LIGO-G070200-00-R

Optical Cooling and Trapping of Macro-scale Objects

MIT
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Caltech
Bork, Heefner, Sigg, Whitcomb

AEI
Chen, Ebhardt-Mueller, Rehbein

LSC meeting, March 2007

Ponderomotive predominance

- An experimental apparatus in which radiation pressure forces dominate over mechanical forces
- Ultimate goals
  - Generation of squeezed states of light
  - Quantum ground state of the gram-scale mirror
  - Mirror-light entanglement
- En route
  - Optical cooling and trapping
  - Diamonds
  - Parametric instabilities
- Disclaimer
  - Any similarity to a gravitational wave interferometer is not merely coincidental. The name and appearance of lasers, mirrors, suspensions, sensors have been changed to protect the innocent.

Cooling and Trapping

Two forces are useful for reducing the motion of a particle

- A restoring force that brings the particle back to equilibrium if it tries to move
  - Position-dependent force → SPRING

TRAPPING

- A damping force that reduces the amplitude of oscillatory motion
  - Velocity-dependent force → VISCOUS DAMPING

COOLING

Mechanical forces

- Mechanical forces come with thermal noise

$$S_F \propto 4k_BT\frac{\Omega_m}{Q_m}$$

- Stiffer spring ($\Omega_m \uparrow$) → larger thermal noise
- More damping ($Q_m \downarrow$) → larger thermal noise

Optical forces

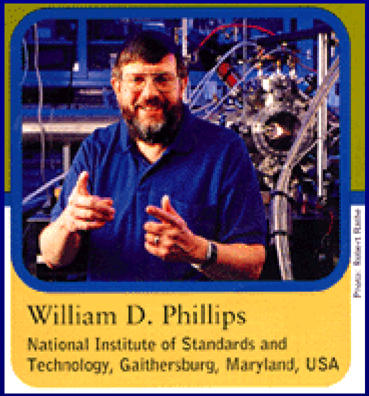
- Optical forces do not introduce thermal noise
- Laser cooling
  - Reduce the velocity spread
    Velocity-dependent viscous damping force
- Optical trapping
  - Confine spatially
    Position-dependent optical spring force

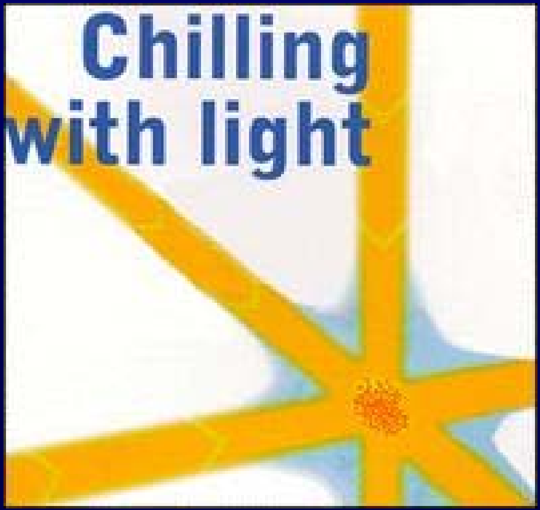
Cooling and trapping

- A whole host of tricks for atoms and ions (or a few million of them)
  - Magneto-Optic Traps (MOTs)
  - Optical molasses
  - Doppler cooling
  - Sisyphus cooling (optical pumping)
  - Sub-recoil limit
    - Velocity-selective coherent population trapping
    - Raman cooling
  - Evaporative cooling

1997 Nobel Prize in Physics

Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**
for their developments of methods to cool and trap atoms with laser light

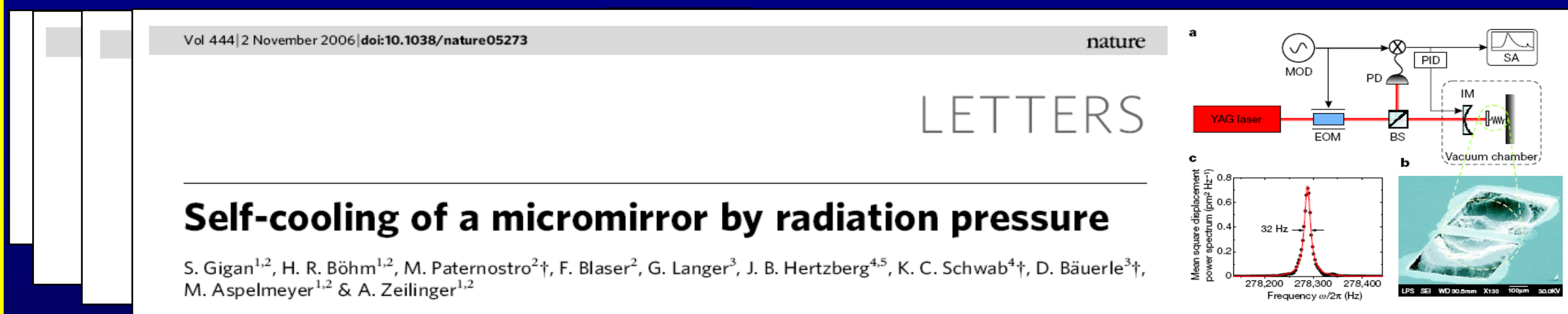




This year's Nobel laureates in physics have developed methods of cooling and trapping atoms by using laser light. Their research is helping us to study fundamental phenomena and measure important physical quantities with unprecedented precision.

What about bigger things?

- Cavity cooling (cold damping)
  - Use the time delay of light stored in an optical cavity to produce a velocity-dependent viscous damping force
  - Nano- and micro-mechanical oscillators


Vol 444 | 2 November 2006 | doi:10.1038/nature05273 nature

LETTERS

Self-cooling of a micromirror by radiation pressure

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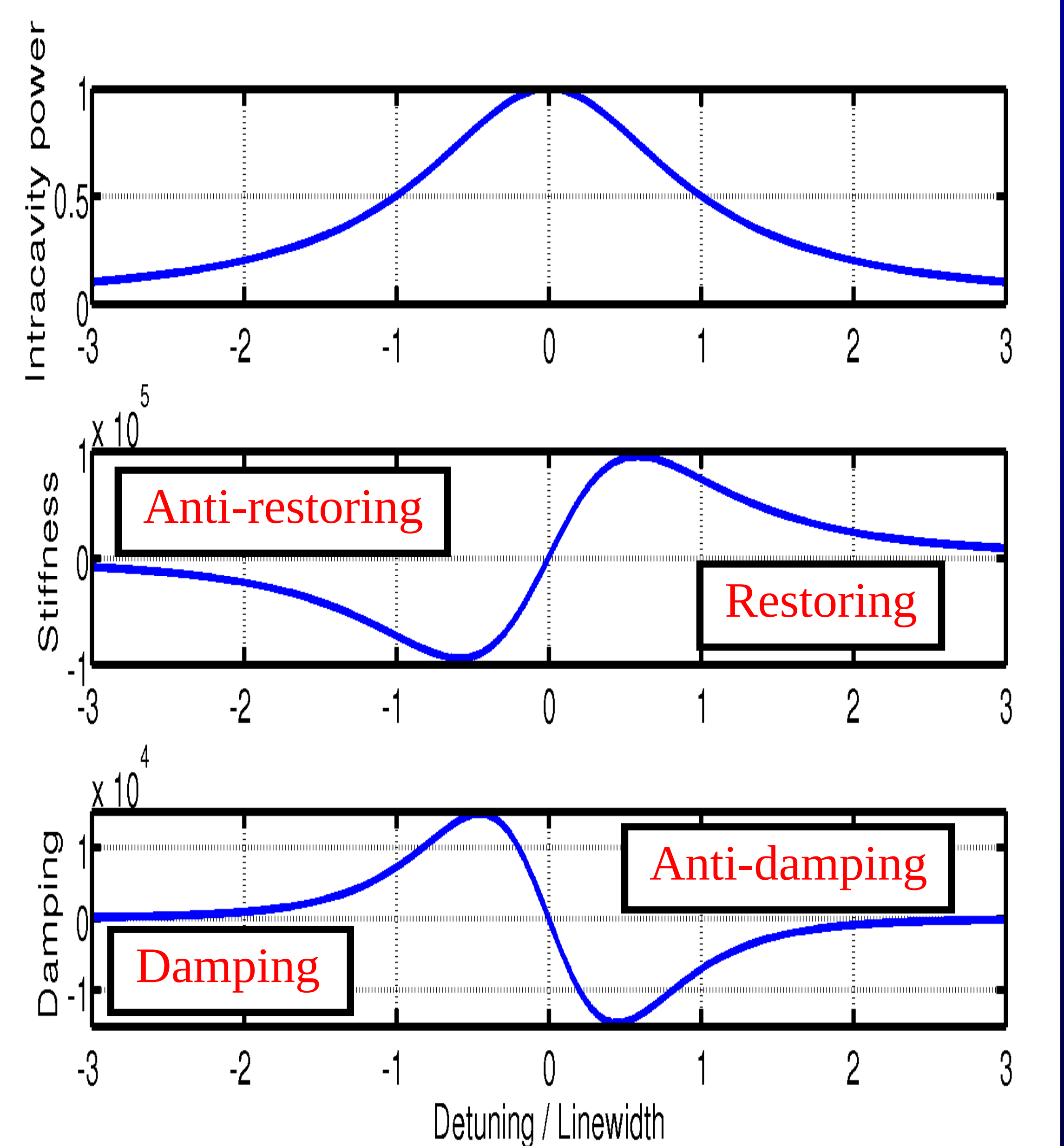
- Trapping requires a position-dependent force
  - Use the position-dependence of the intensity in an optical cavity → OPTICAL SPRING
  - Gram-scale objects

Optical springs and damping

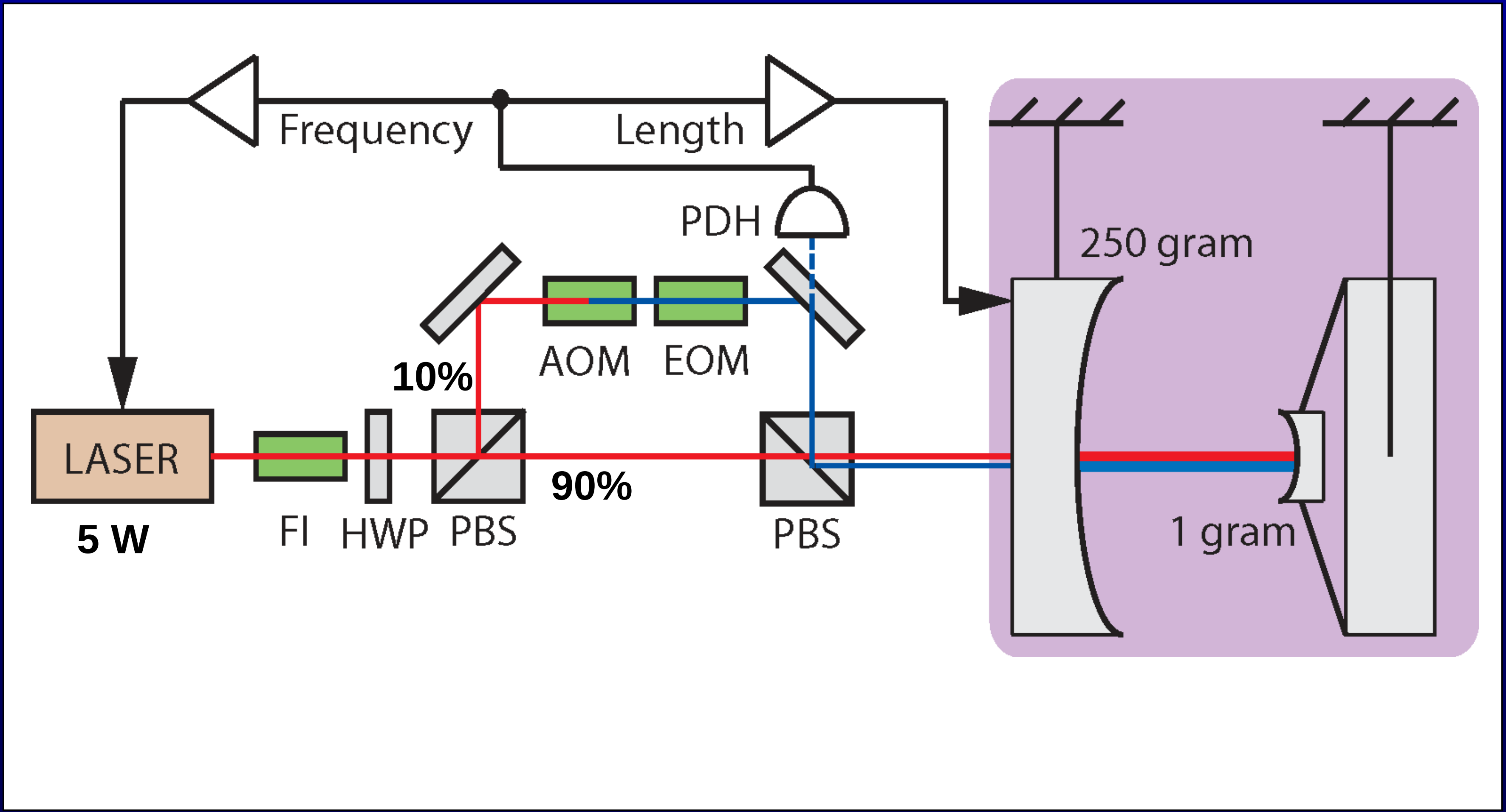
- Detune a resonant cavity to higher frequency (blueshift)
- Opposite detuning than cold damping
- Real component of optical force
  → restoring
- But imaginary component (cavity time delay)
  → anti-damping
- Unstable
- Stabilize with feedback

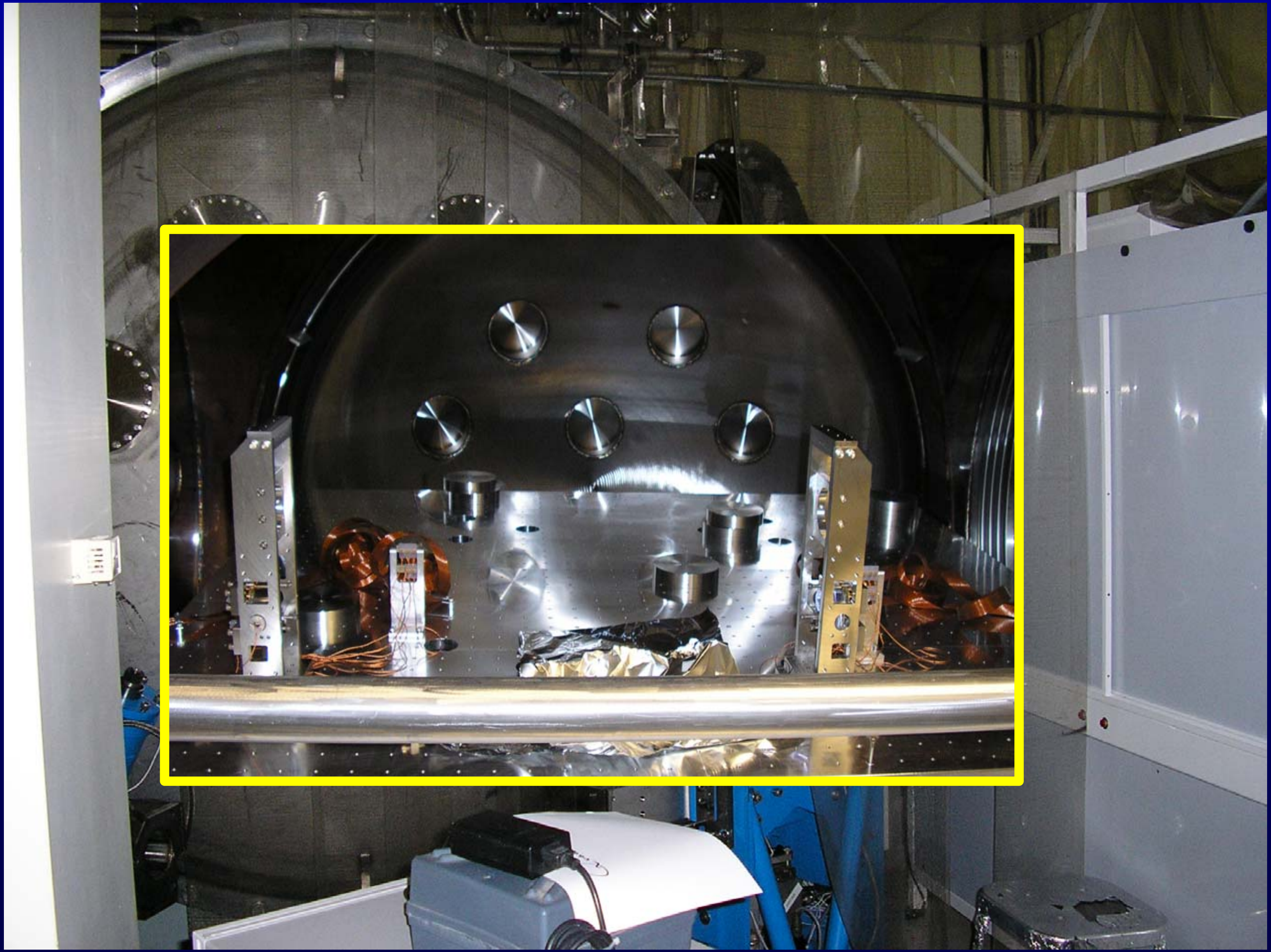


Stable optical springs

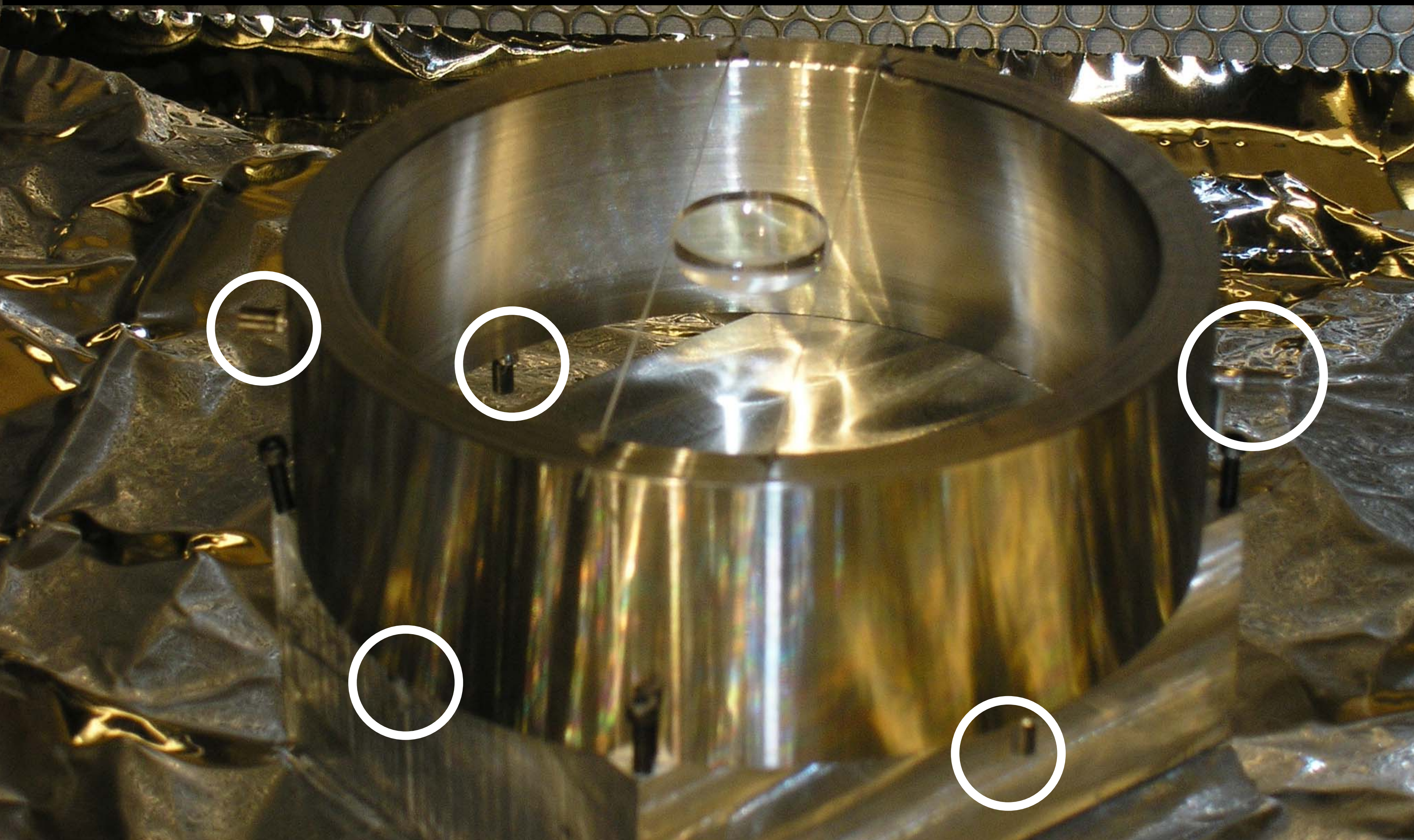
- Optical springs are always unstable if optical forces dominate over mechanical ones
  - Stabilized by electronic feedback in the past
- Key idea:
  The optical damping depends on the response time of the cavity, but the optical spring does not
  So use two fields with a different response time
  - Fast response creates restoring force and small anti-damping
  - Slow response creates damping force and small anti-restoring force
- Can do this with two cavities with different lengths or finesses
- But two optical fields with different detunings in a single cavity is easier

Phase II cavity

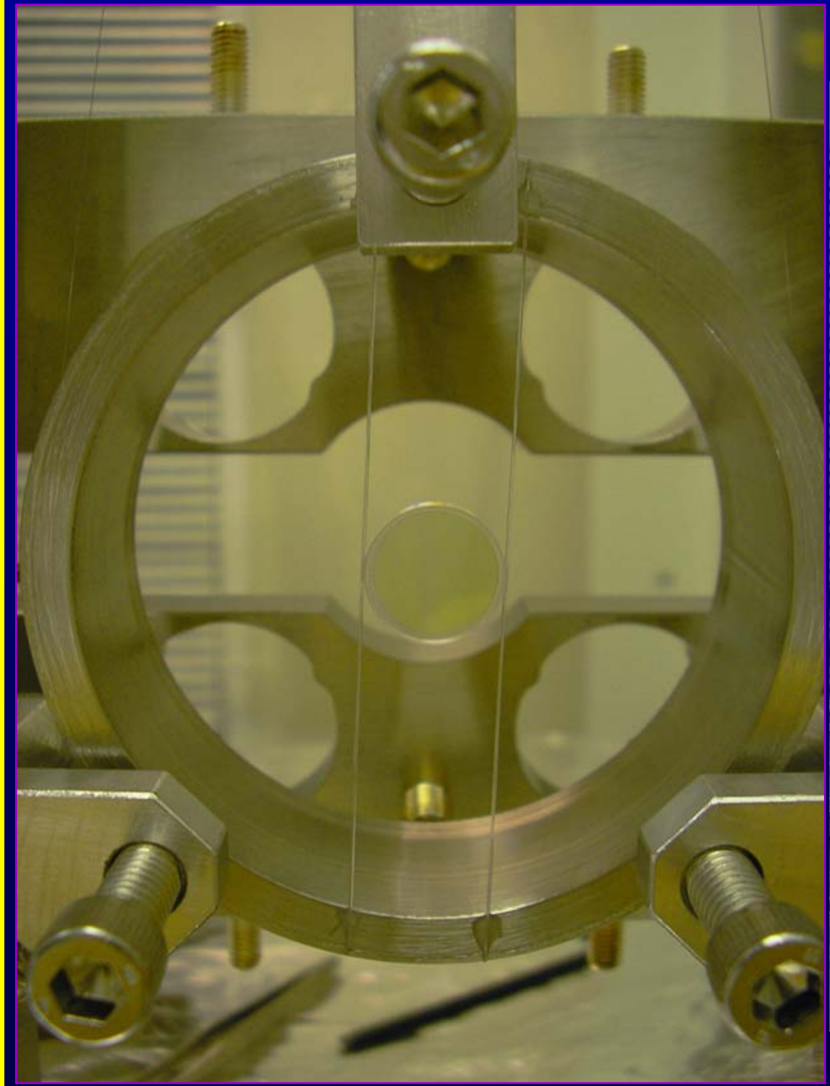


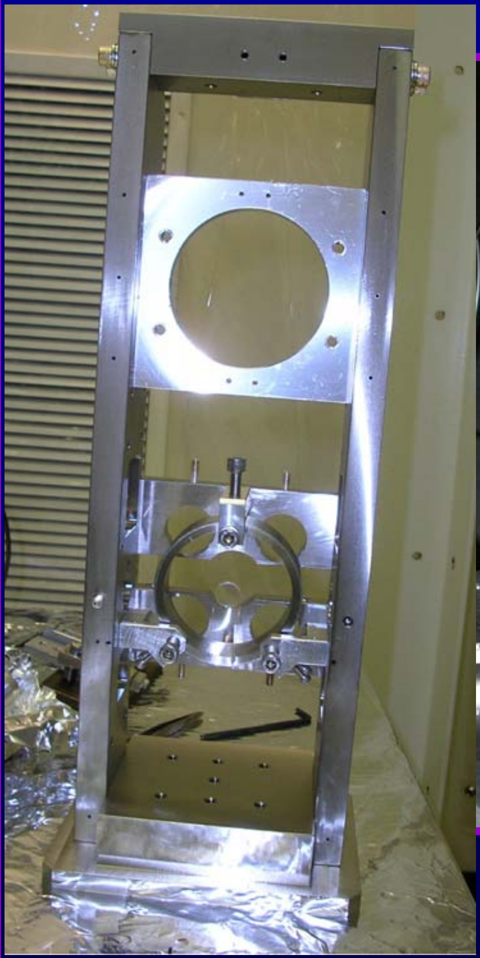


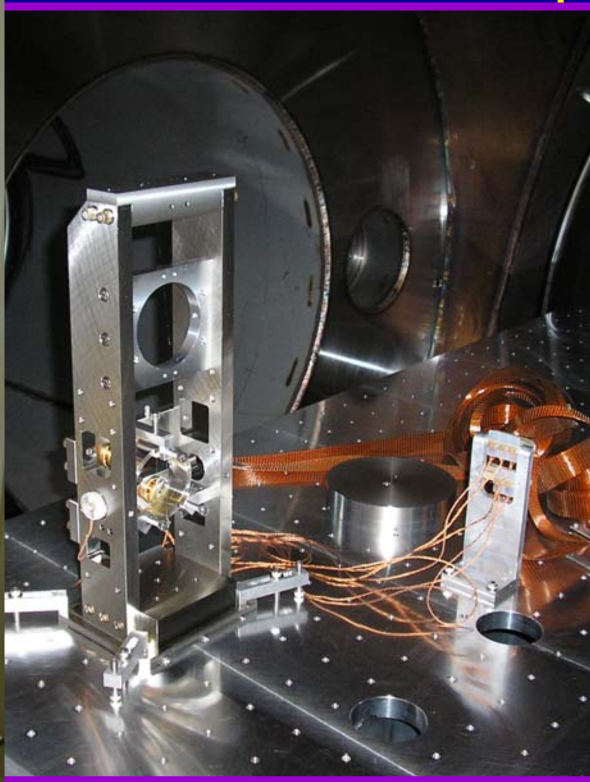
- Steel shell of same diameter as LIGO auxiliary optics
- Suspended with magnets (actuation), standoffs (thermal noise)
- Mini mirror attached by two 300 micron fused silica fibers



Double suspension for mini mirror

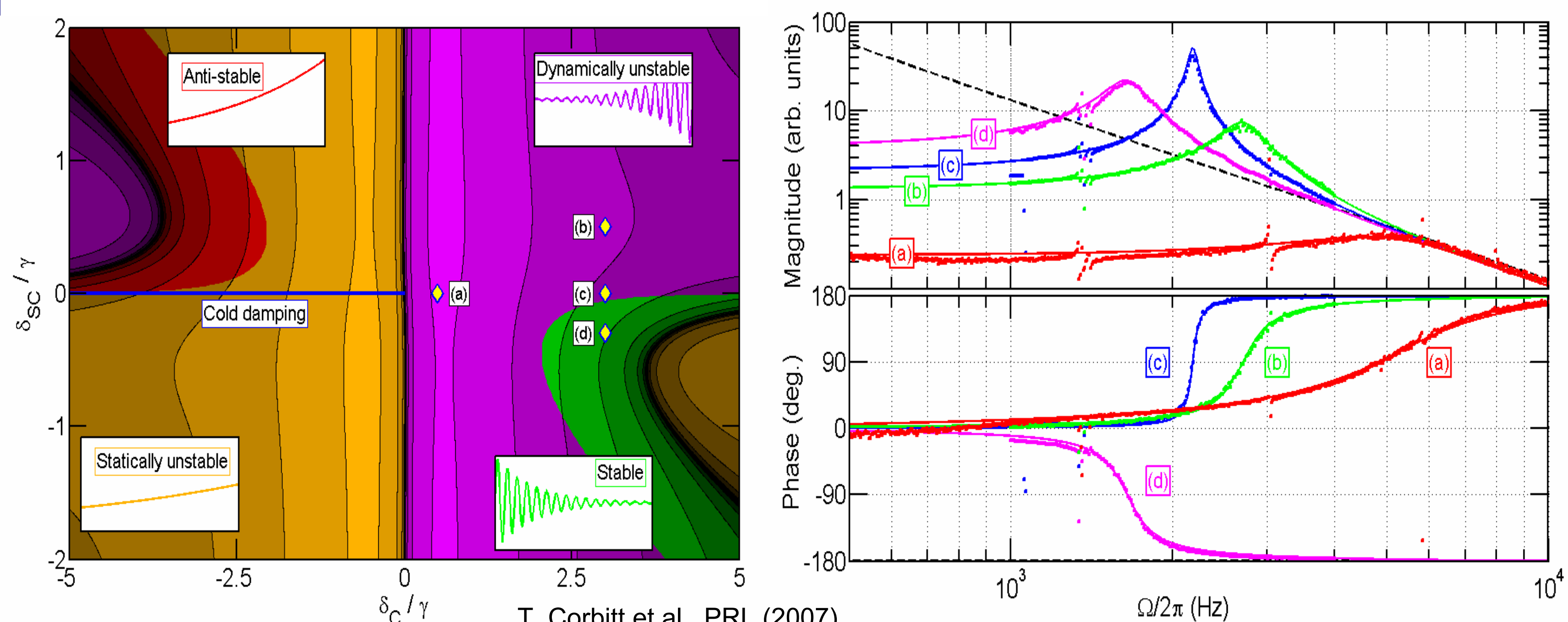






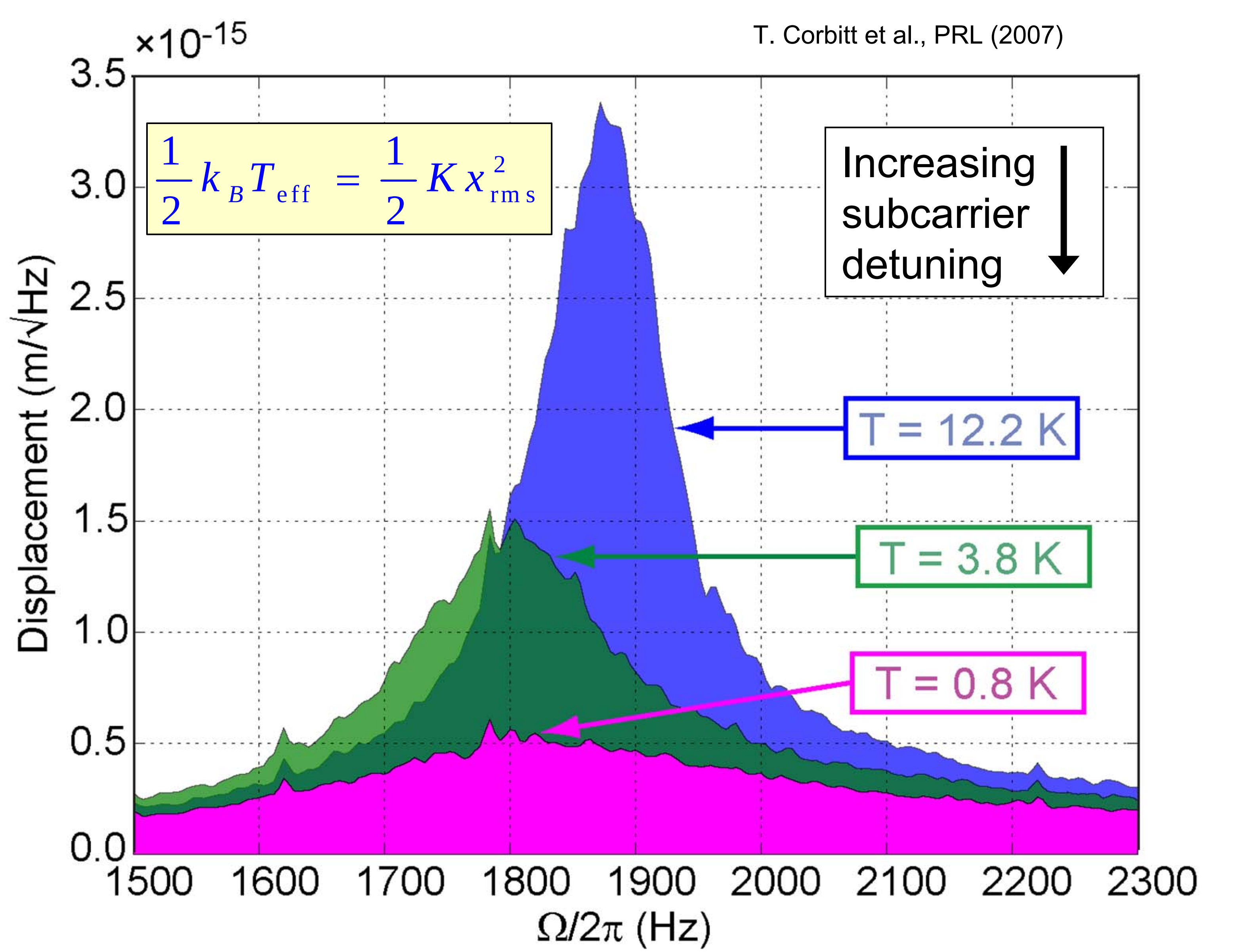
Stable Optical Trap

- Two optical beams → double optical spring
  - Carrier detuned to give restoring force
  - Subcarrier detuned to other side of resonance to give damping force
  - Independently control spring constant and damping



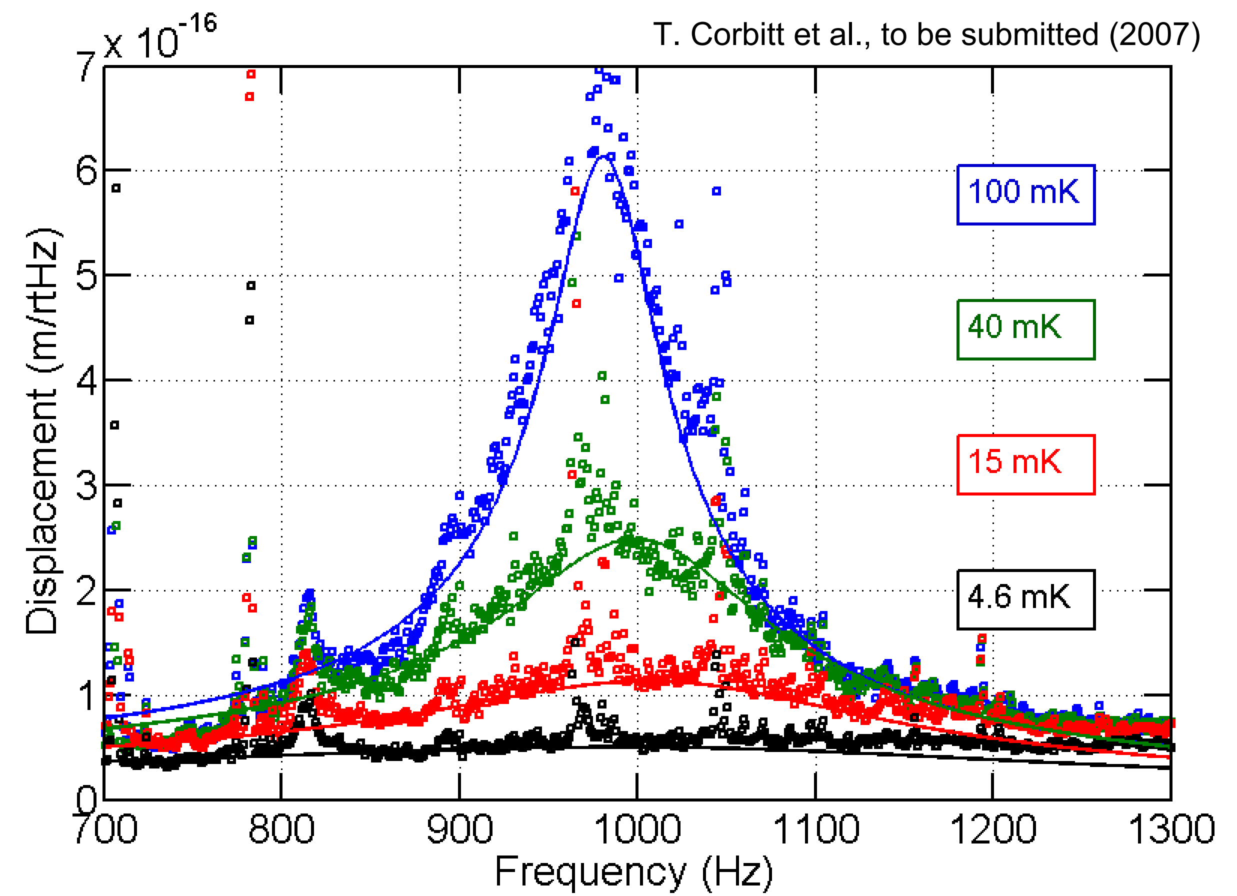
T. Corbitt et al., PRL (2007)

Optical cooling



Cooler mirror

- Lower frequency mechanical resonance → 13 Hz
- Shorter cavity (0.1 m) → less frequency noise
- Some acoustic features (beam clipping?)
- Electronic damping



$$\Omega_{\rm eff} = 2\pi \times 1000 \text{ Hz}$$

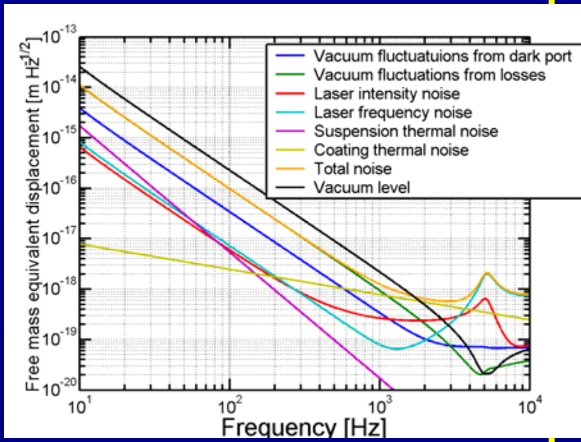
$$\Gamma_{\rm eff} = \Omega_{\rm eff} / Q_{\rm eff} \approx 6000$$

$$T_{\rm eff} = 5 \text{ mK}$$

$$N = \frac{k_B T_{\rm eff}}{\hbar \Omega_{\rm eff}} = 1 \times 10^5$$

cooling factor = 40000

Approaching a quantum state



- Ponderomotive experiment with two cavities
- Without optical trapping

$$\Omega_{\text{eff}} = \Omega_{\text{m}} = 2\pi \times 1\ \text{Hz} \qquad T = 295\ \text{K}$$

$$\Gamma_{\text{eff}} = \Gamma_m = \Omega_m / Q_m \approx 10^{-6} \qquad \bar{n} = 10^{-7}$$

$$T_{\text{eff}} = \hbar\Omega_{\text{eff}} / k_B \approx 5\times10^{-8}\ \text{K}$$

- With optical trap at 1 kHz

$$\Omega_{\text{eff}} = 2\pi \times 1\ \text{kHz} \qquad T = 3\times10^{-6}\ \text{K}$$

$$\Gamma_{\text{eff}} = \Omega_{\text{eff}} / Q_m \approx 10^3 \qquad \bar{n} = 0.1$$

In principle…

- Present limit from laser frequency and VCO noise
- Expect 1000x suppression of this with second cavity (installed, waiting for vacuum)
- Output light squeezing
  - Suspension and coating thermal noise low enough?
  - Optical losses low enough?
- Cooling
  - Temperature drops as noise^2 ➔ expect to get to μK
  - Within factor of 10 to 100 of occupation number = 1
  - Prospect of seeing quantum behavior of an object with 10^{22} atoms by coupling it to an optical field with 10^{15} photons

Thanks to

National Science Foundation
LIGO Laboratory and Collaboration
Steve Girvin

(Cavity) cooling comparison

	M_{eff} (g)	$\Omega_m /2\pi$ (kHz)	Q_m	T_{eff} (K)	N	$\overline{n}$	**Cooling factor**
Munich (2004)	4×10^{-9}	7.3	2000	18	5×10^{7}	7×10^{-7}	17
UCSB (2006)	2×10^{-8}	12.5	137000	0.135	2×10^{5}	2×10^{-3}	2000
Vienna (2006)	4×10^{-9}	278	9000	8	6×10^{5}	4×10^{-3}	33
Paris (2006)	2×10^{-4}	814	10000	10	3×10^{5}	4×10^{-4}	33
Yale (2006)	6×10^{-8}	67	2000	50	1×10^{7}	2×10^{-5}	6
ANU (2007)	1	0.1	44500	0.082	2×10^{7}	1×10^{8}	3700
IBM (2006)	1×10^{-9}	4	46000	0.005	2×10^{4}	2×10^{-4}	800
MIT (2006)	1	0.013	3200	0.006	1×10^{5}	1×10^{-4}	40000