Radiation Pressure Dominated Optomechanical Systems

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LIGO Seminar
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Outline

- Motivation
  - The role of radiation pressure in LIGO
  - Squeezing in interferometers
  - Probe of quantum mechanics
- Experiments
  - Parametric instabilities and optical springs
  - Control issues
  - Noise issues
  - Cooling
- Looking ahead
  - Quantum radiation pressure noise, the Standard Quantum Limit and beyond

Radiation pressure in (Advanced) LIGO

- Higher power used to reduce shot noise
- Leads to quantum radiation pressure noise, enforcing the Standard Quantum Limit (SQL)
- Dynamical effects
  - Angular and parametric instabilities
  - Optical spring
  - Control issues
- Effects are generally detrimental, except for optical spring, which allows the free mass SQL to be beat

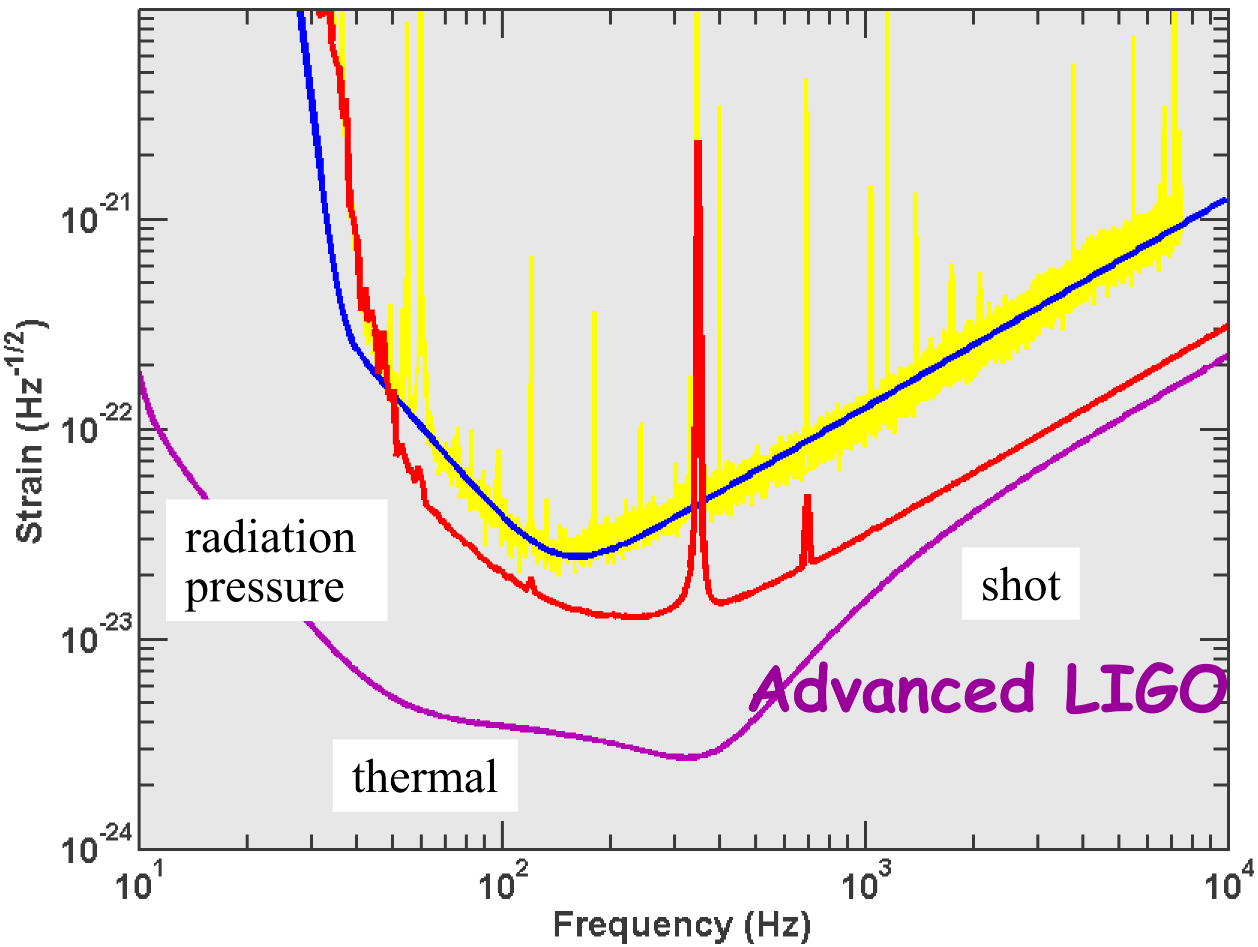
LIGO

Quantum noise and squeezing

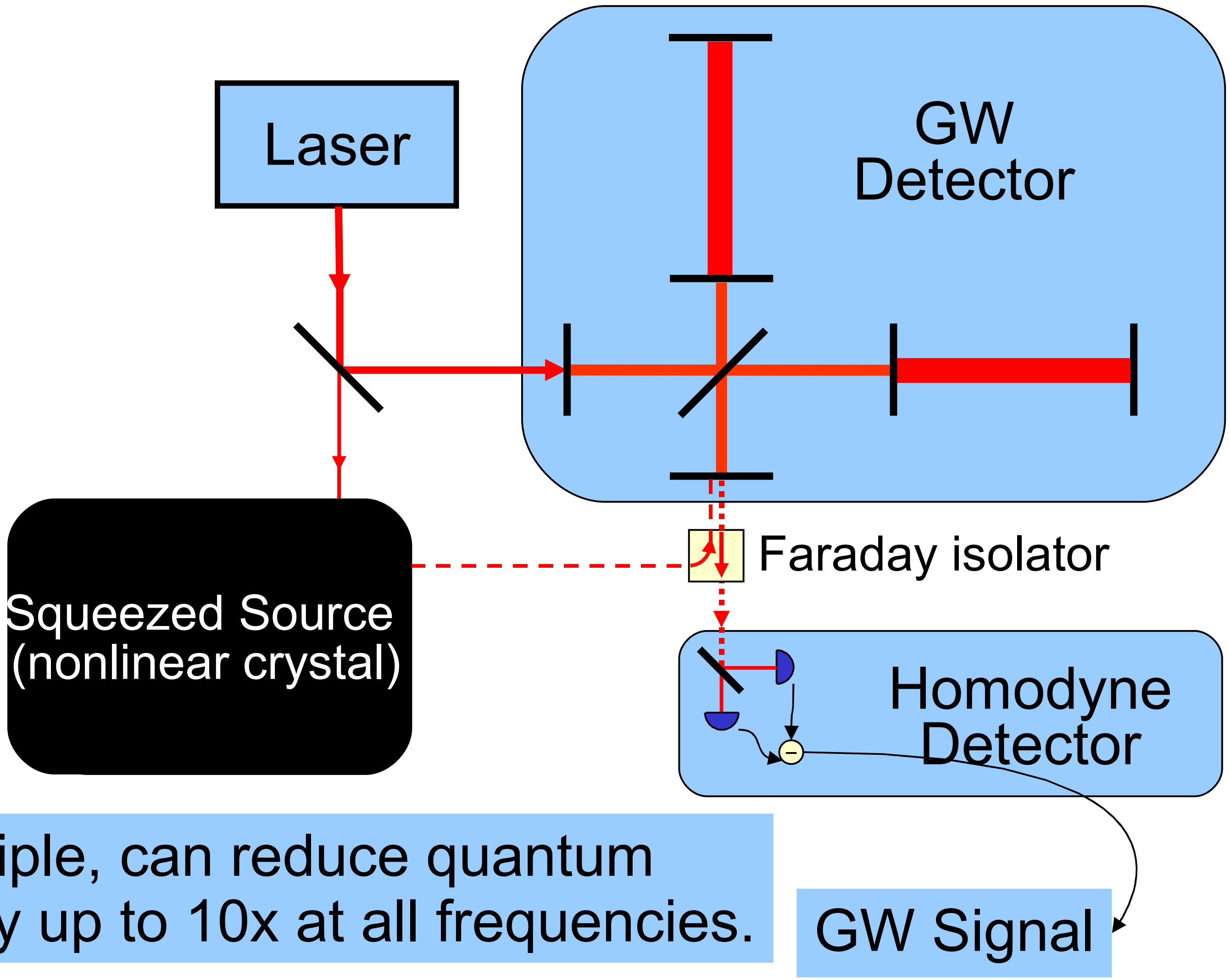
Input laser power
> 100 W

Circulating power
> 0.5 MW

Mirror mass
40 kg



"Input" squeezing – squeezing produced outside of IFO



In principle, can reduce quantum noise by up to 10x at all frequencies.

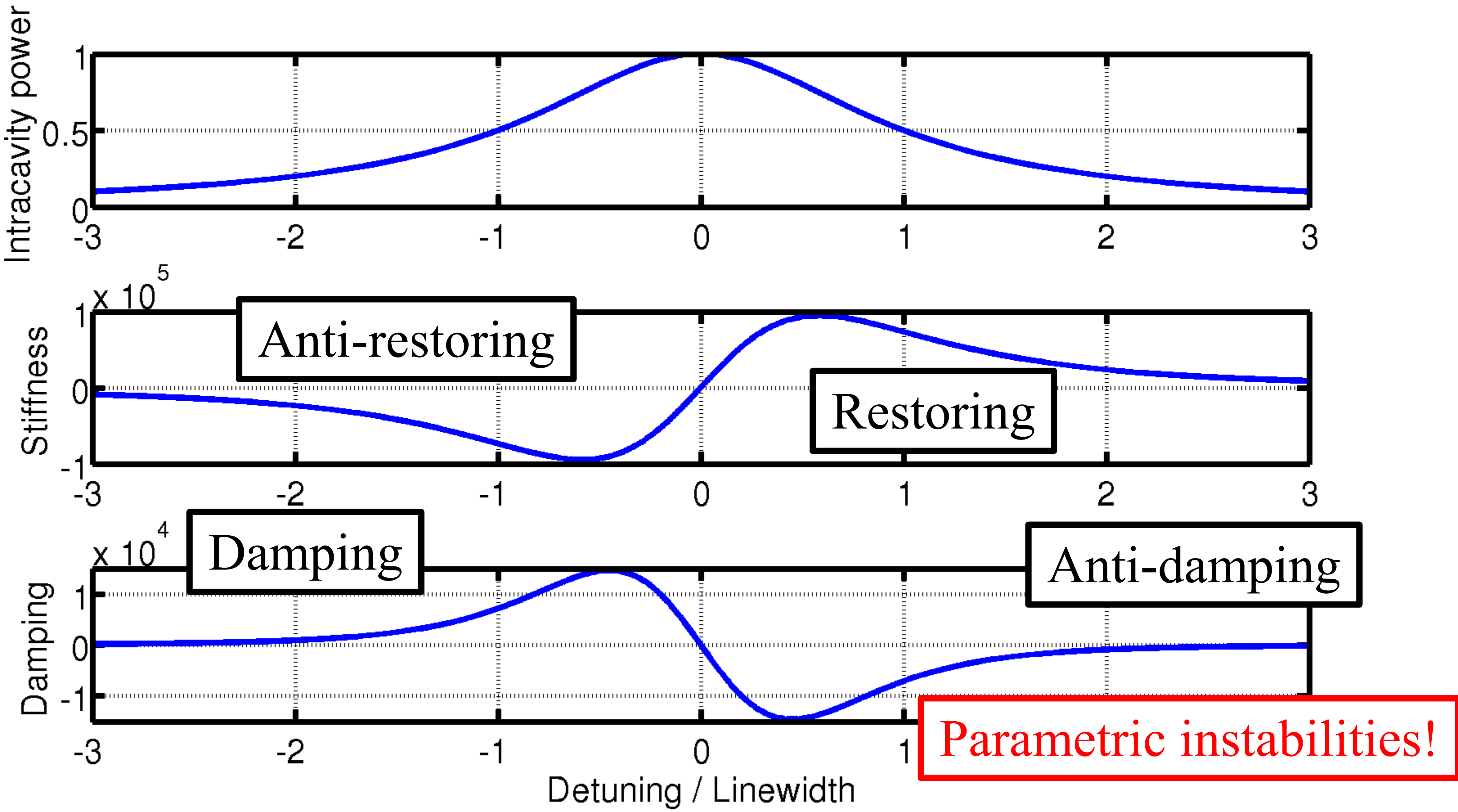
Ponderomotive squeezing

- An interferometer itself squeezes the light incident upon it:
  - Radiation pressure (intensity fluctuations) excite mirror motion.
  - Mirror motion is imposed onto the phase of the light reflected from the mirror.
- A pendular mass responds to forces with a frequency^{-2} dependence above its resonant frequency.
- We'd like a frequency independent response, so use a low-noise optical spring to boost the resonant frequency.

Optical springs

For a detuned cavity, the radiation pressure force is linearly dependent on the length of the cavity, giving a force proportional to the position of the mirror, analogous to a spring constant.

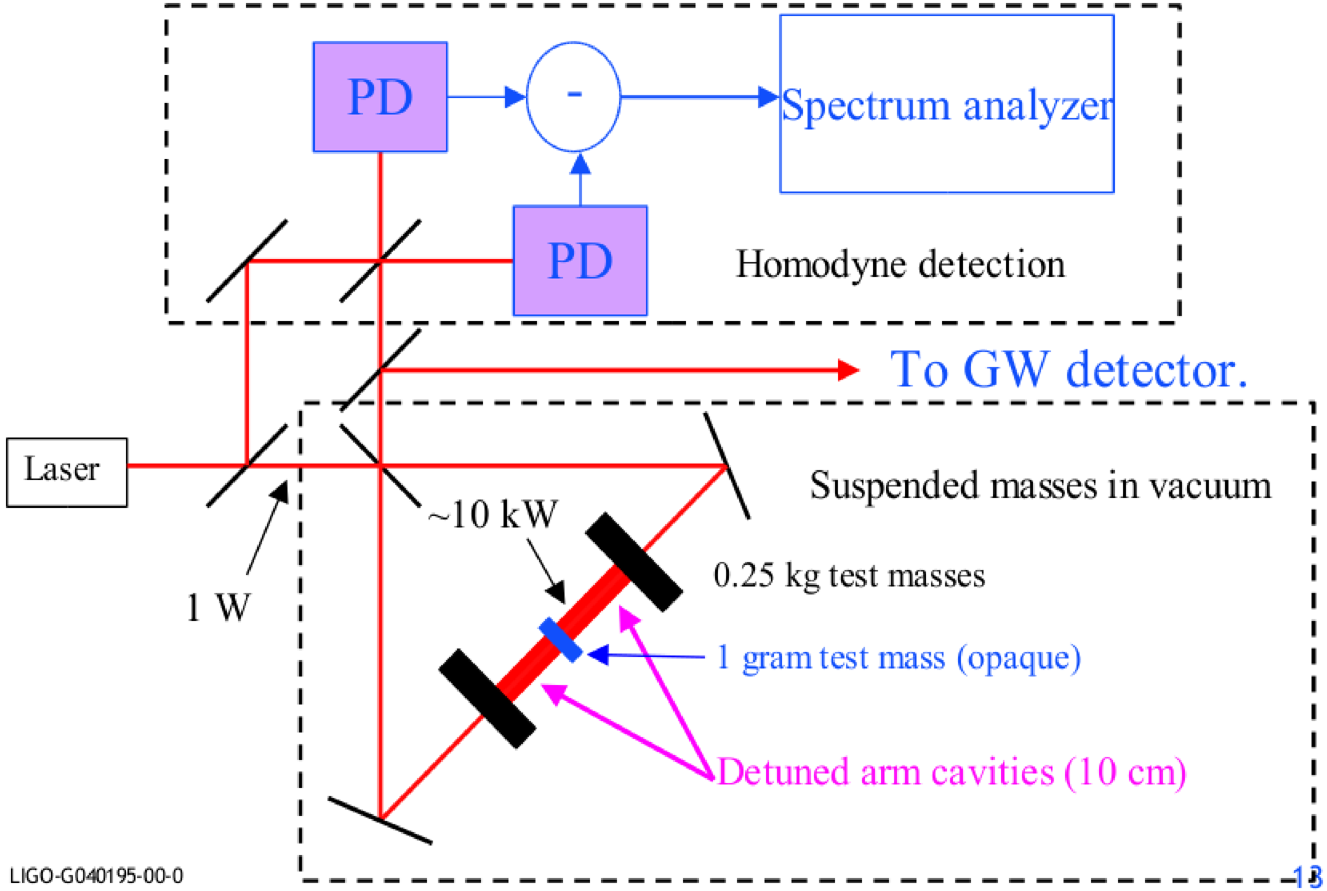
Due to the finite response time of the cavity, a force proportional to the velocity, a viscous damping force, is also formed. This makes the optical spring unstable and also creates parametric instabilities.

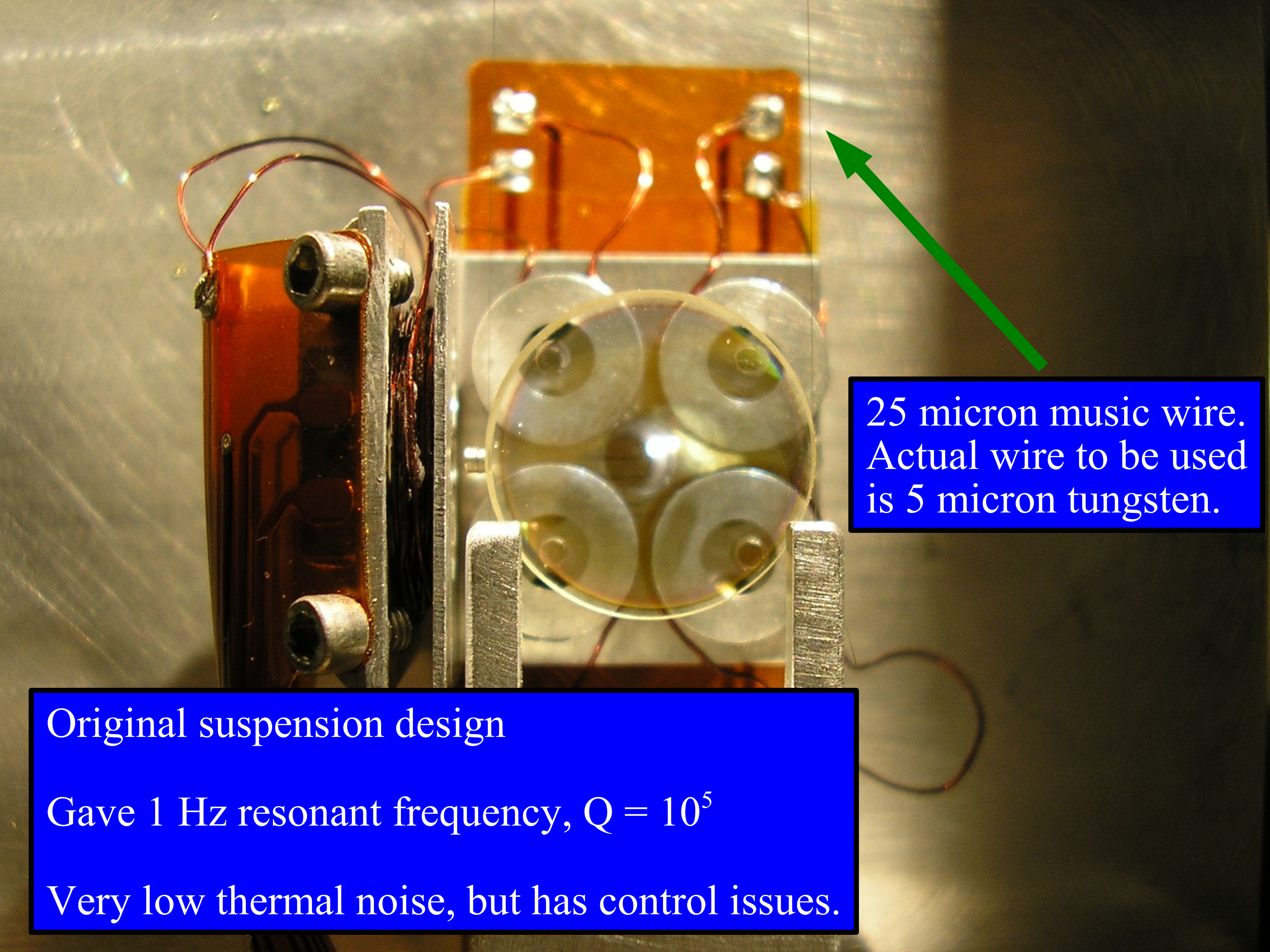


Our experiment

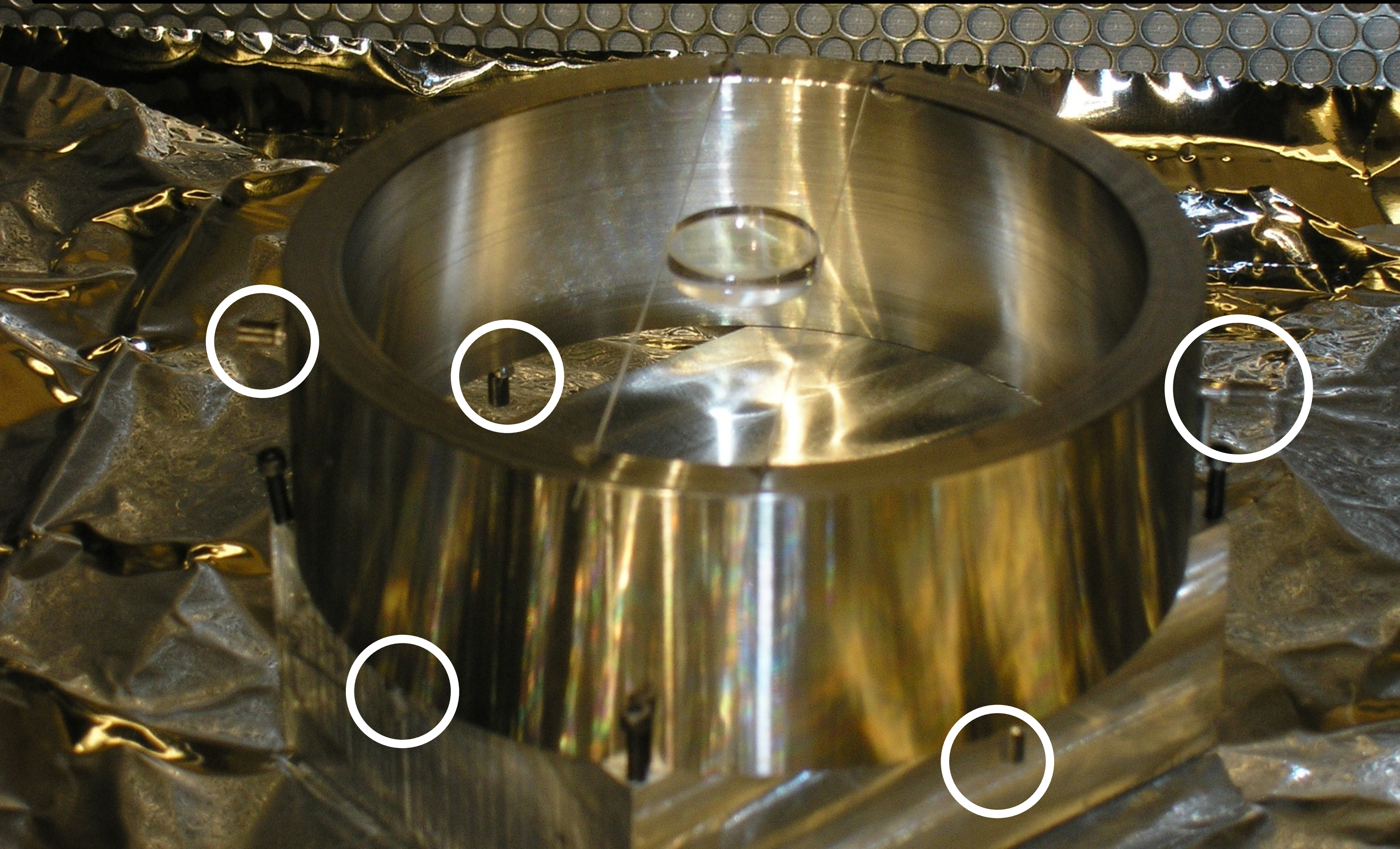
Designed to maximize RP effects, with goal of measuring ponderomotive squeezing.

Design shown here was presented at Caltech seminar nearly 4 years ago.




25 micron music wire. Actual wire to be used is 5 micron tungsten.
Original suspension design
Gave 1 Hz resonant frequency, Q = 10^5
Very low thermal noise, but has control issues.

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

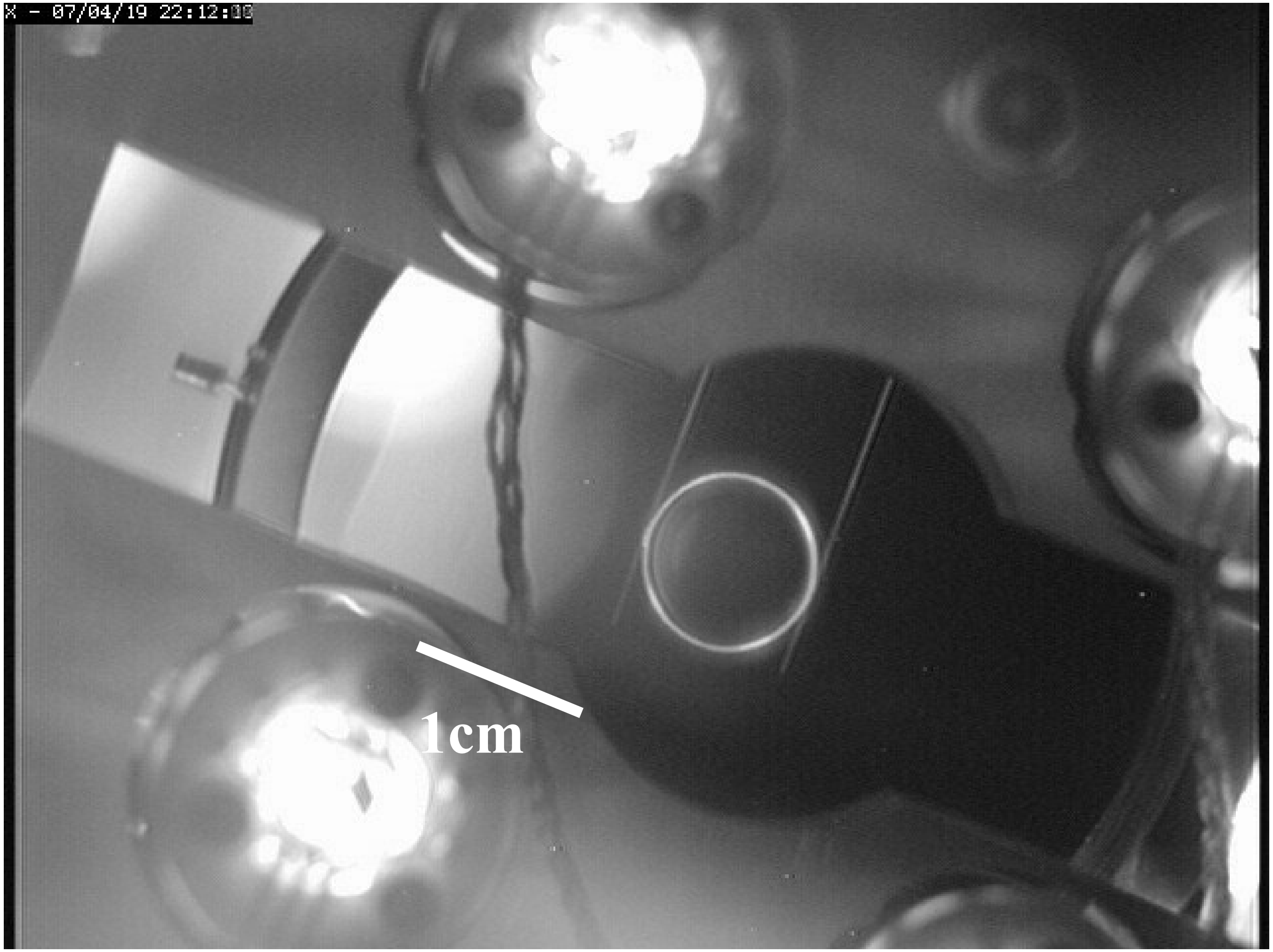


Easy suspension

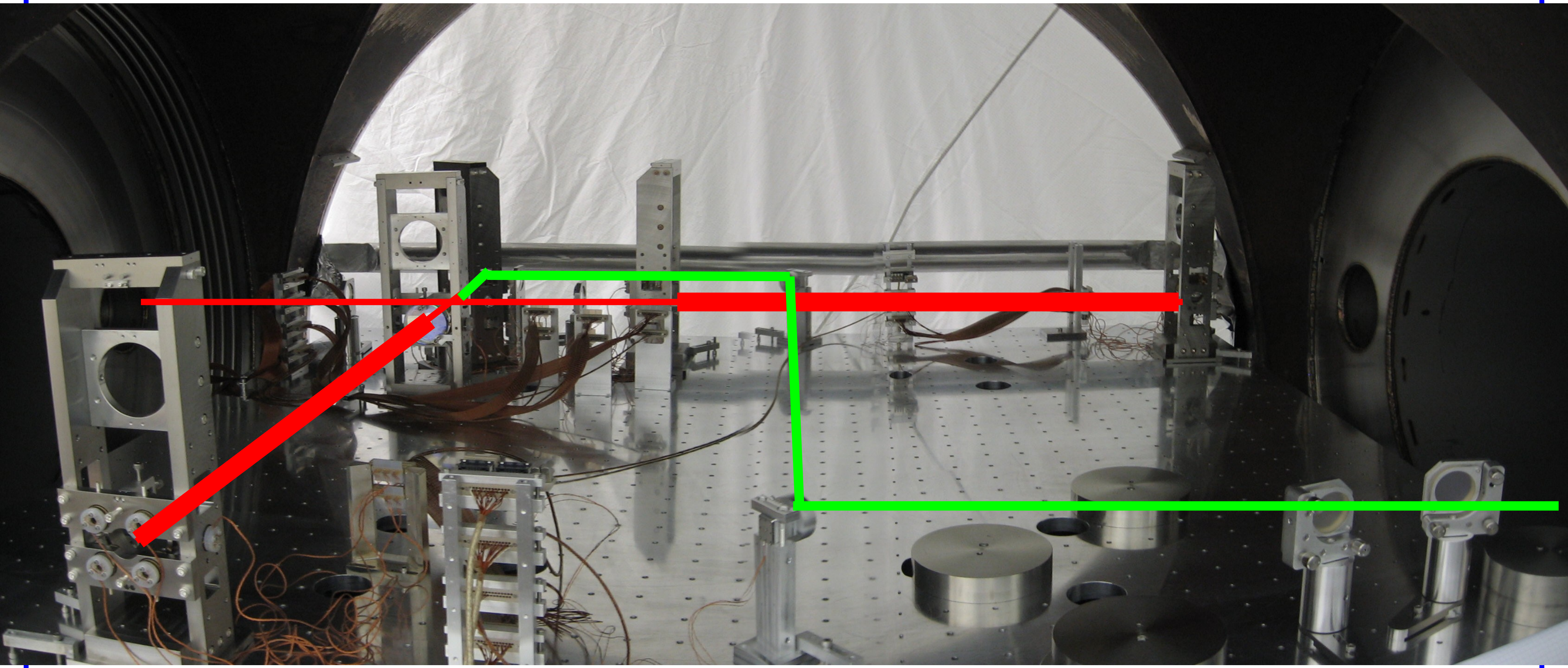
M ~ 1 g
f ~ 6.3 Hz
Q ~ $10^3 – 10^4$

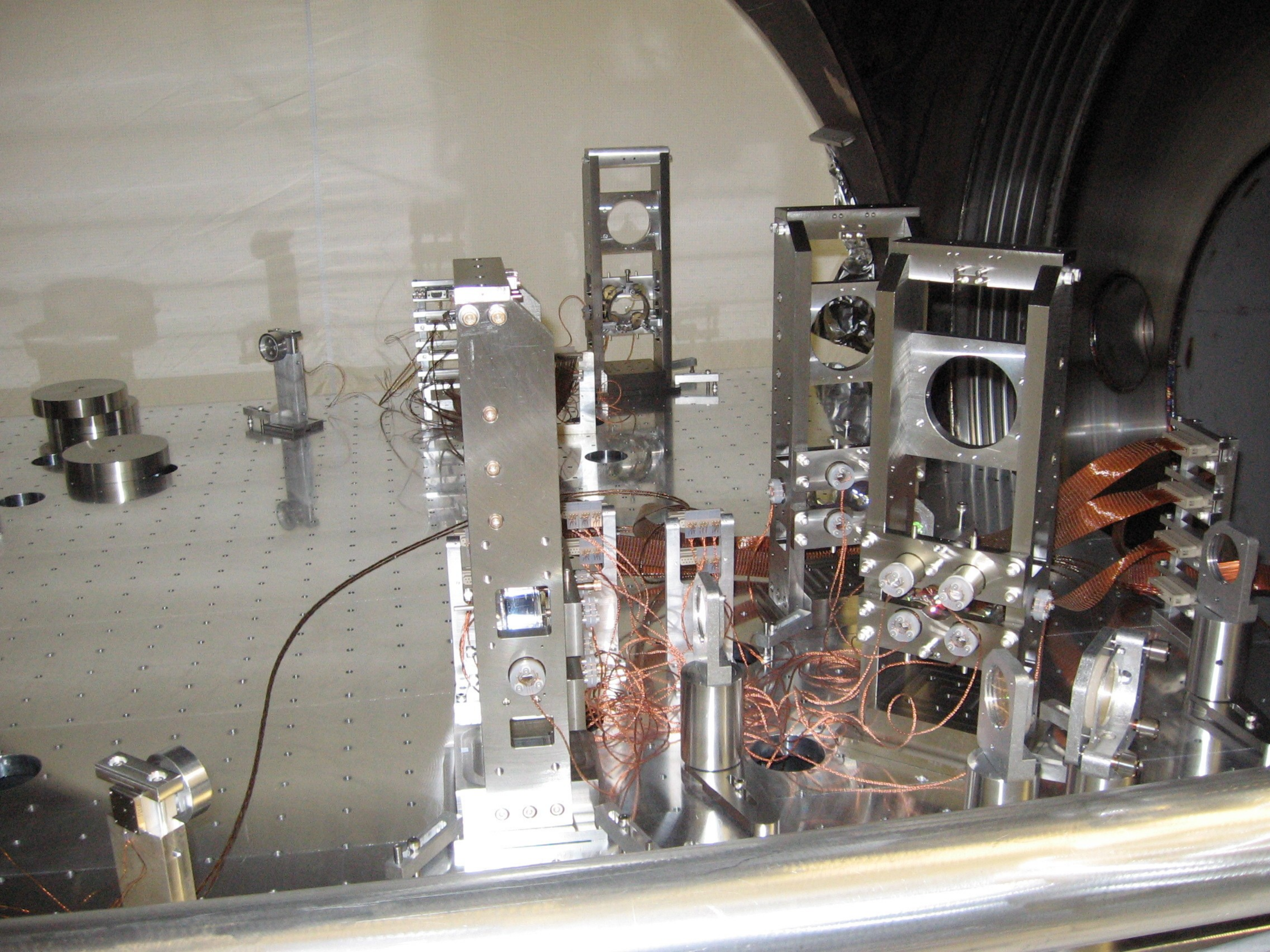
Poor thermal noise, but easy to construct and to control.

Uses LIGO-I OSEMs.



In vacuum components



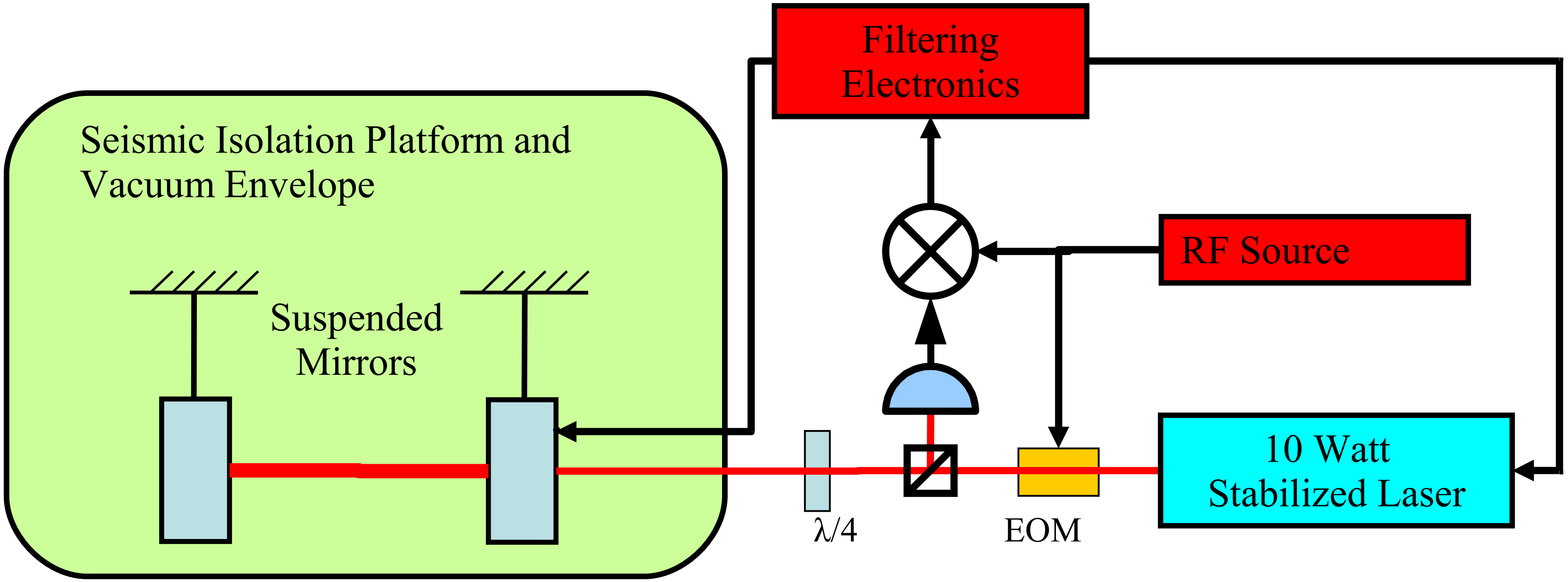


Phases of the experiment

	ETM Mass	ETM Freq	ETM Q	Finesse	Len
Single cavity					
Phase 1	250 g	1 Hz	??	1000	1 m
Phase 2	1 g	170 Hz	3000	8000	1 m
Phase 2.5	1 g	12.7 Hz	20000	8000	0.1 m
Interferometer (current setup)					
Phase 3	1 g	6.3 Hz	~10000	8000	1 m
In the near future...					
Phase 4	1 g	6.3 Hz	10^6	8000	1 m

Phase I Experiment

250 gram mirrors, finesse is 1000.



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

Parametric instability

- **Optical forces couple can couple to every mode of the mirrors, not just the bulk pendular motion.**
  - Drumhead motion of mirror couples most strongly to the light, due to the overlap of the optical beam with the structure of the mode.
  - The mechanical stiffness of these modes is much larger than the optical spring stiffness.
  - However, the modes are very high Q ($\sim 10^6$), so the optical damping is important.
  - Expected to be major problem in Advanced LIGO.
  - Different from 3 mode PI – see talk tomorrow by David Blair.

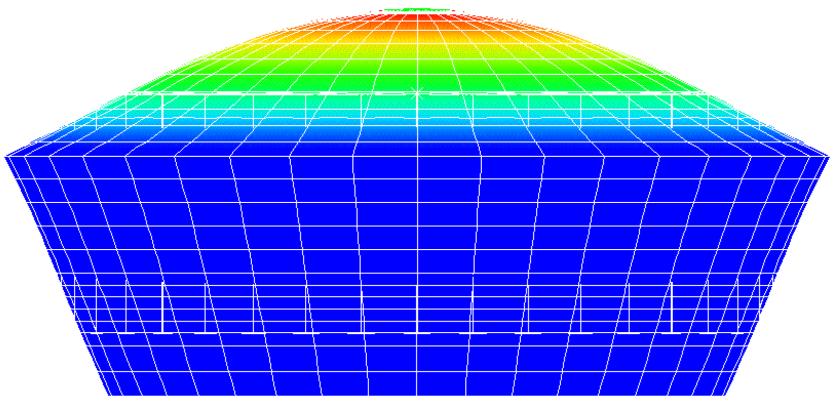


Image from Dennis Coyne

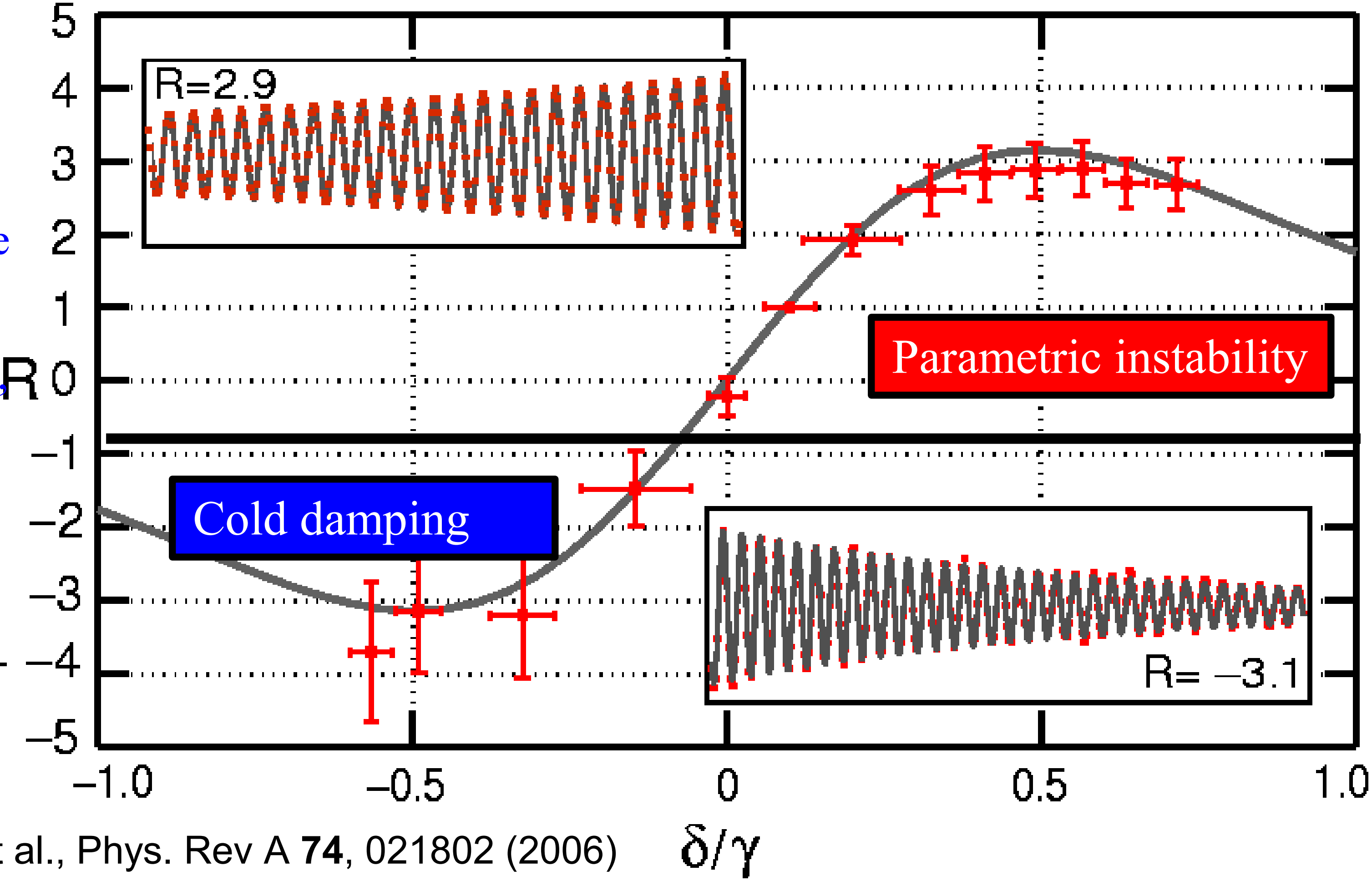
Parametric instability observed and damped! (Phase 1)

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.

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



T. Corbitt et al., Phys. Rev A **74**, 021802 (2006)

Parametric instabilities

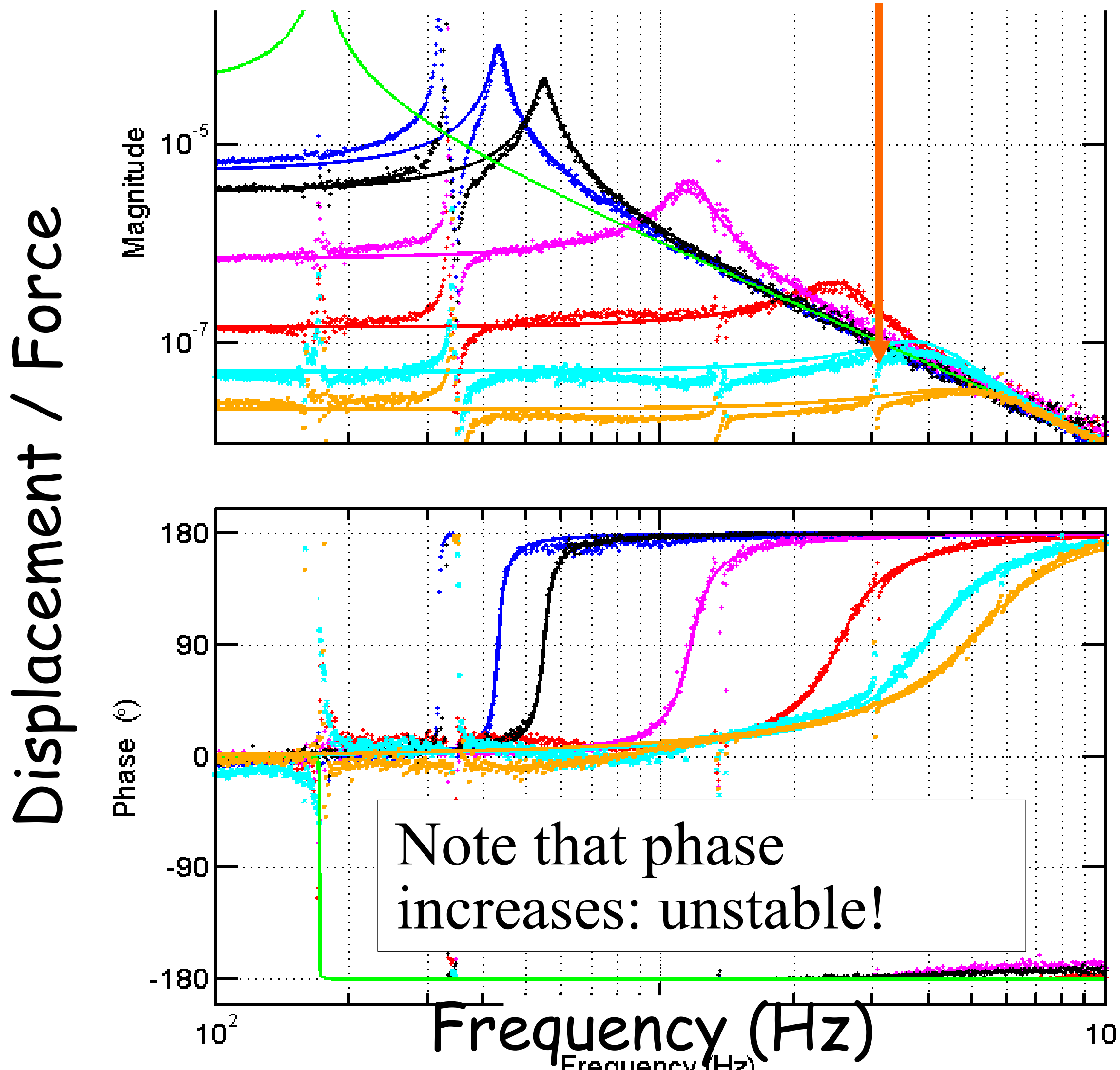
- We've seen PIs in every phase of the experiment, sometimes in several modes.
- With the 0.1 meter cavity, the 140 kHz drumhead mode of the 1 gram mirror would become unstable with ~150 mW of input power.
- Currently, we actively damp the 28 kHz drumhead modes of the ITMs by active feedback to the magnets. (Digital feedback using aliased/imaged signals)

Extreme optical stiffness… (Phase 2)

- 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

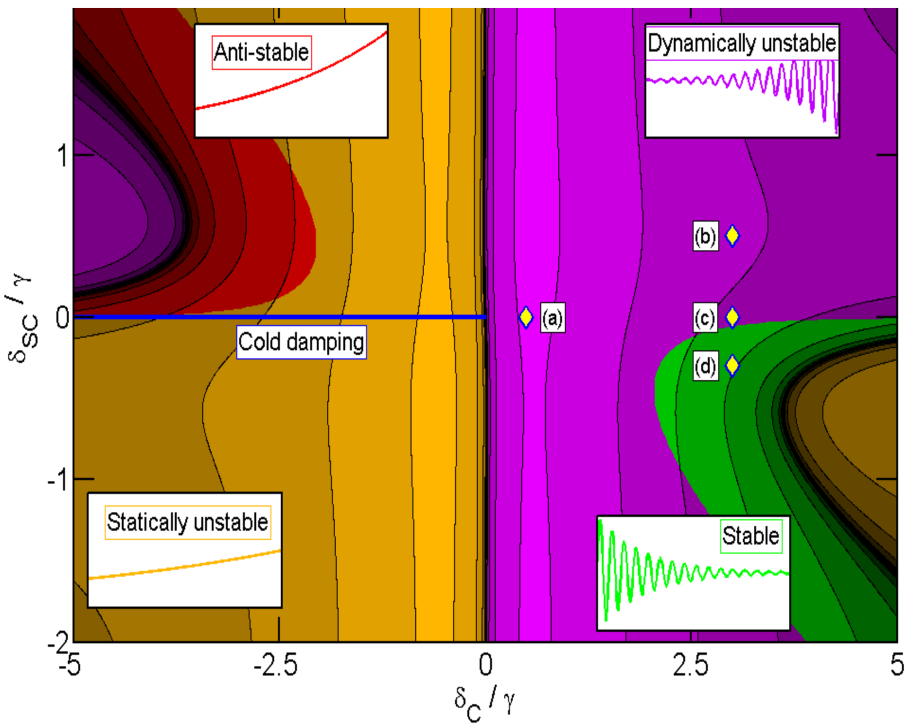
5 kHz ➔K = 2 x 10^6 N/m

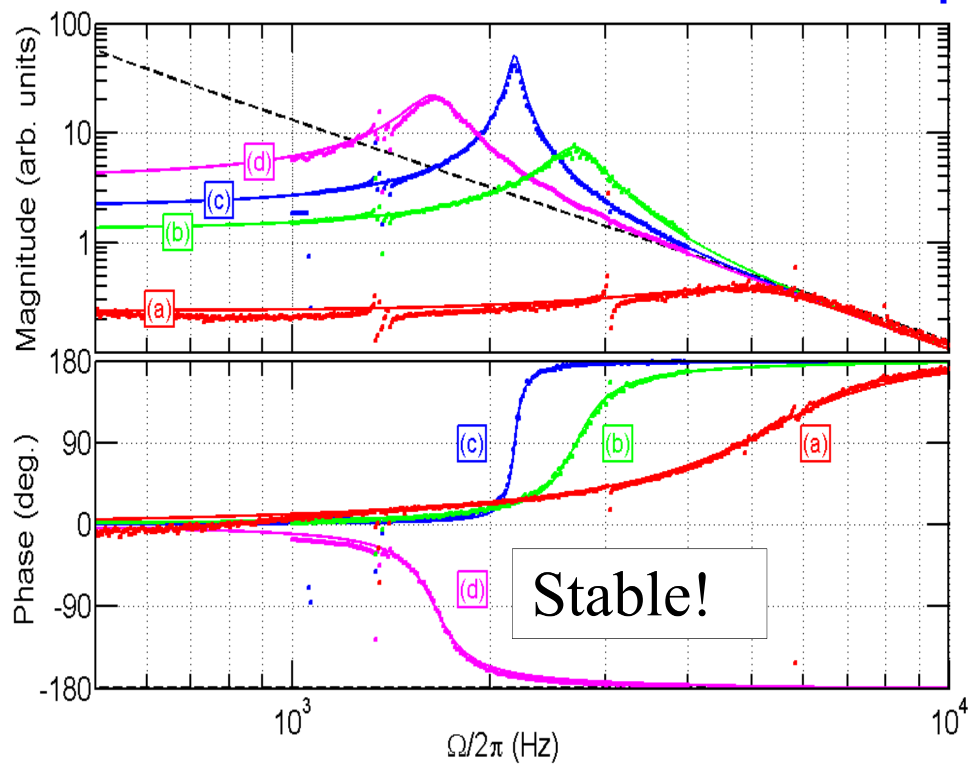
Cavity optical mode → diamond rod



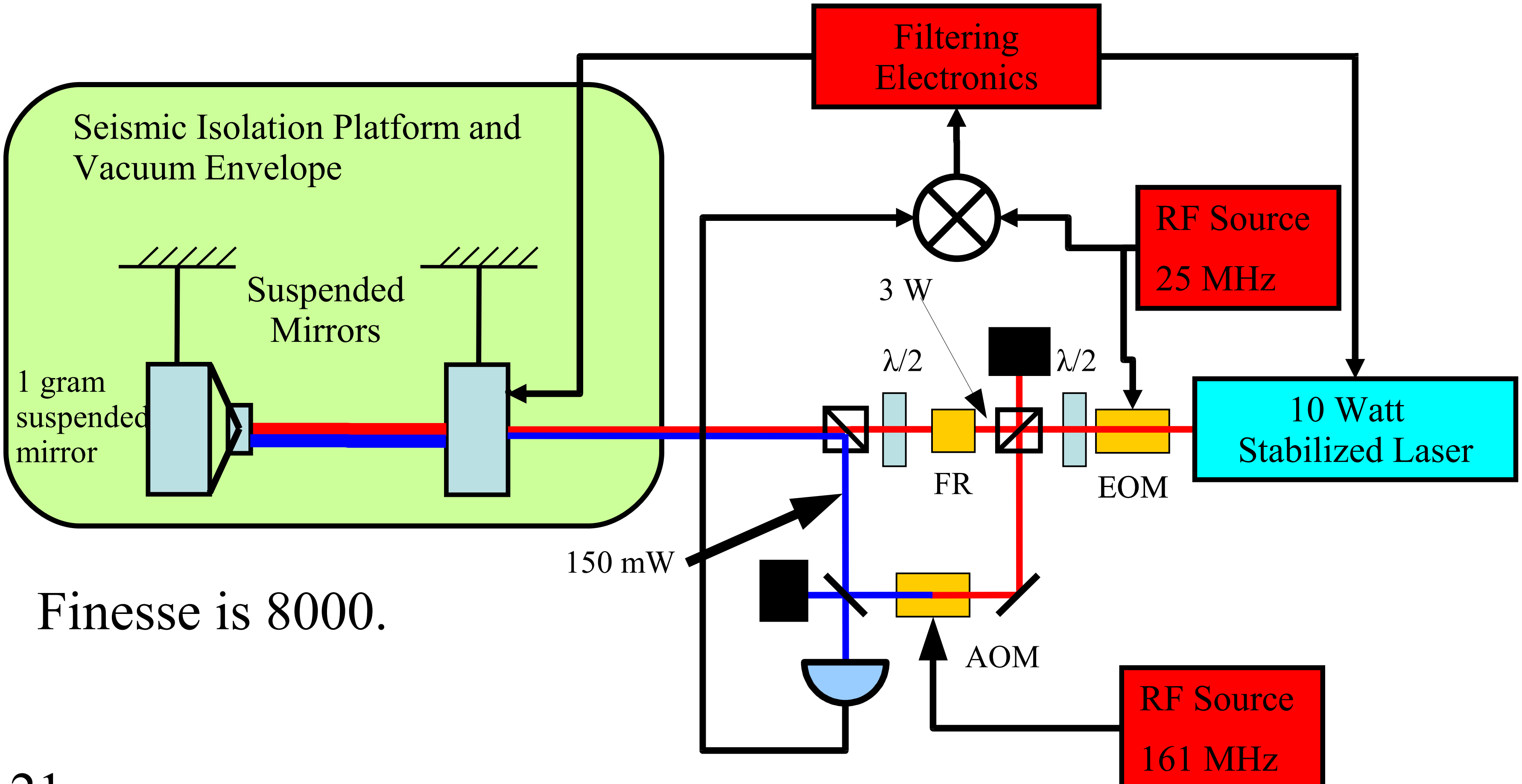
Double optical spring

- With different detunings, the two fields respond with different time constants, since they are more/less resonant in the cavity.
- Carrier creates optical spring, subcarrier creates optical damping.
- $P_C / P_{SC} = 20$
- When operating in stable regime, electronic feedback that damps OS may be turned off.
- Phys. Rev. Lett. 98, 150802 (2007)





Phase II Experiment



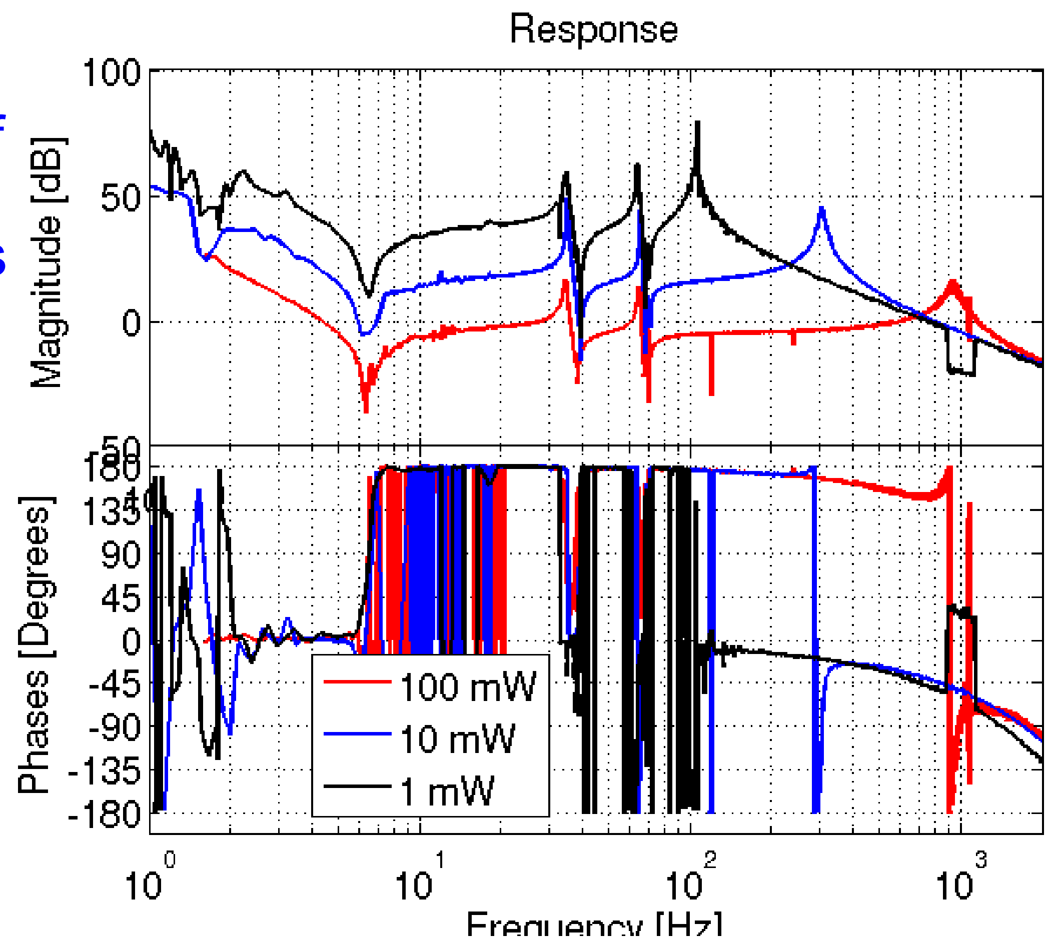
Finesse is 8000.

Control-free optical springs

- Double optical spring is stable, but low frequency motion could still disturb the resonance condition of the cavity.
- The optical spring suppresses motion below the mechanical resonant frequency by the ratio of the optical spring frequency to the mechanical frequency squared.
- If this ratio is sufficiently large, the cavity should self-lock without the need for any control!
- This was first seen by Dorsel et al., Phys. Rev. Lett. 51, 1550 (1983), with single OS.

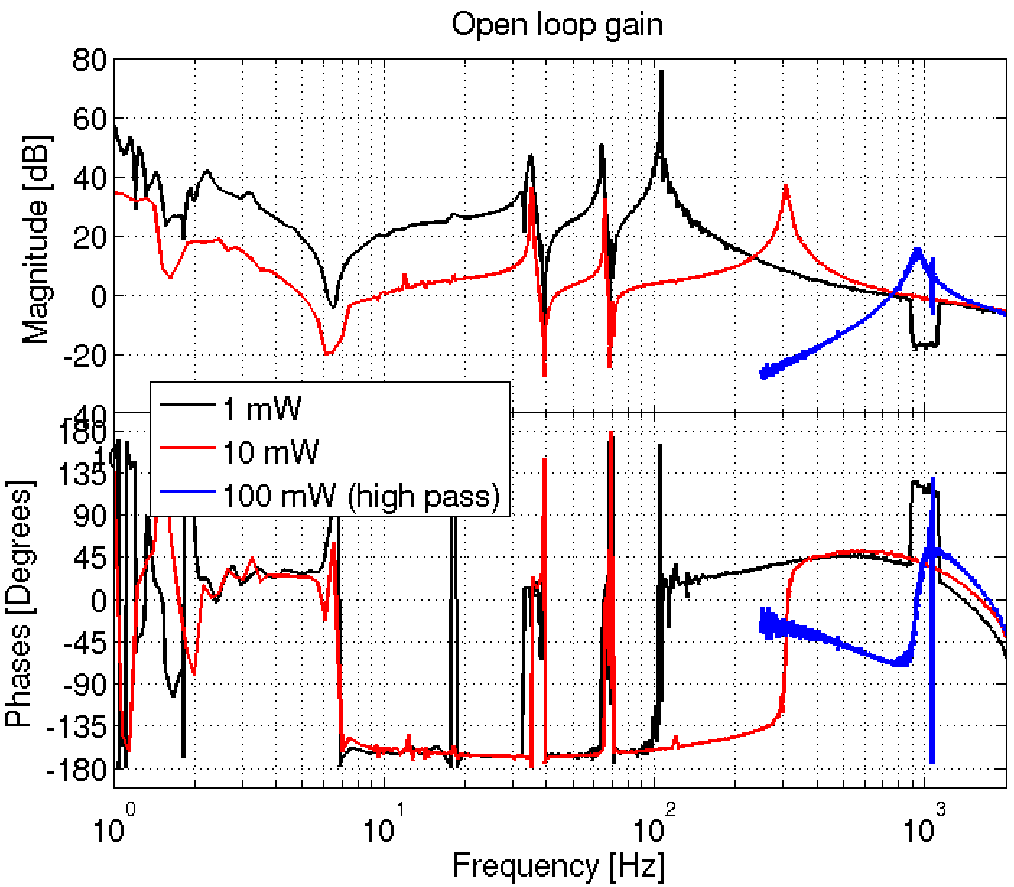
Advantages to no control (Phase 3)

- Coupling to other degrees of freedom of the end mirrors creates sharp notches in the optical response.
- These notches place requirements on the servo system used to hold the cavity on resonance, which limits the gain, and can lead to stability issues.
- Not having to use control at all eases many issues.



Almost control-free (Phase 3)

- At 1 and 10 mW input powers, we need a control system with large DC gain to hold the system on resonance.
- At 100 mW, we're able to AC-couple the feedback (with a 100 Hz high pass filter), and the system may behave freely.
- If we added a second optical field to stabilize the OS, we could be completely control-free.



A note about noise with optical springs

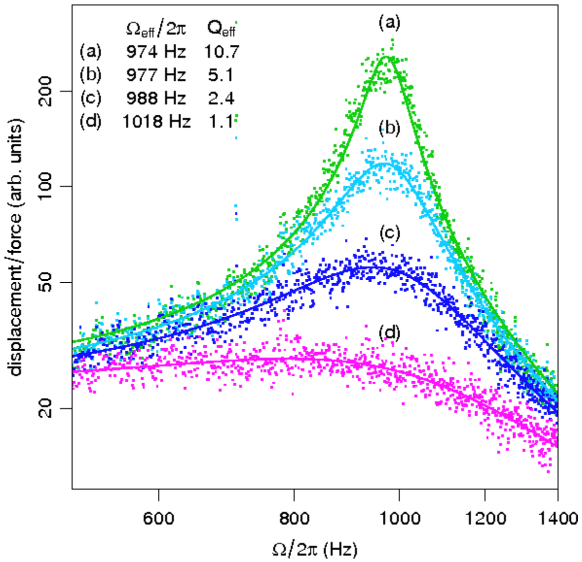
- Optical springs reduce the optical response of the system below their resonant frequency.
- Any noise sources that enter outside of the cavity (scattered light, electronics noise, acoustics, etc...) appears to be much larger than in the absence of the OS.
- For example, at 100 Hz, a 5 kHz optical spring reduces the optical gain by 2500.
- Could be relevant for Adv. LIGO.

Reaching the quantum limit in oscillators

- The goal is to measure non-classical effects, and thereby probe quantum mechanics with large test masses.
- One figure of merit for the "quantumness" of these systems is the thermal occupation number.
- Thermal energy should be close to one quantum of energy, $k_b T \sim \hbar\omega$.
- For ω=1 kHz, T ~ 50 nK (typical large object)
- For ω=10 MHz, T ~ 0.5 mK (typical small object)
- Cooling needed!

Cooling from damping

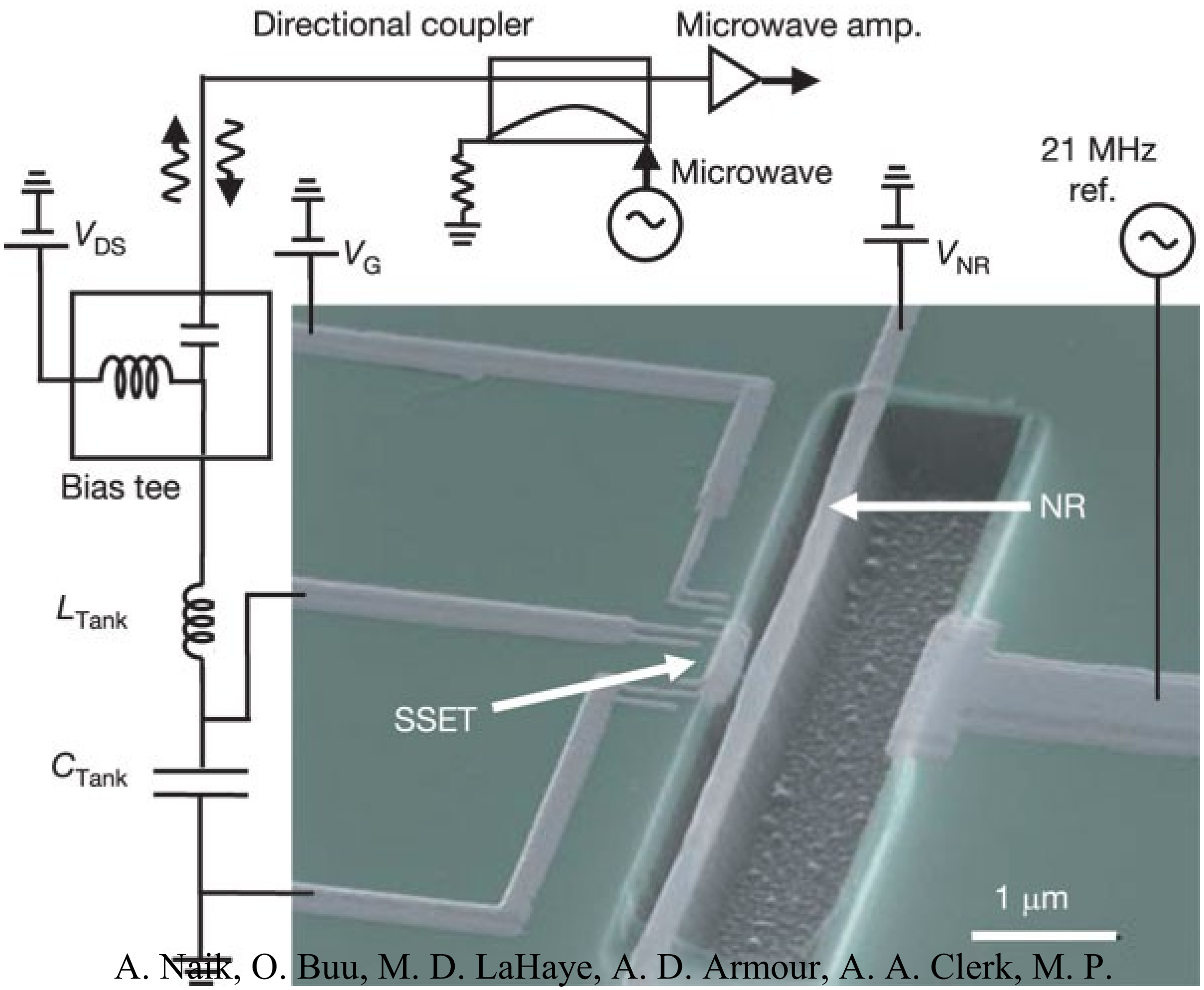
- Cold damping scheme:
  - Mancini et al.,
    Phys. Rev. Lett. 80, 688
  - Detect position of oscillator.
  - Differentiate signal.
  - Feed the velocity back
    as a force on the oscillator.



- This scheme removes energy from the oscillator, thereby lowering its temperature.
- This may be accomplished by an active feedback loop, or passively through radiation pressure in a detuned cavity.
- Does NOT increase signal to noise ratio – useless for GW detectors.

NEMS

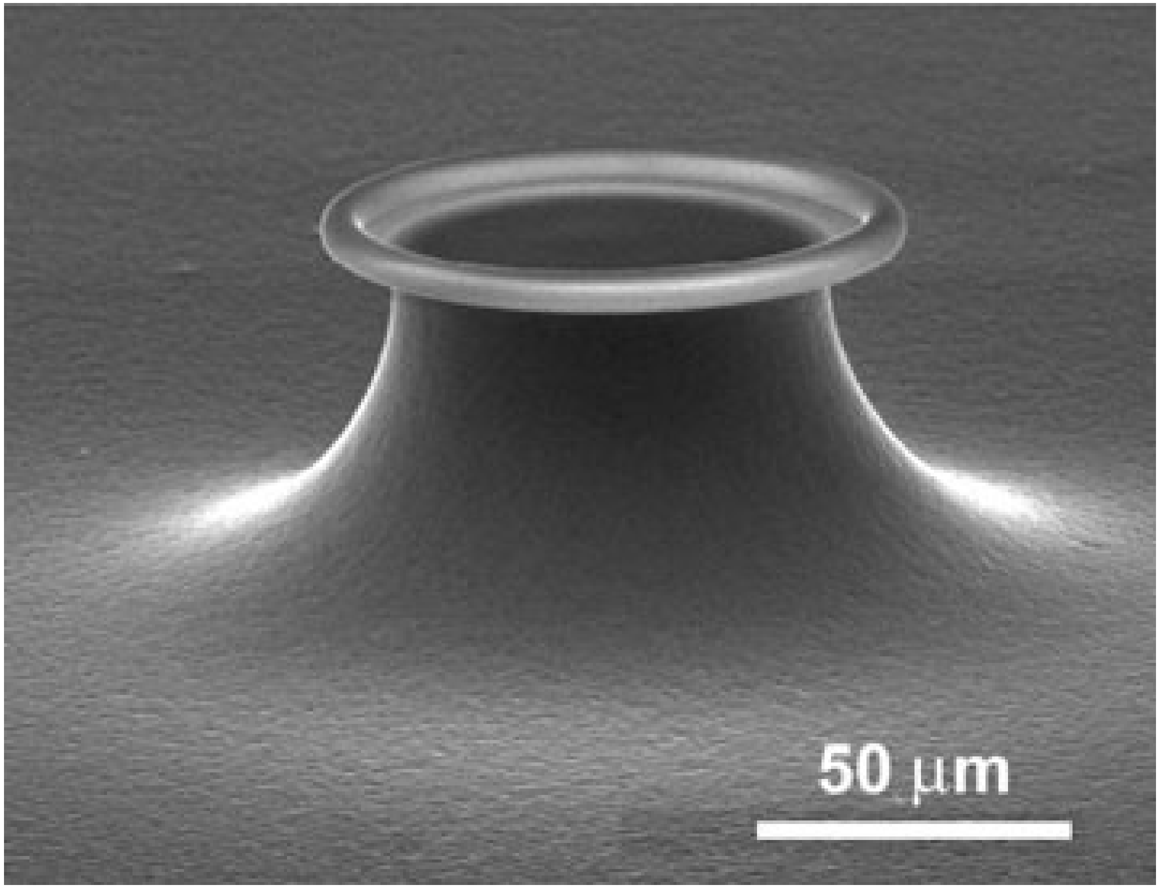
M ~ 1 pg
~ 10^{10} atoms
f ~ 25 MHz



A. Naik, O. Buu, M. D. LaHaye, A. D. Armour, A. A. Clerk, M. P. Blencowe and K. C. Schwab
Nature 443, 193-196(14 September 2006)

Toroidial microcavities

M ~ 15 ng
~ 10^{14} atoms
f ~ 50 MHz

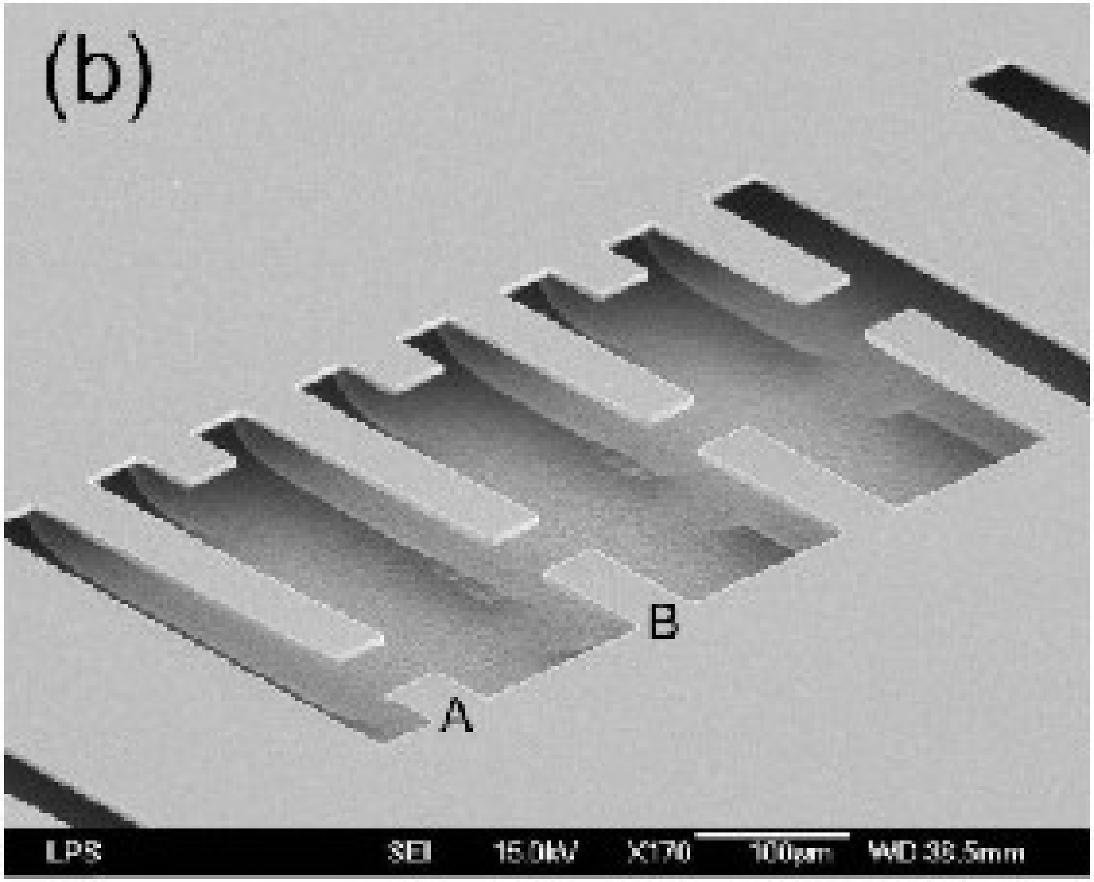


A. Schließer, P. Del'Haye, N. Nooshi, K. J. Vahala and T. J. Kippenberg
Physical Review Letters 97, 243905 (December 2006)

LIGO

Micromirrors

M ~ 100ng
~ 10^{15} atoms
f ~ 500 kHz



Simon Groblacher, Sylvain Gigan, Hannes R. Bohm, Anton Zeilinger, and Markus Aspelmeyer, arXiv:0705.1149

Limits to cooling

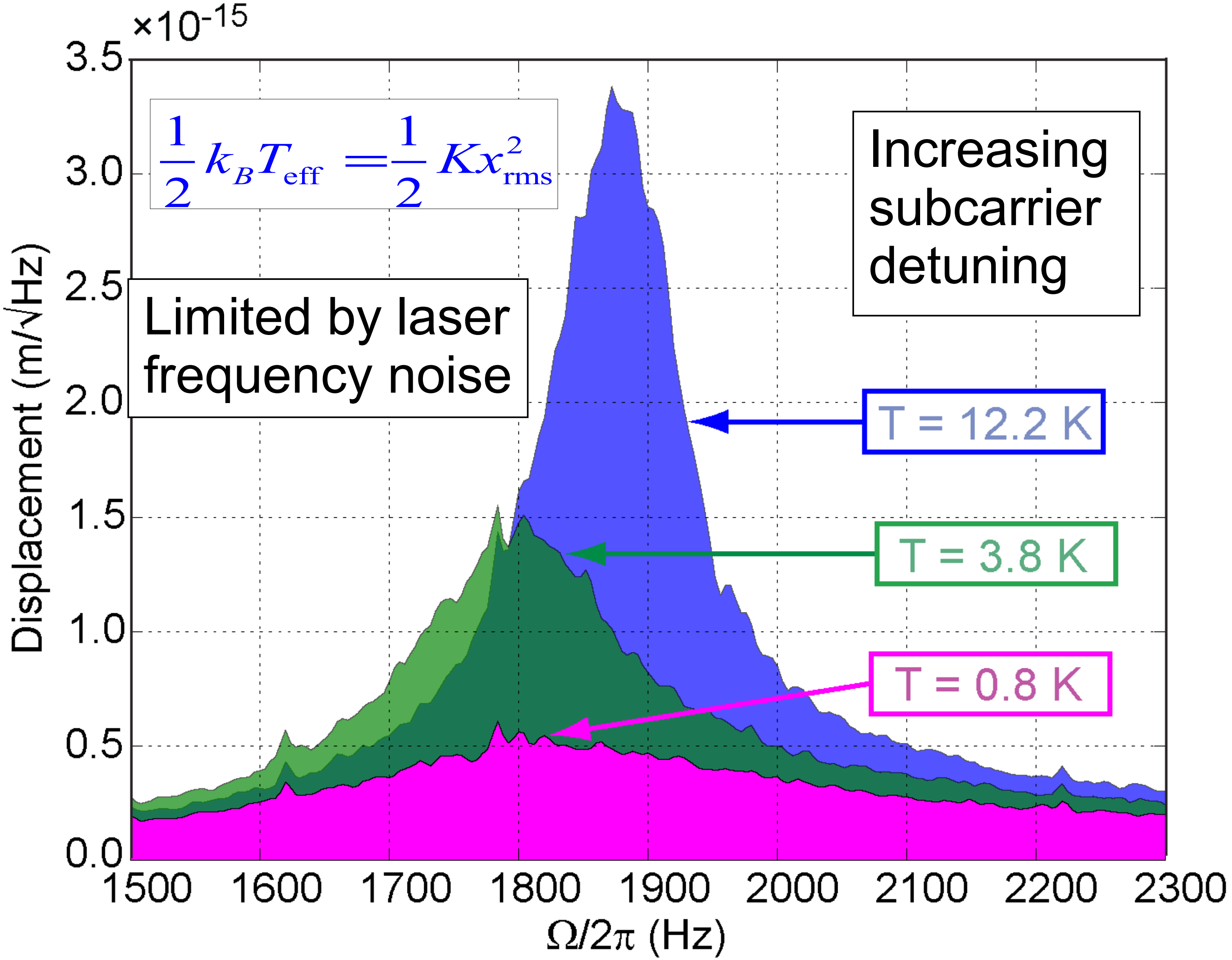
- The limit of cooling arises from the quality factor of the oscillator being cooled. Once the oscillator is critically damped, it's not meaningful to cool it further.
- This implies that to reach the ground state, starting from room temperature, we need a quality factor of:
  - 10^6 for 10 MHz
  - 10^{10} for 1 kHz

LIGO

Making ultra-high Q oscillators

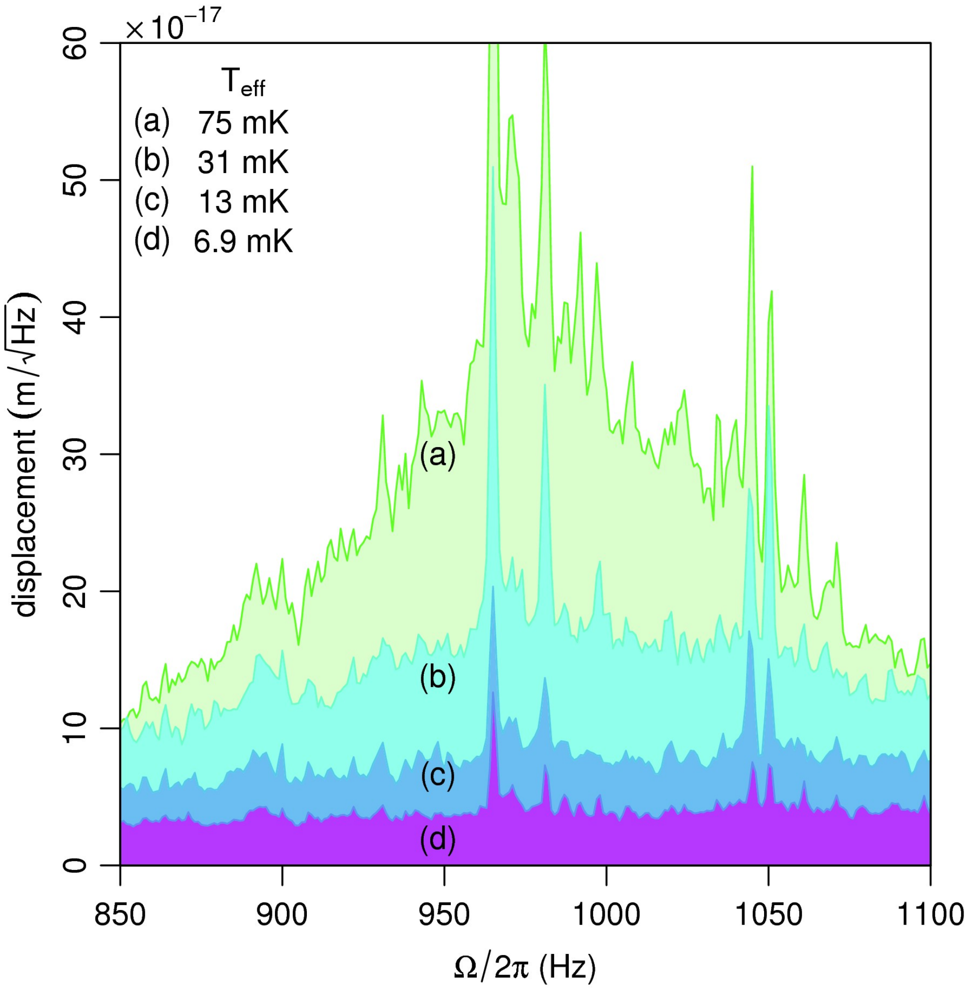
- The quality factor (=resonant frequency / damping rate) is typically limited by internal friction in the material of the oscillator.
- We can make the damping rate very small by using a low frequency oscillator.
- Then, we just need a way to increase the resonant frequency without changing the damping rate. This may be done gravitationally (as with pendulums) or with an optical spring.
- We call this “dilution.”

Optical cooling with double optical spring (Phase 2)



Better cooling (Phase 2.5)

- 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, so use feedback cooling.
- Shorter cavity length also makes 140 kHz drumhead mode of little mirror unstable – limited to relatively low power.
- Only cooling result where the cooling factor is larger than the natural Q.



Phys. Rev. Lett. 99, 160801 (2007)

LIGO

Where are the experiments headed?

- MIT experiment:
  - Currently reducing technical noise (scattering, electronics,...).
  - We think we're close to being limited by thermal noise.
  - New monolithic fused silica suspensions to be installed in the coming months.
  - Next measurement: quantum radiation pressure noise.
    - Install squeezer at dark port and squeeze/anti-squeeze radiation pressure noise, and confirm how it relates to shot noise.
  - And someday: squeezing, entanglement.
- Distant future: quantum jumps (J. D. Thompson, B. M. Zwickl, A. M. Jayich, Florian Marquardt, S. M. Girvin, J. G. E. Harris, arXiv:0707.1724)