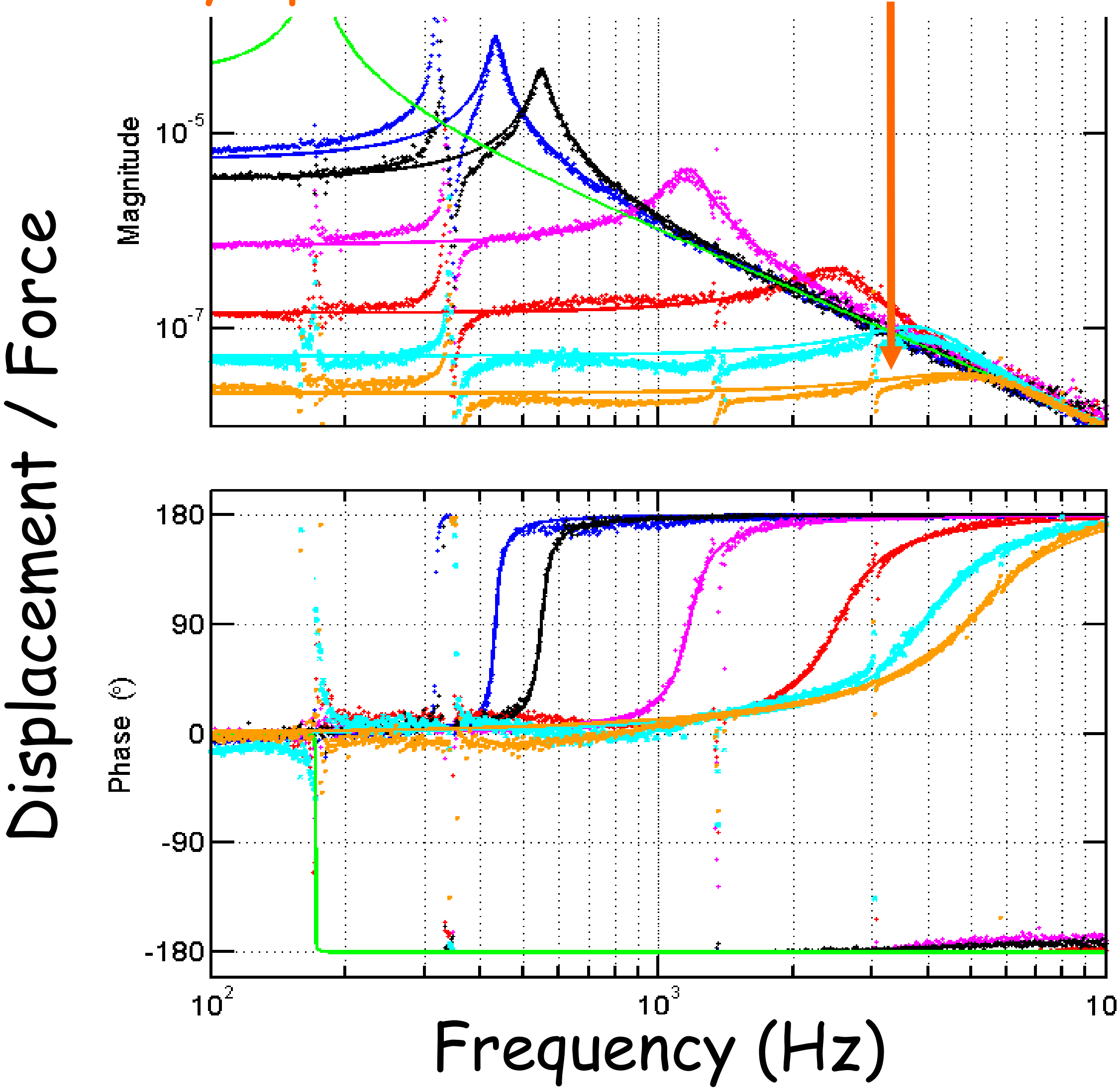


Extreme optical stiffness…

- How stiff is it?
  - 100 kg person
    ➔ F_{grav} ~ 1,000 N
    ➔ x = F / k = 0.5 mm
- Very stiff, but also very easy to break
  - Maximum force it can withstand is only ~ 100 μN or ~1% of the gravitational force on the 1 gm mirror
- Replace the optical mode with a cylindrical beam of same radius (0.7mm) and length (0.92 m) ➔ Young's modulus E = KL/A
  - Cavity mode ***1.2 TPa***
  - Compare to
    - Steel ~0.16 Tpa
    - Diamond ~1 TPa
    - Single walled carbon nanotube ~1 TPa

5 kHz ➔K = 2 x 10^6 N/m

Cavity optical mode → diamond rod



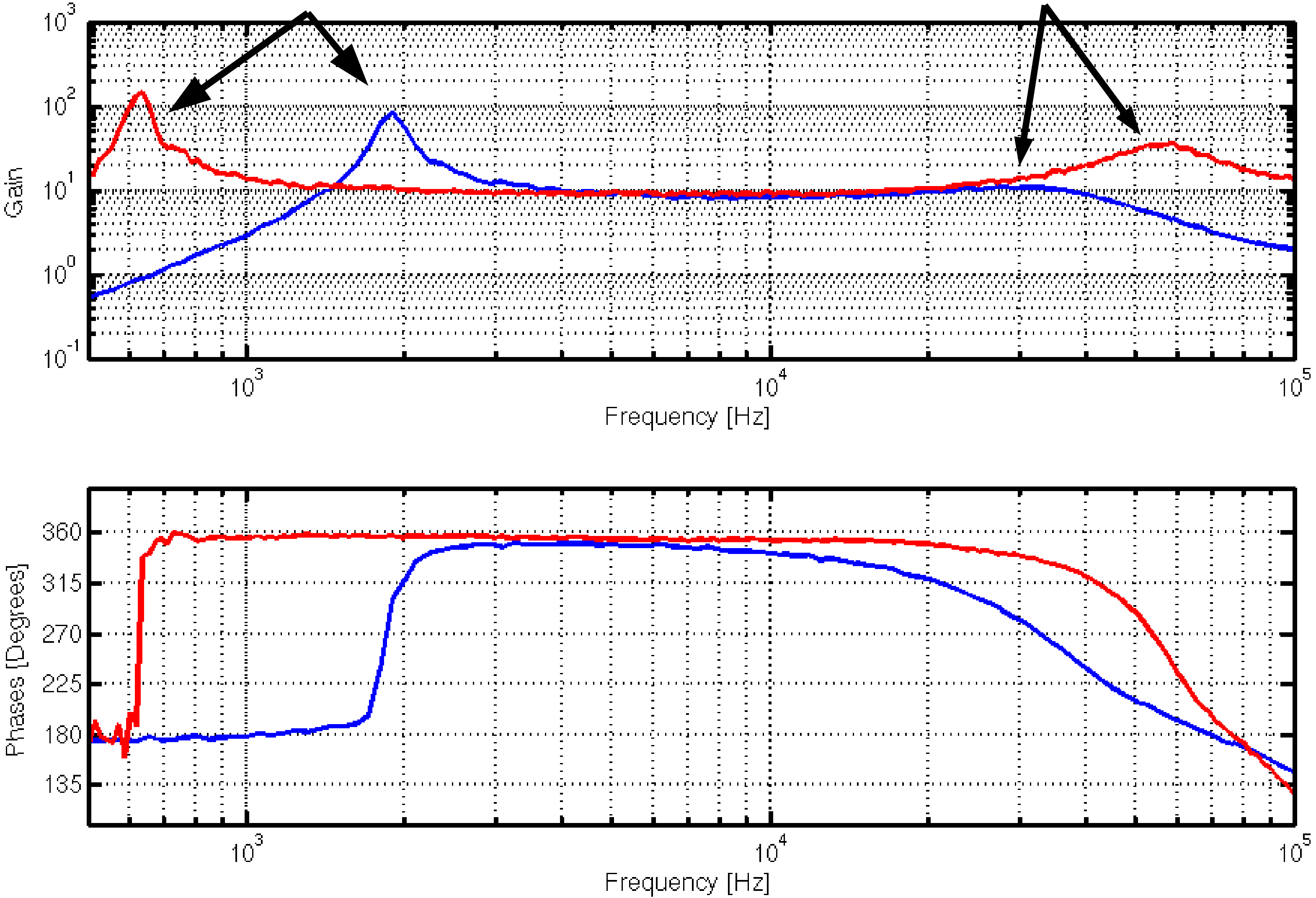
Doubly resonant cavity

Detuning = 30, 60 kHz, Linewidth = 11 kHz

Optical spring resonance

Optical resonance

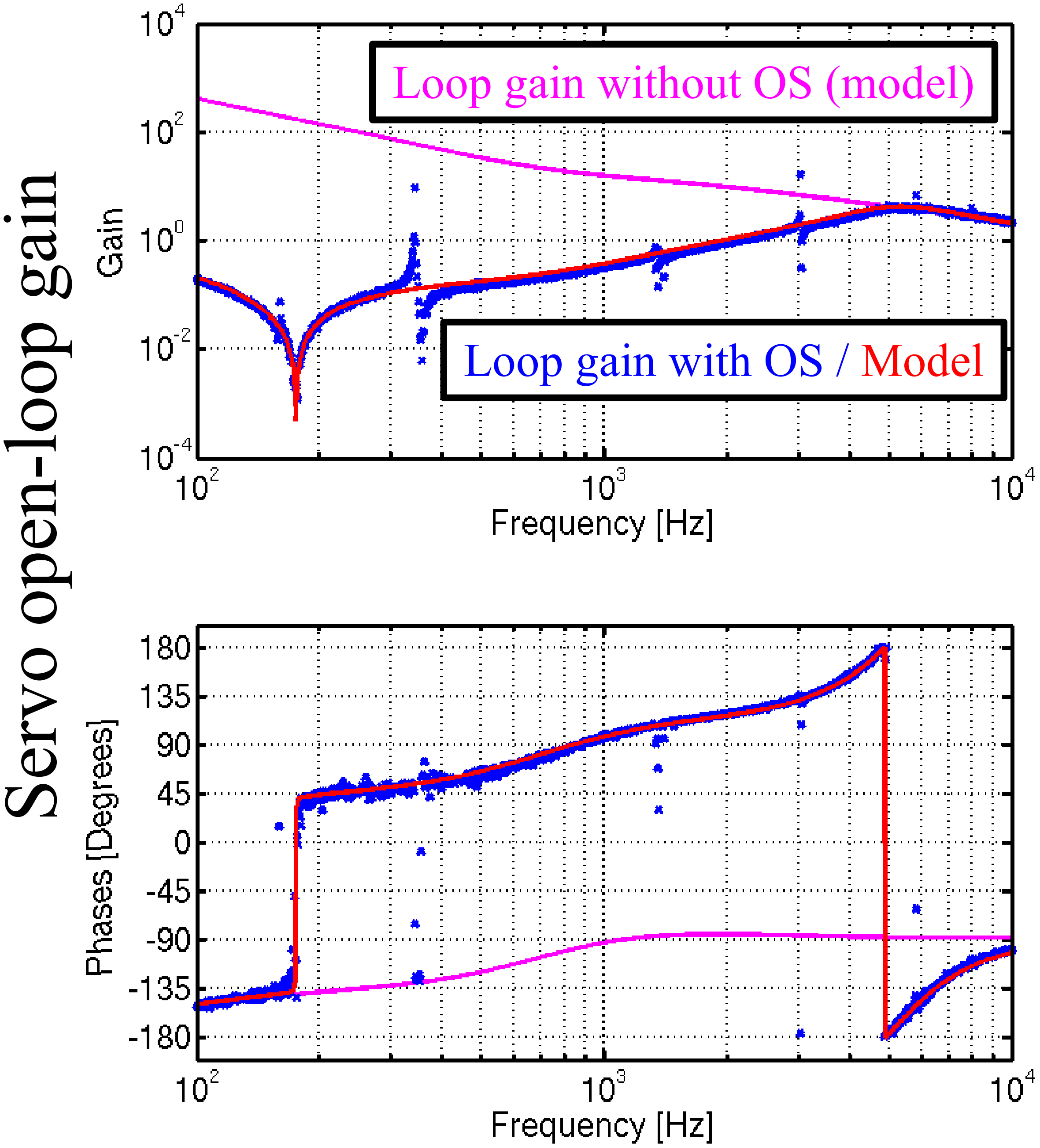
Optical gain



Practical lesson

Optical rigidity makes cavity rigid to both force and frequency fluctuations. This can wreak havok on your control system! Our servo is overwhelmed by the optical stiffness.

But this is good, since the cavity becomes more stable, and the servo won't interfere with the dynamics – which is essential for ponderomotive squeezing.



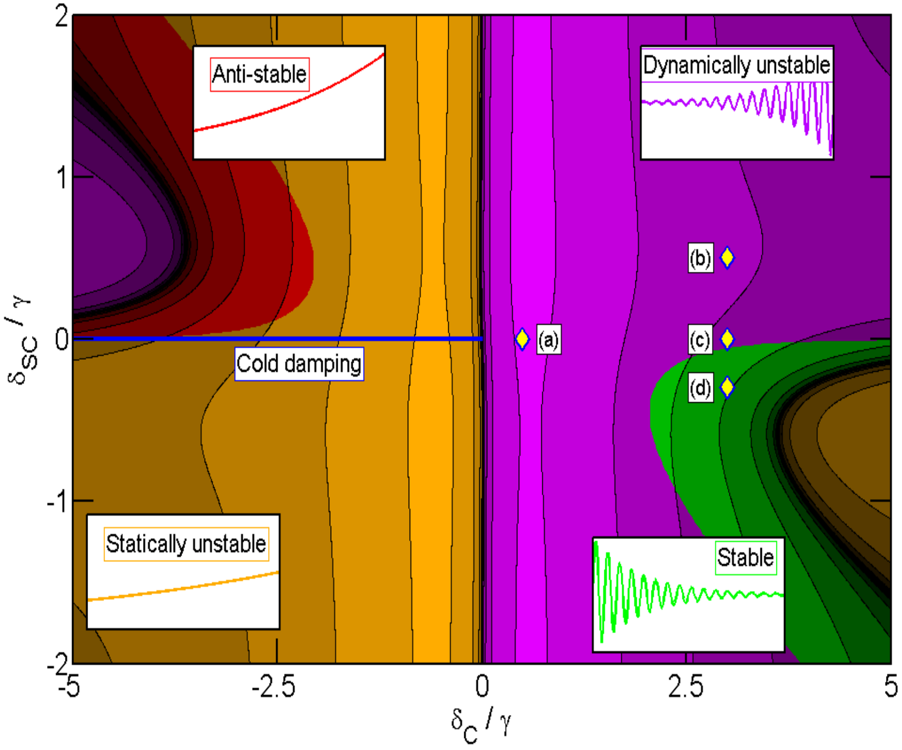
Stable optical springs

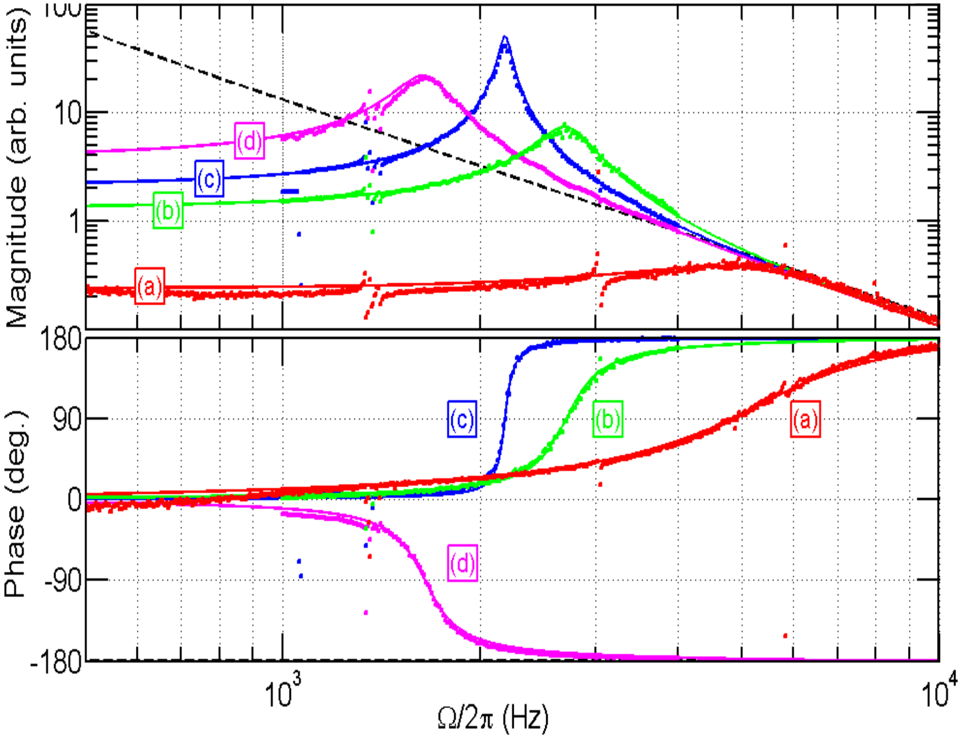
- Long detuning (optical spring): anti-damping
- Short detuning (cold damping): anti-restoring
- Always unstable if optical forces dominate over mechanical. Stabilized by electronic feedback in the past.
- Key idea: the optical damping depends on the response time of the cavity, but the optical spring does not. Therefore, use two fields with a different response time:
    - Fast response creates restoring force and small anti-damping
    - Slow response creates damping force and small anti-restoring force
- Two cavities with different lengths or finesses could accomplish this, but a single cavity and two fields with different detunings is easier.

Double optical spring

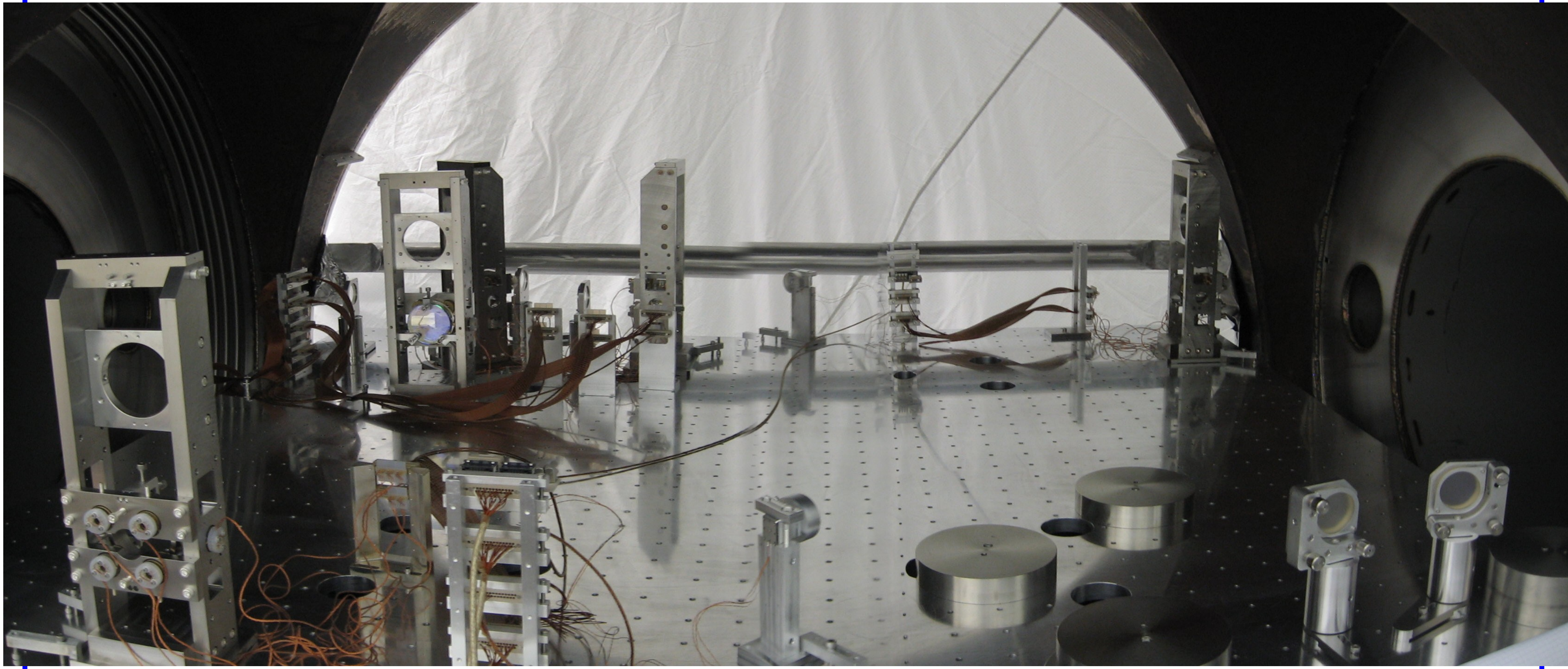
- With different detunings, the two fields respond with different time constants, since they are more/less resonant in the cavity.
- P_C / P_{SC} = 20, more power in the highly detuned field.
- When operating in stable regime, electronic feedback may be turned off. Parametric instability is also be stabilized for certain parameters. Control-free cavity? Almost, but not yet (current best is ~3 Hz bandwidth)

Accepted in PRL

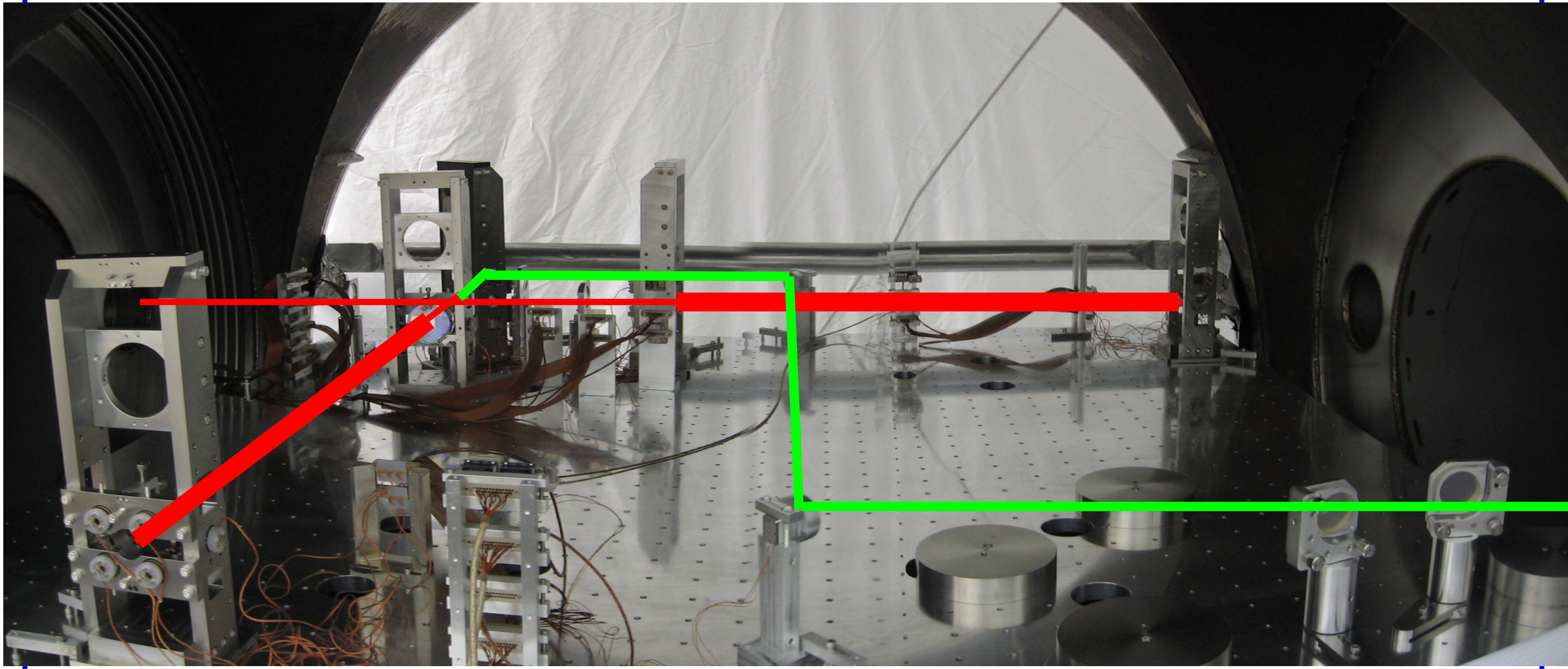




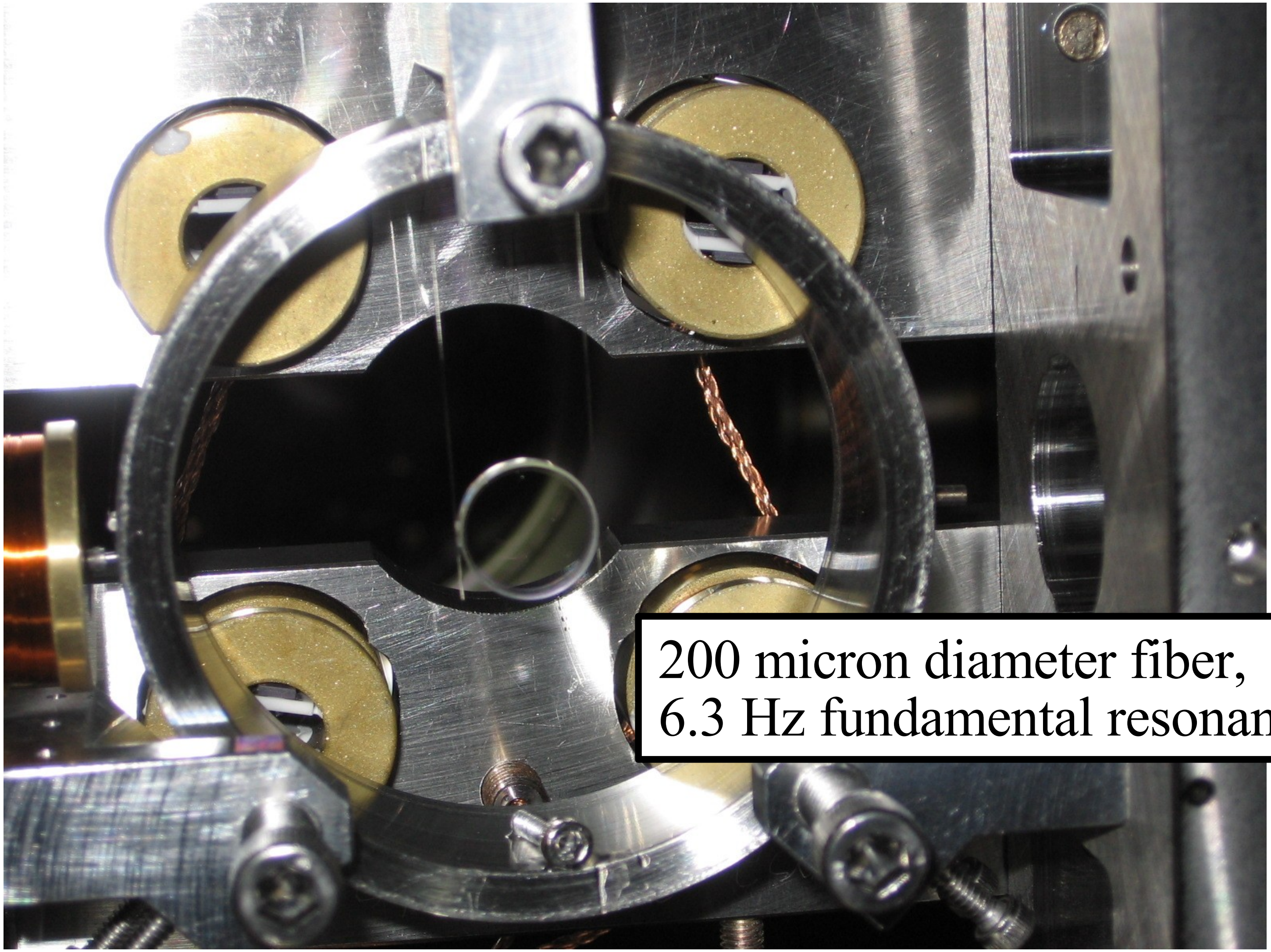
What's next?



What's next?

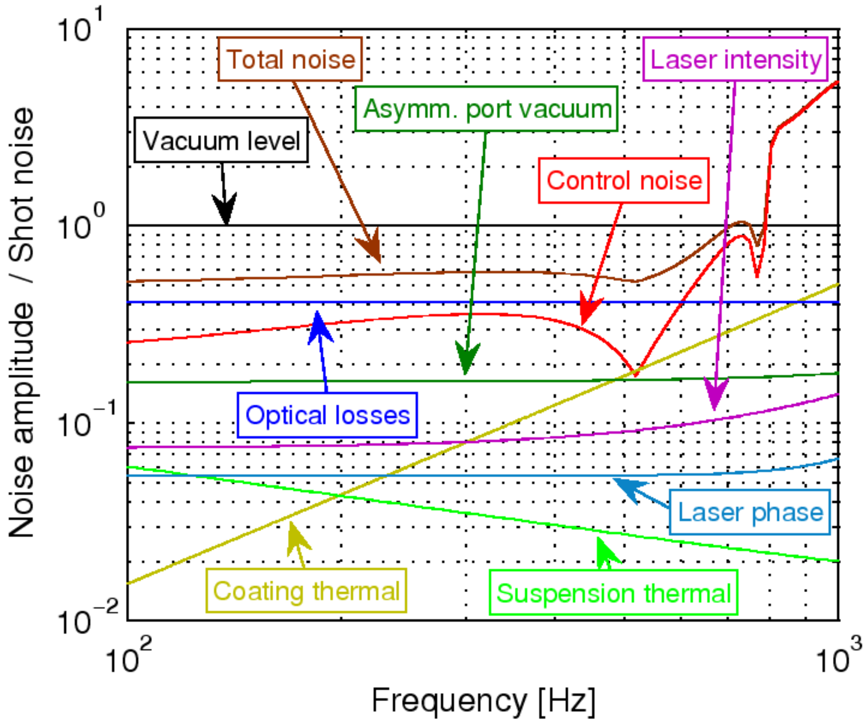


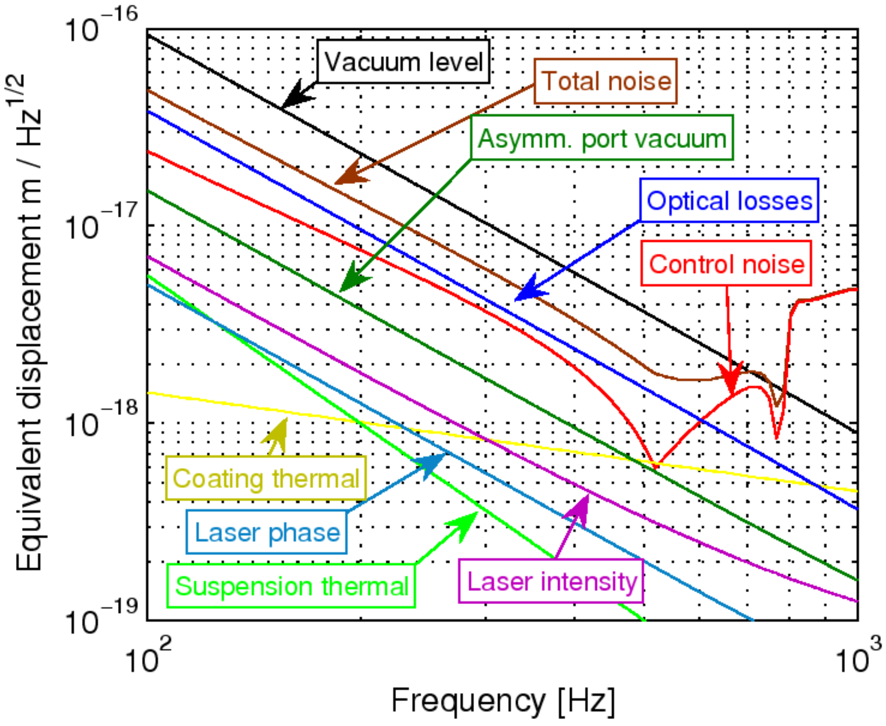
Suspension



200 micron diameter fiber,
6.3 Hz fundamental resonance

Noise budget

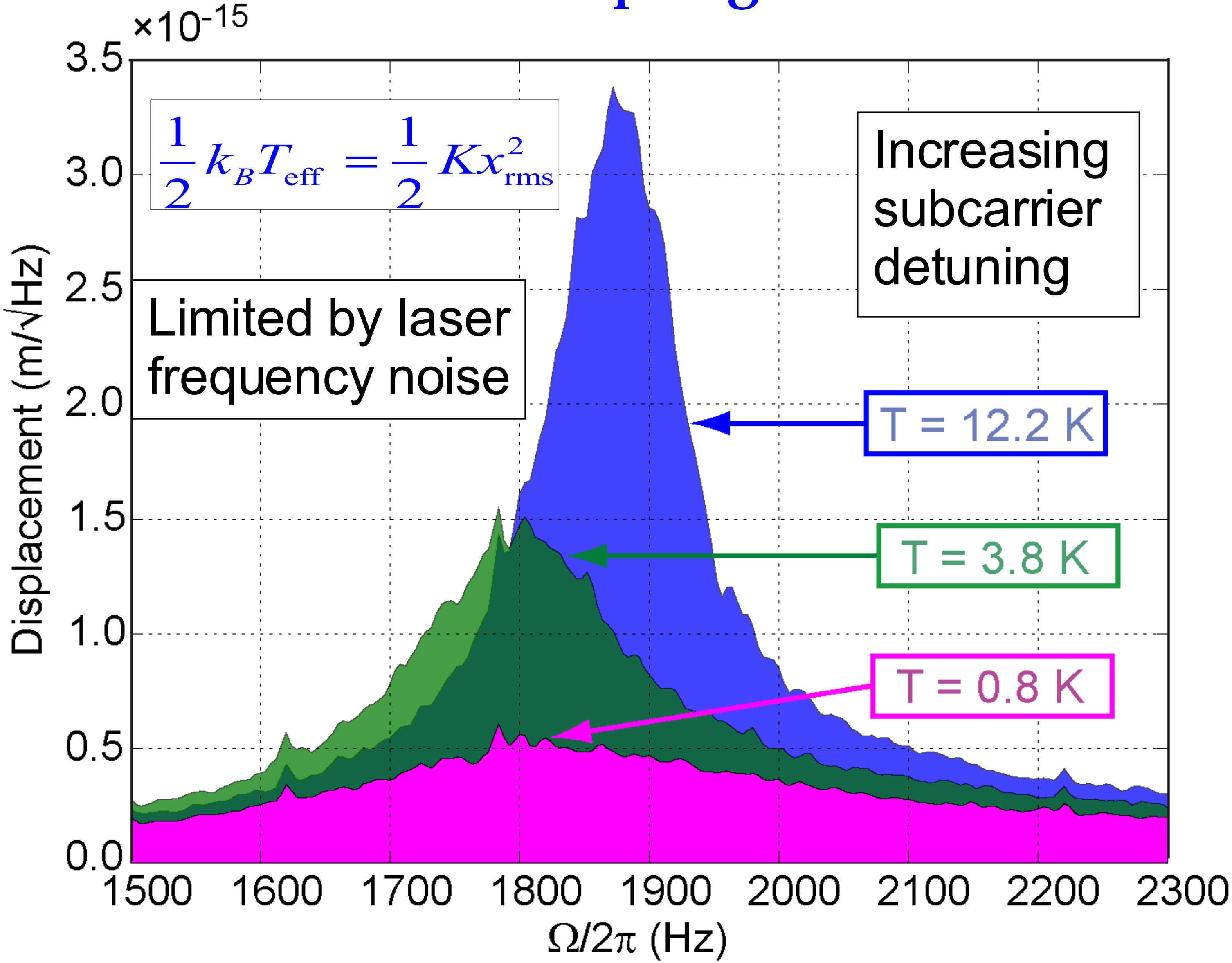




Optical spring cooling

- Our motivation for using the optical spring was low thermal noise. It turns out that this is useful for more than just squeezing:
    - Many proposals and experiments use optical damping or electronic feedback to cool micro/nano-mechanical oscillators close to their ground state. These techniques reduce the motion of the oscillator by damping its motion, thereby reducing its temperature. The limit to these techniques is determined by the mechanical quality factor.
        - P. F. Cohadon et al., Phys. Rev. Lett. **83**, 3174 (1999)
        - C. H. Metzger and K. Karrai, Nature **432**, 1002 (2004)
        - S. Gigan et al., Nature **444**, 67 (2006)
        - D. Kleckner and D. Bouwmeester, Nature **444,** 75 (2006)
        - O. Arcizet et al., Nature **444**, 71 (2006)
    - Since optical springs introduce no mechanical damping, they create resonators with enhanced mechanical quality factors: $Q_{\mathrm{mech,eff}} = Q_{\mathrm{mech}} \times \Omega_{\mathrm{OS}} / \Omega_{\mathrm{mech}}$
    - Extreme cooling possible using this technique.

Optical cooling with double optical spring



$$\frac{1}{2}k_B T_{\mathrm{eff}} = \frac{1}{2}K x_{\mathrm{rms}}^2$$

Limited by laser frequency noise

Increasing subcarrier detuning

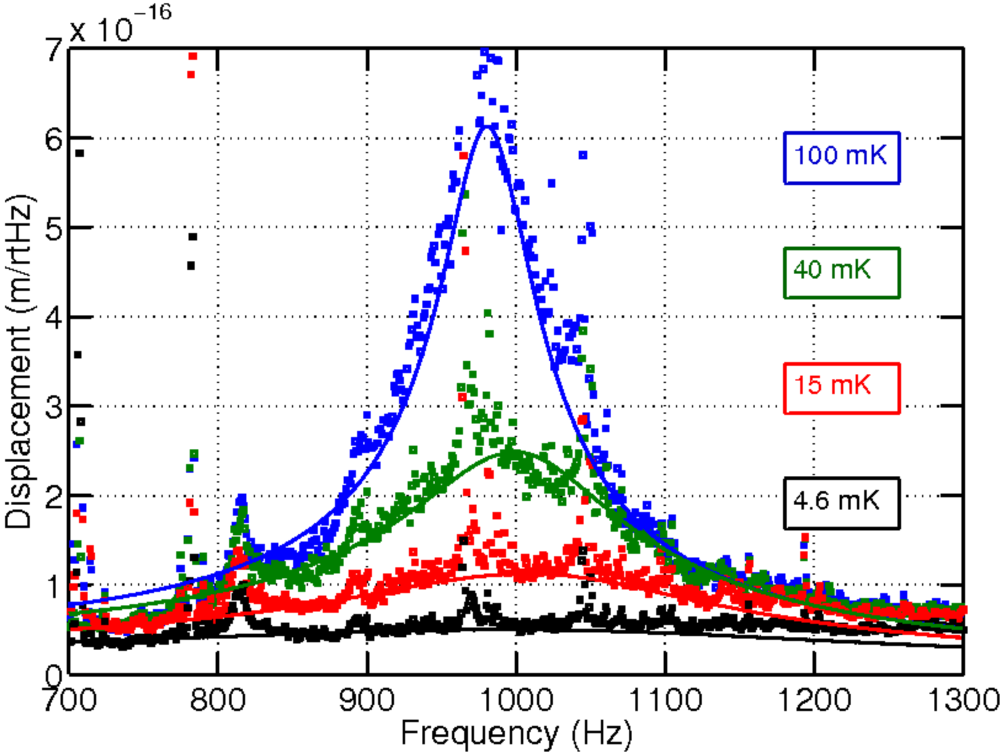
T = 12.2 K

T = 3.8 K

T = 0.8 K

Better cooling

- Reduce frequency noise coupling – reduced cavity length by factor of 10.
- Also reduced resonant frequency of end mirror suspension to 13 Hz (from 172 Hz) to avoid thermal noise.
- Shorter cavity length makes use of subcarrier more difficult because of large FSR.
- Feedback cooling.
- Shorter cavity length also makes 140 kHz drumhead mode of little mirror unstable – limited to relatively low power.
- Still laser noise limited.



Summary

- Radiation pressure effects observed and characterized
  - Optical spring
  - Parametric instability
  - Cooling
- Techniques for future experiments explored
  - Damping of extremely unstable OS
  - Control system interaction with OS and PI
- Cooled single mode of mechanical oscillator to 5 mK.
- Interferometer built and installed – waiting for vacuum to begin operation, but cavities have already been locked in air at low power
  - Quantum limited radiation pressure and ponderomotive squeezing soon?
  - Temperature reductions of 100 to 1,000 times larger than observed so far are expected, due to rejection of laser noise. Thermal occupation number of oscillator should be about 100. Quantum behavior of the 1 gram mirror soon?