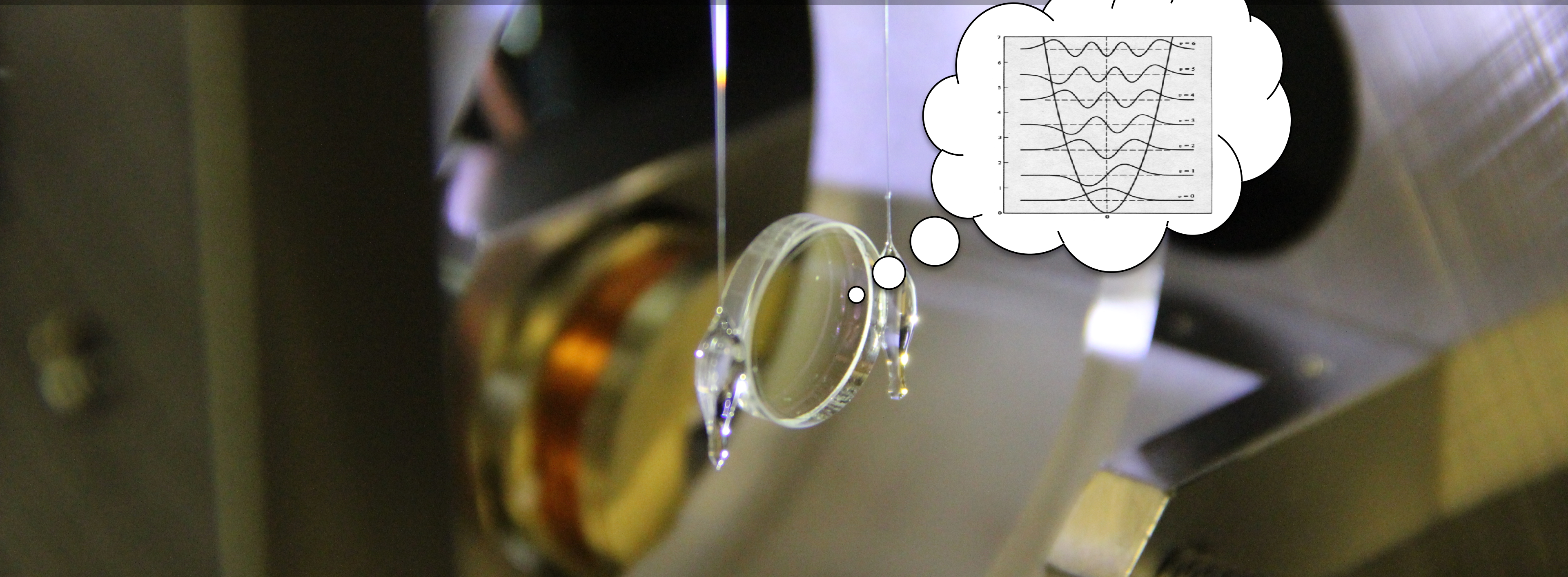
Toward Quantum Opto-Mechanics in a Gram-Scale Suspended Mirror Interferometer



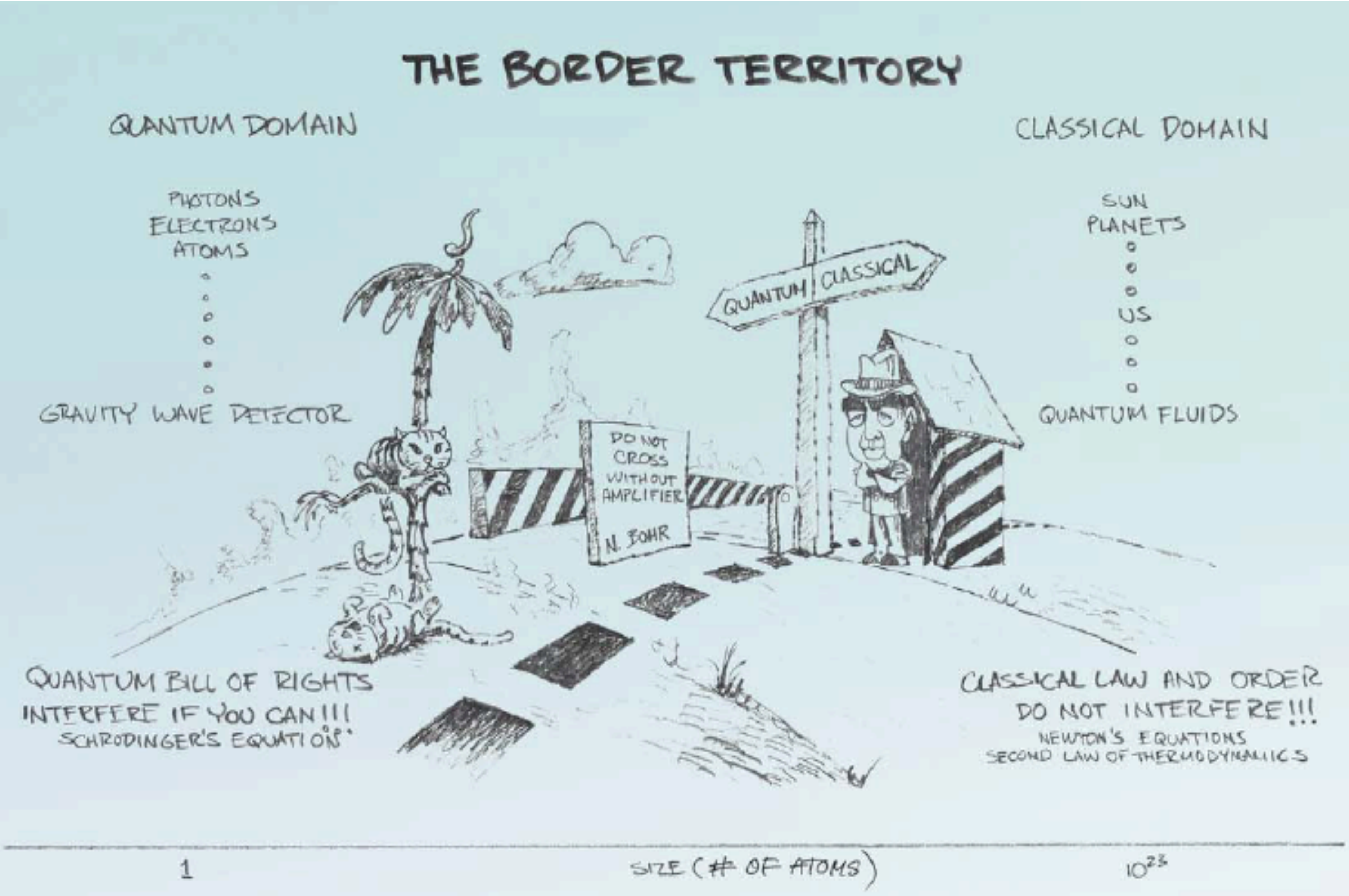
Christopher Wipf

Thesis Supervisor: **Nergis Mavalvala**

Thesis Committee Members: **Leonid Levitov, Vladan Vuletic**

Overview

- **Gravitational Wave Detectors & Quantum Limits**
  - Gram Scale Opto-Mechanics Experiment
    - Quantum States of Unusual Size
      - Quantum Back-Action vs. Thermal Noise
        - Toward Squeezed & Entangled Light

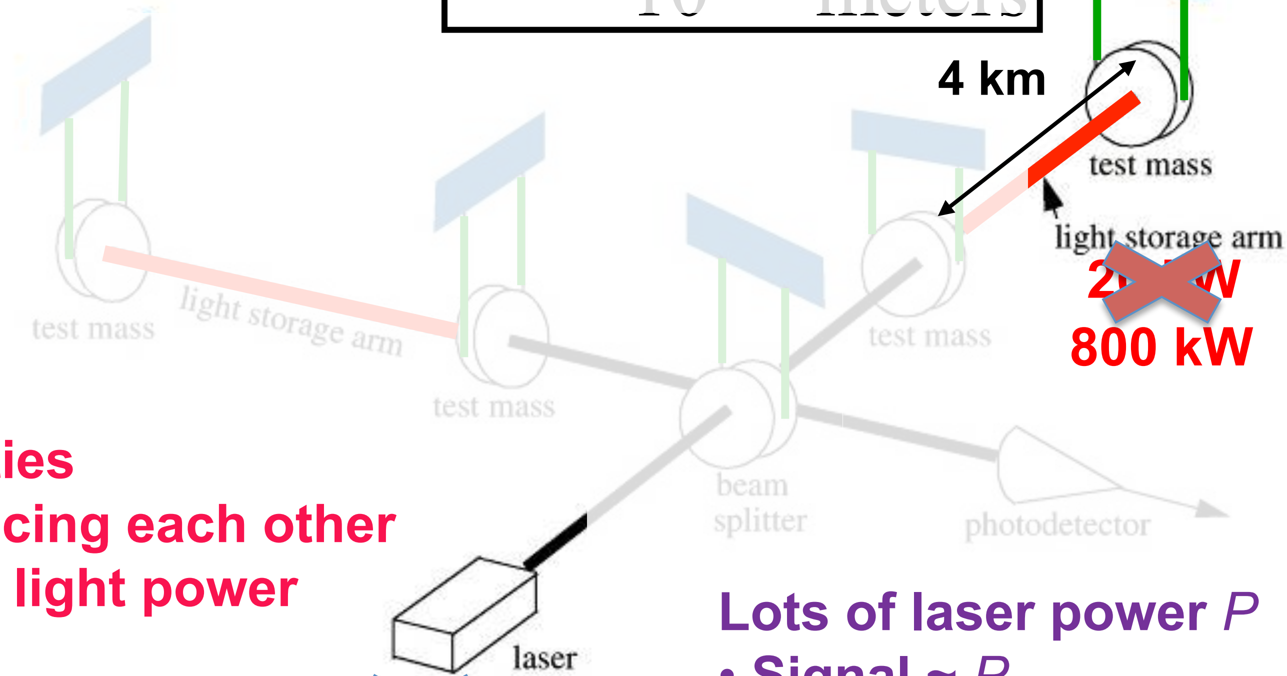


W. Zurek, Los Alamos Science (2002)

How to Catch a Gravitational Wave

Mirrors hang as pendulums
- **Quasi-free particles**
- **Respond to passing GW**
- **Filter external force noise**

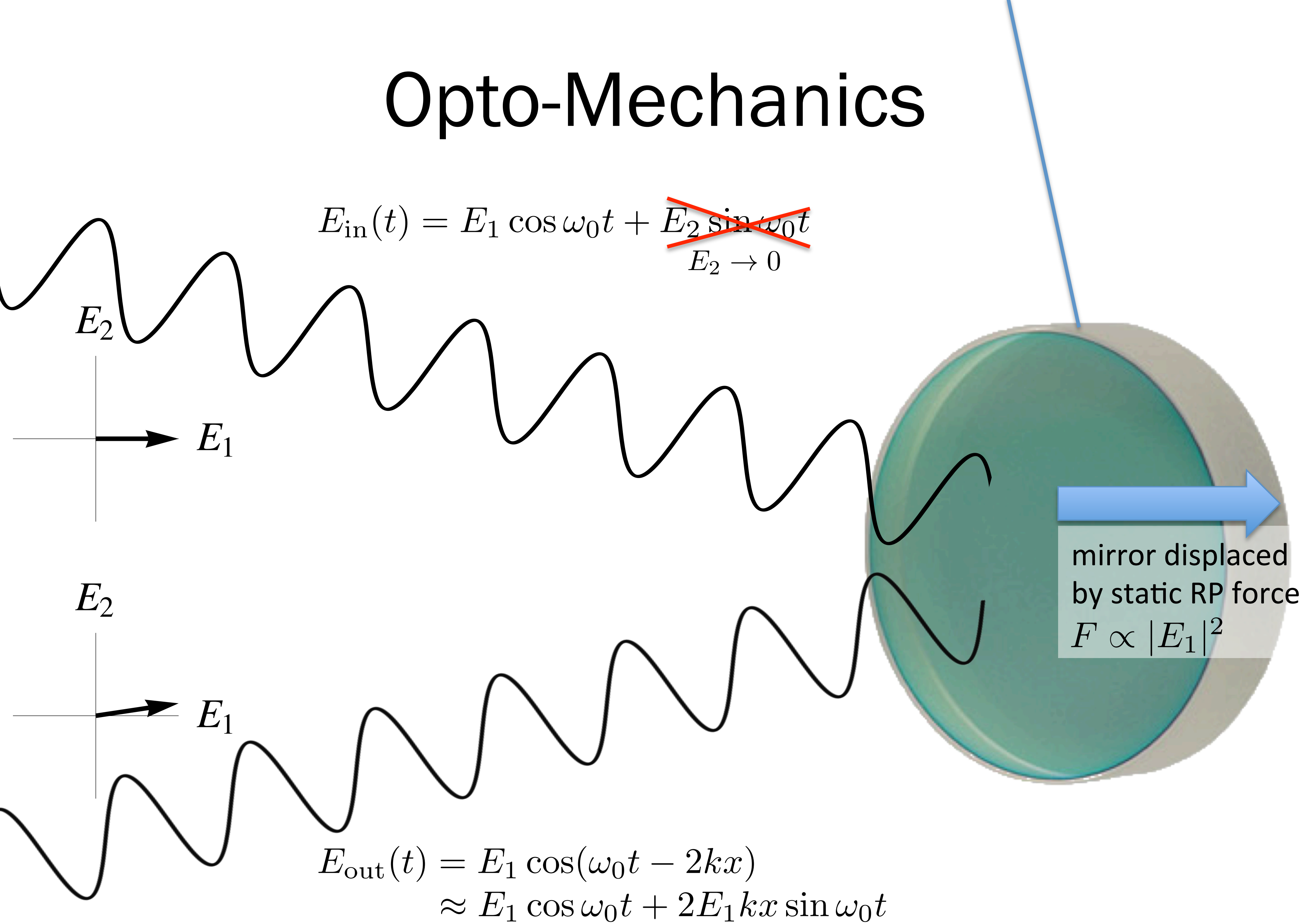
$$\Delta L = h_{GW} L$$
$$= 10^{-21} \times 4000$$
$$\sim 10^{-18} \text{ meters}$$



Optical cavities
- **Mirrors facing each other**
- **Builds up light power**

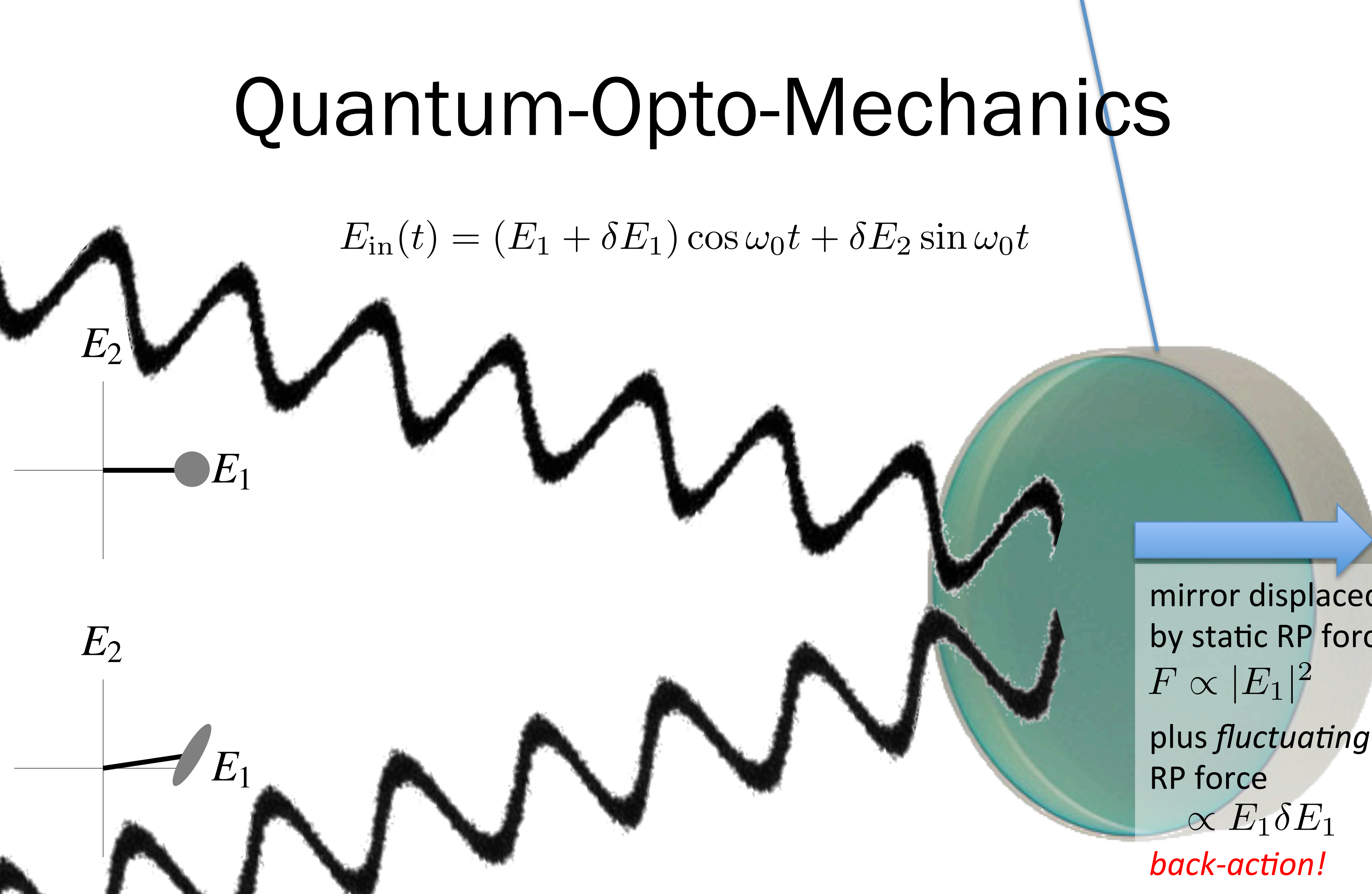
Lots of laser power *P*
- **Signal ~ *P***
- **Noise ~ $\sqrt{P}$**

Opto-Mechanics



Quantum-Opto-Mechanics

$$E_{\text{in}}(t) = (E_1 + \delta E_1)\cos\omega_0 t + \delta E_2 \sin\omega_0 t$$



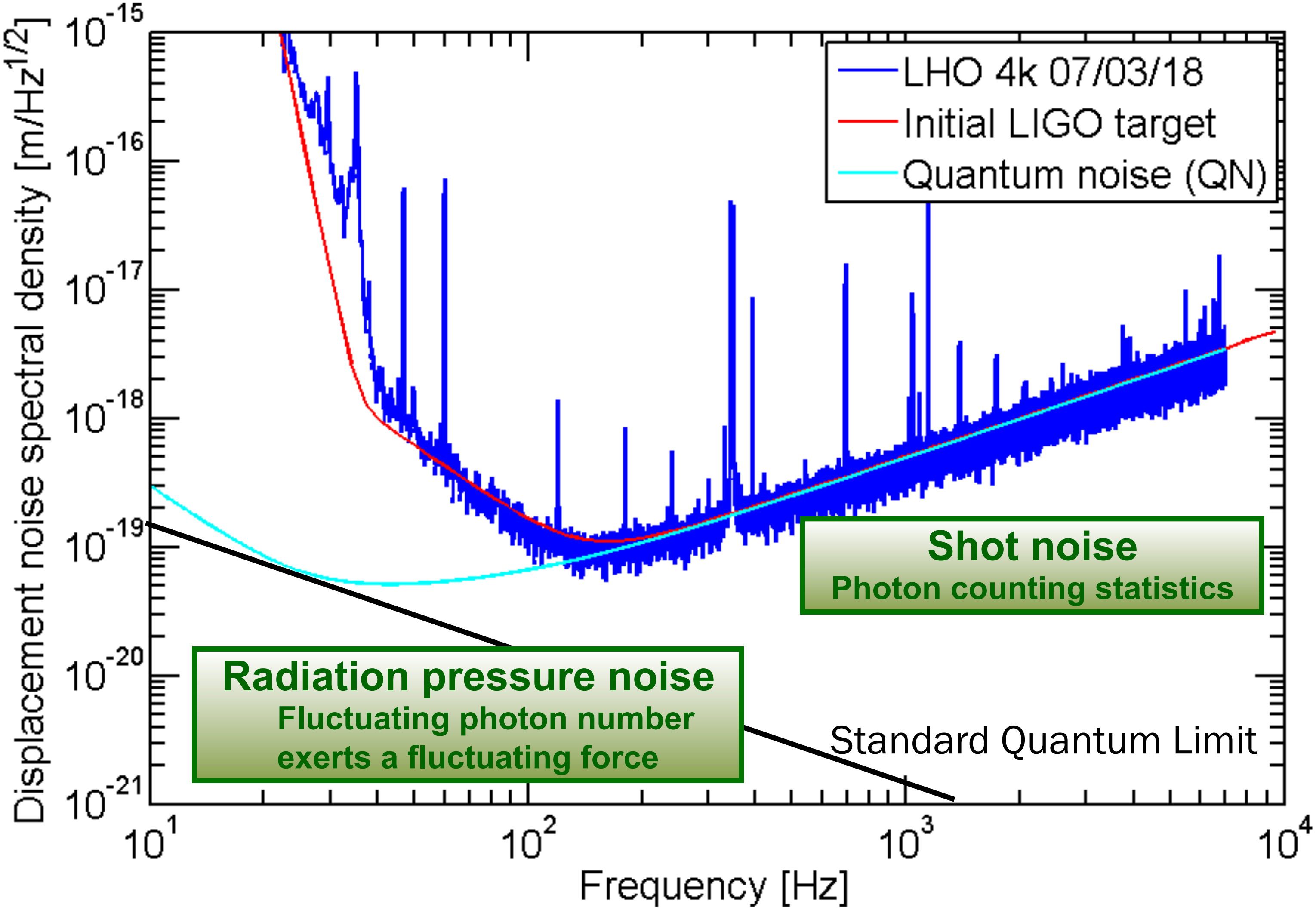
mirror displaced by static RP force $F \propto |E_1|^2$

plus *fluctuating* RP force $\propto E_1 \delta E_1$

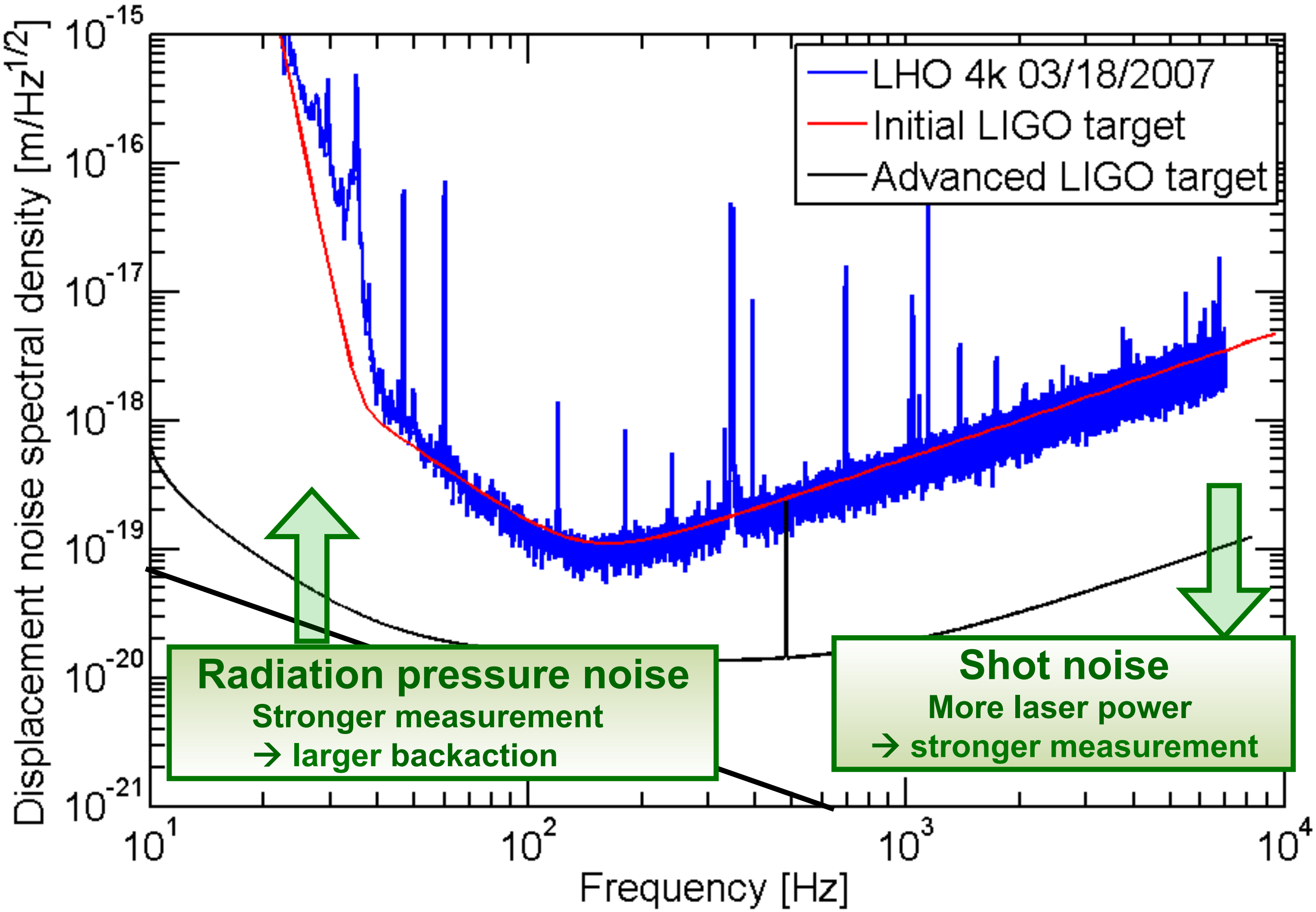
back-action!

$$E_{\text{out}}(t) = (E_1 + \delta E_1)\cos(\omega_0 t - 2kx) + \delta E_2 \sin\omega_0 t$$
$$\approx (E_1 + \delta E_1)\cos\omega_0 t + (2E_1 kx + \delta E_2)\sin\omega_0 t$$

Quantum Noises in Initial LIGO



Quantum Limit in Advanced LIGO



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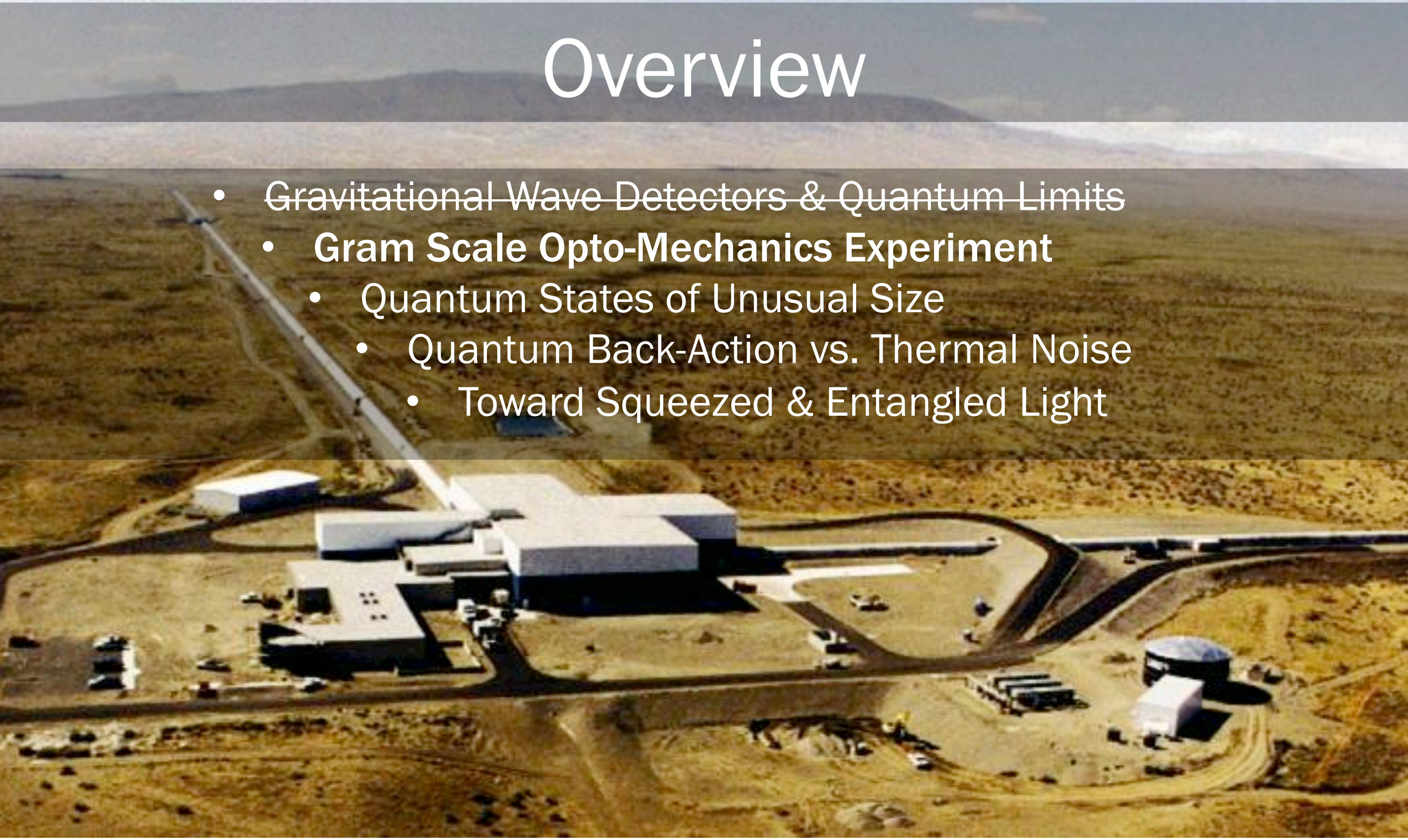
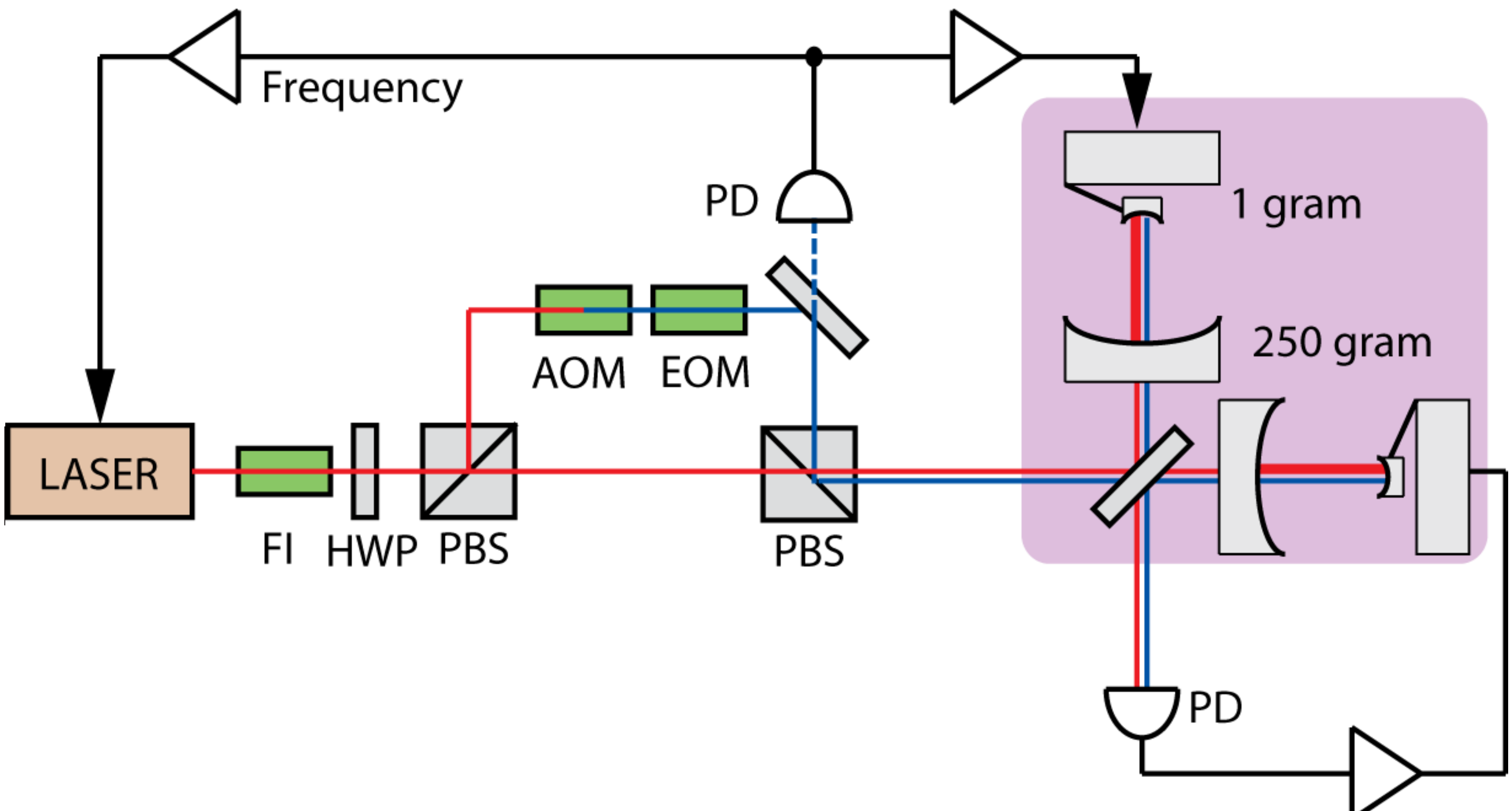


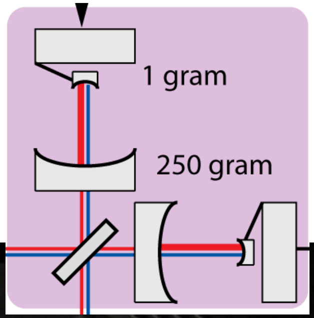
Why a Gram-Scale Experiment?

- Testbed for opto-mechanical effects anticipated for Advanced LIGO
  - Classical radiation pressure forces
  - Quantum radiation pressure noise, squeezing
- New regime for “Macroscopic Quantum Mechanics”
  - Cooling to the ground state
  - Entanglement

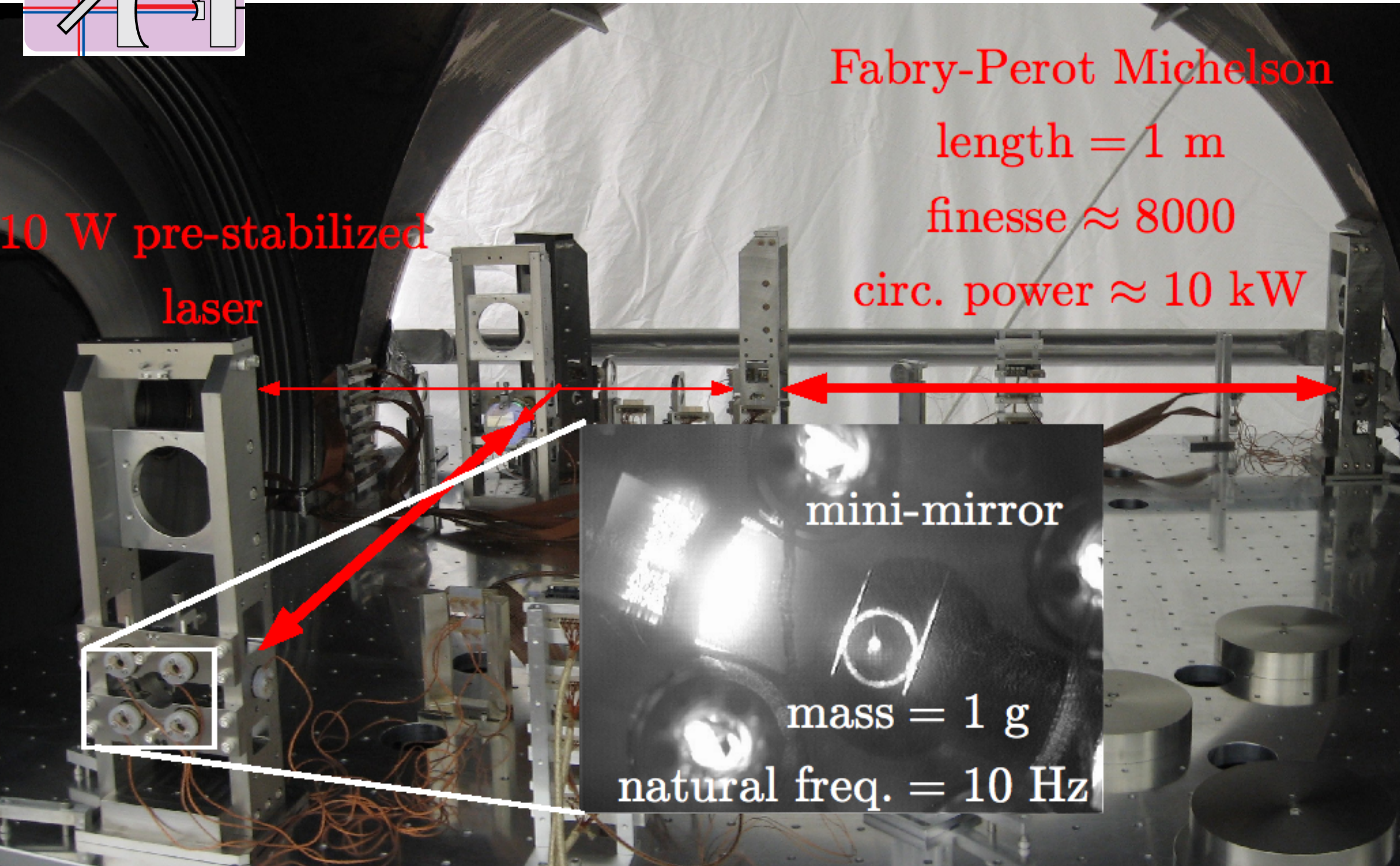
Design Features

- Reuse techniques and components developed for GW detectors
- Low frequency, high *Q* mirror suspensions
- Tabletop testbed: gram scale masses, 1 meter optical path
- Dual optical fields with tunable frequency offset
- Michelson interferometer to cancel laser noise

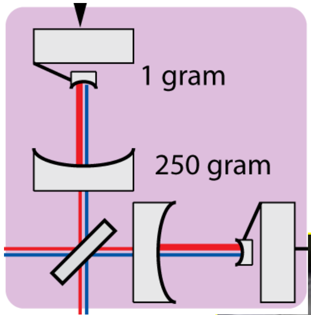


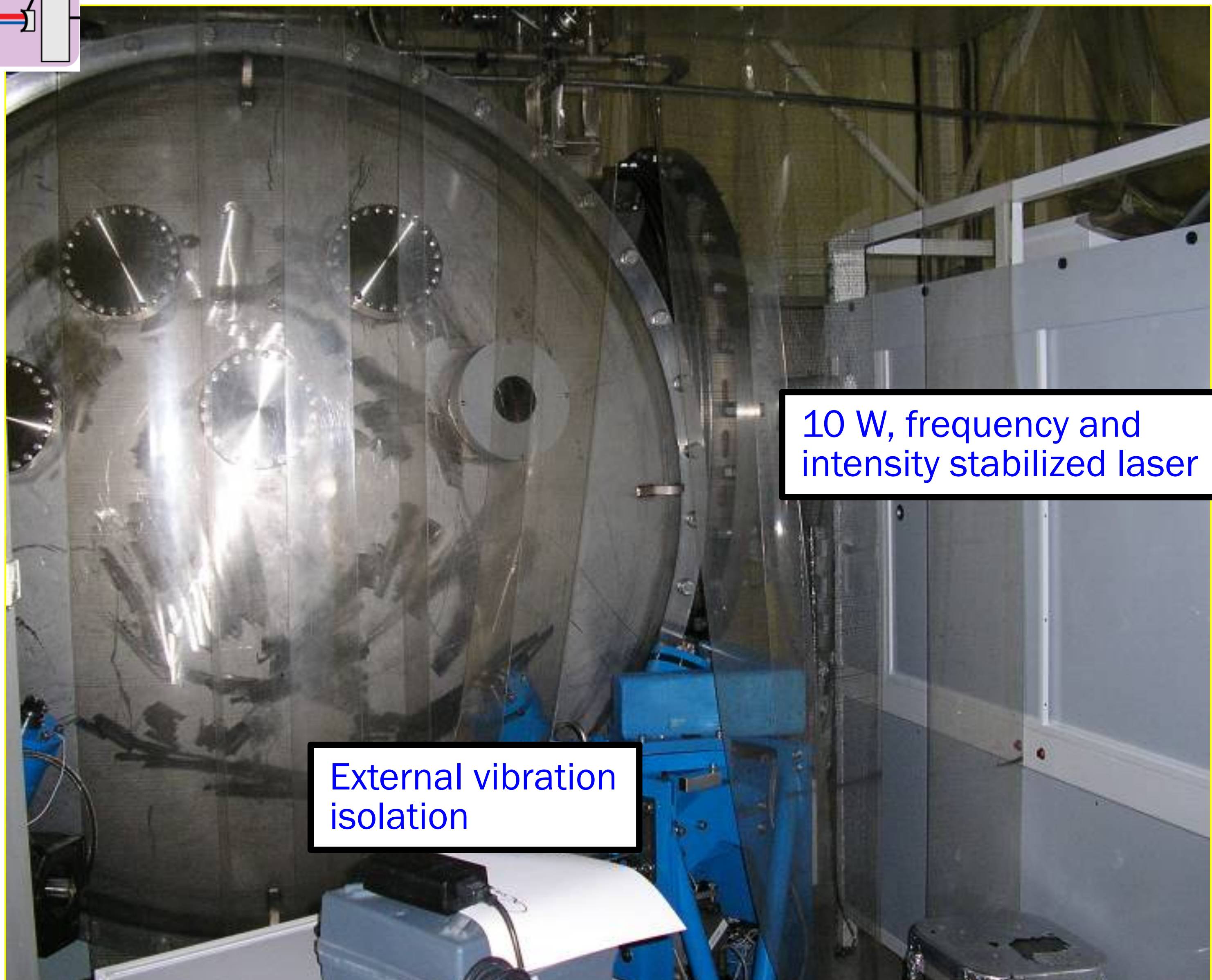

1 gram
250 gram

Lab Tour


Fabry-Perot Michelson
length = 1 m
finesse ≈ 8000
circ. power ≈ 10 kW
10 W pre-stabilized
laser
mini-mirror
mass = 1 g
natural freq. = 10 Hz

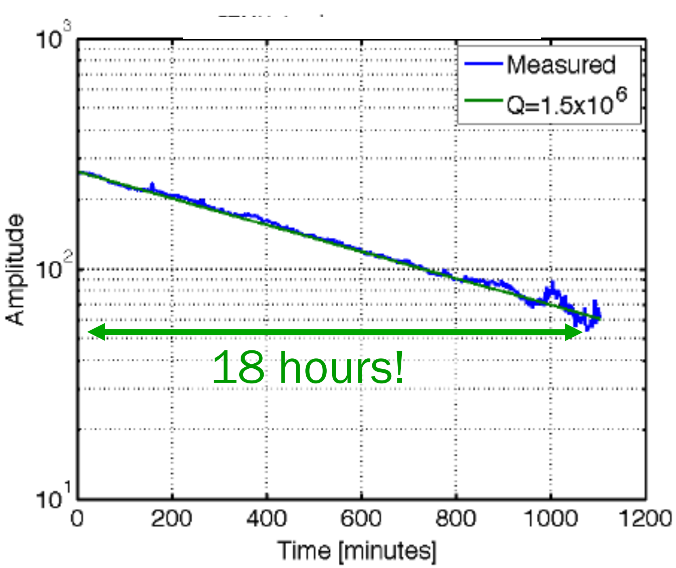
Lab Tour

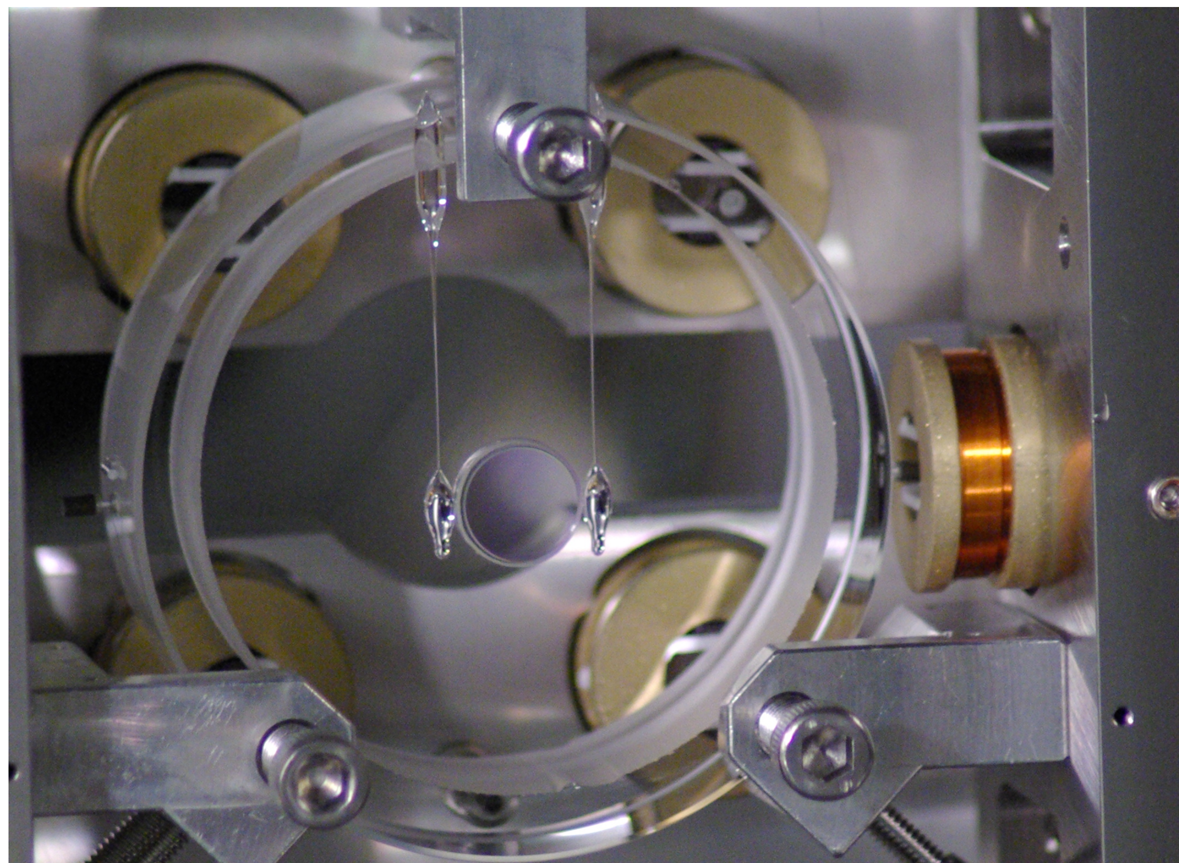

1 gram
250 gram


10 W, frequency and intensity stabilized laser
External vibration isolation

1 Gram Mirror Suspension

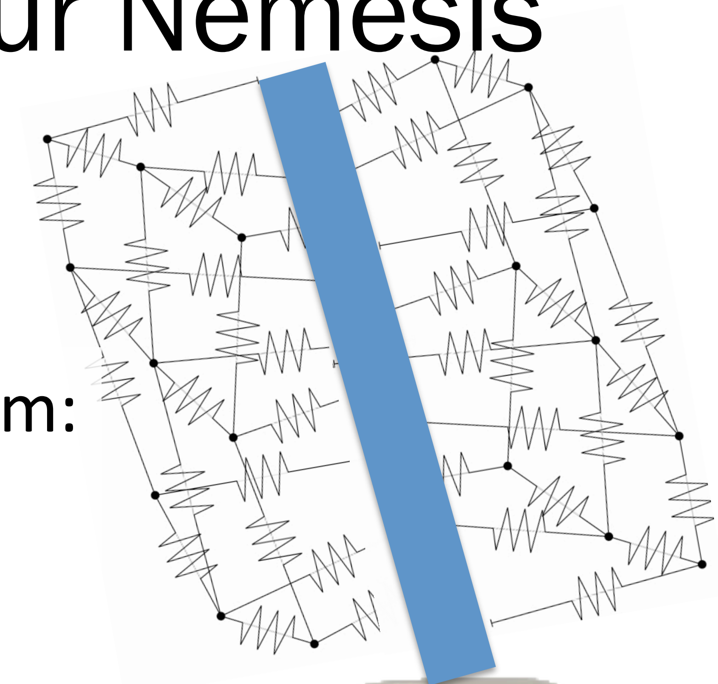
- Double suspension with actuators on the intermediate mass (the “ring”)
- Bottom stage: glass fibers tapered to 200 μm diameter
- “Ears” prevent bending at the glue joints, reducing losses
- Q > 10^6 for 10 Hz mode





Thermal Noise, Our Nemesis

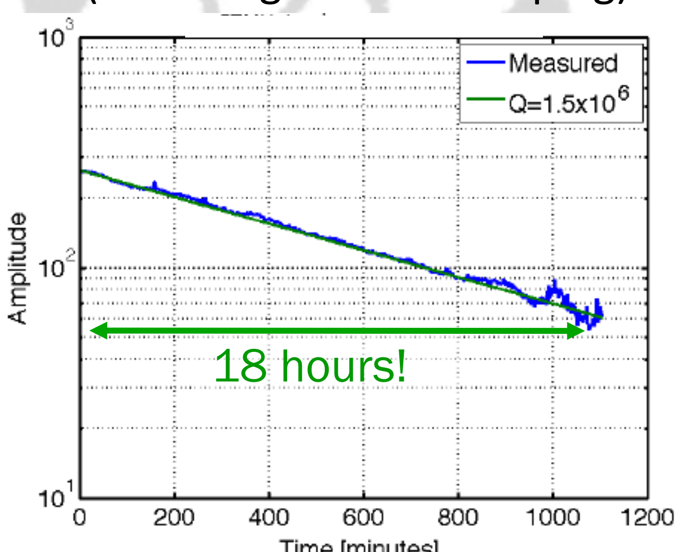
Mirror oscillator is coupled to its room temperature environment (model as a bath of weakly coupled oscillators, each with energy $k_b T$)

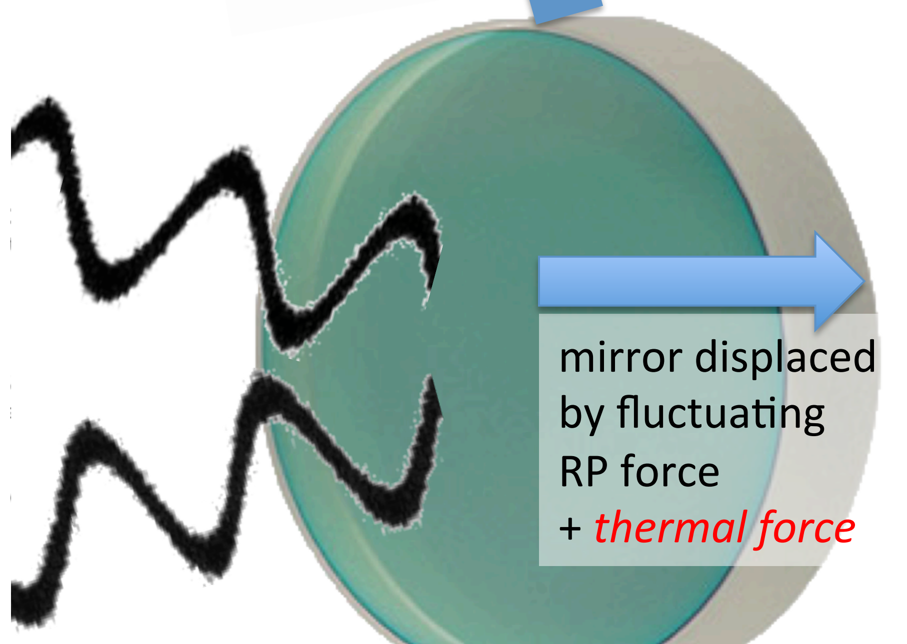


Fluctuation Dissipation Theorem: Damping ⇔ Thermal Noise

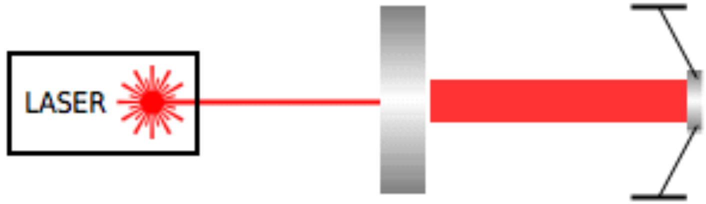
$$S_F^{(T)}(\Omega) = 4 k_b T m \Gamma_m$$

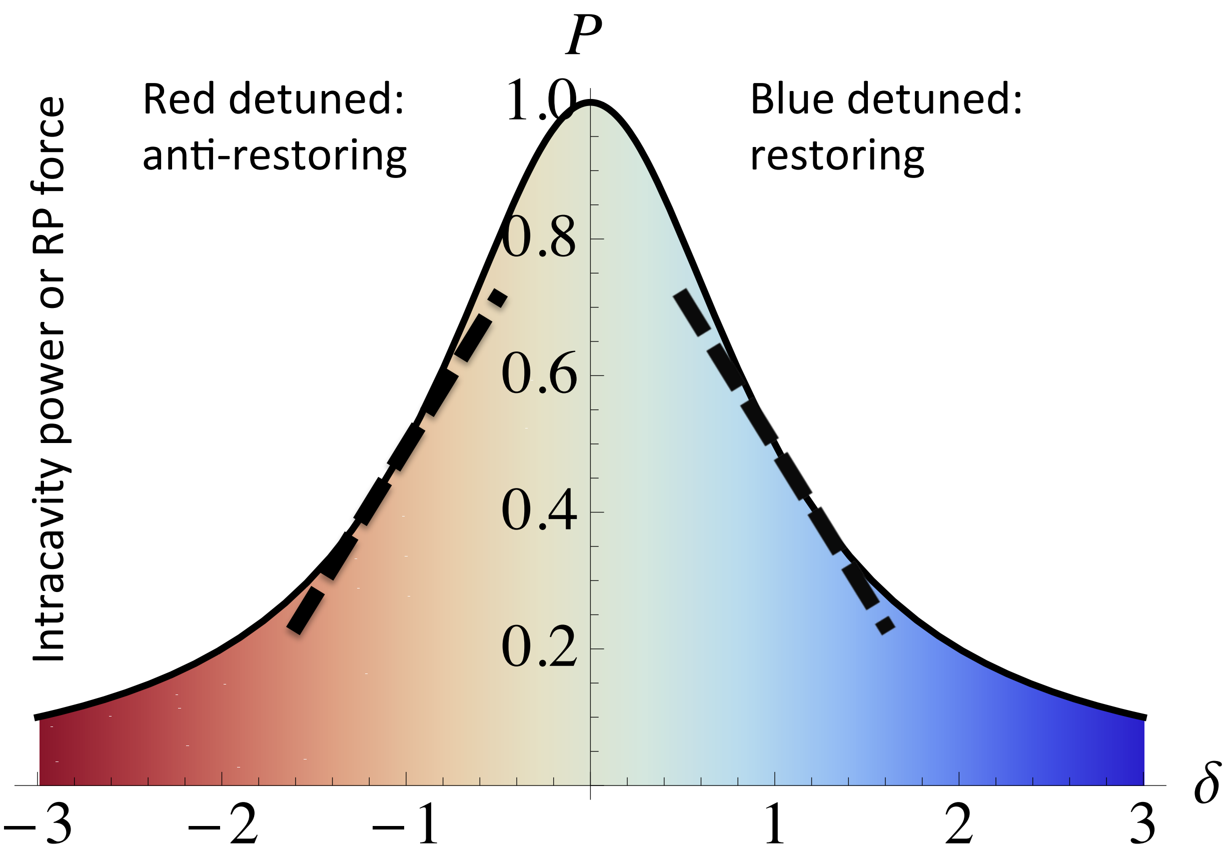
(assuming viscous damping)



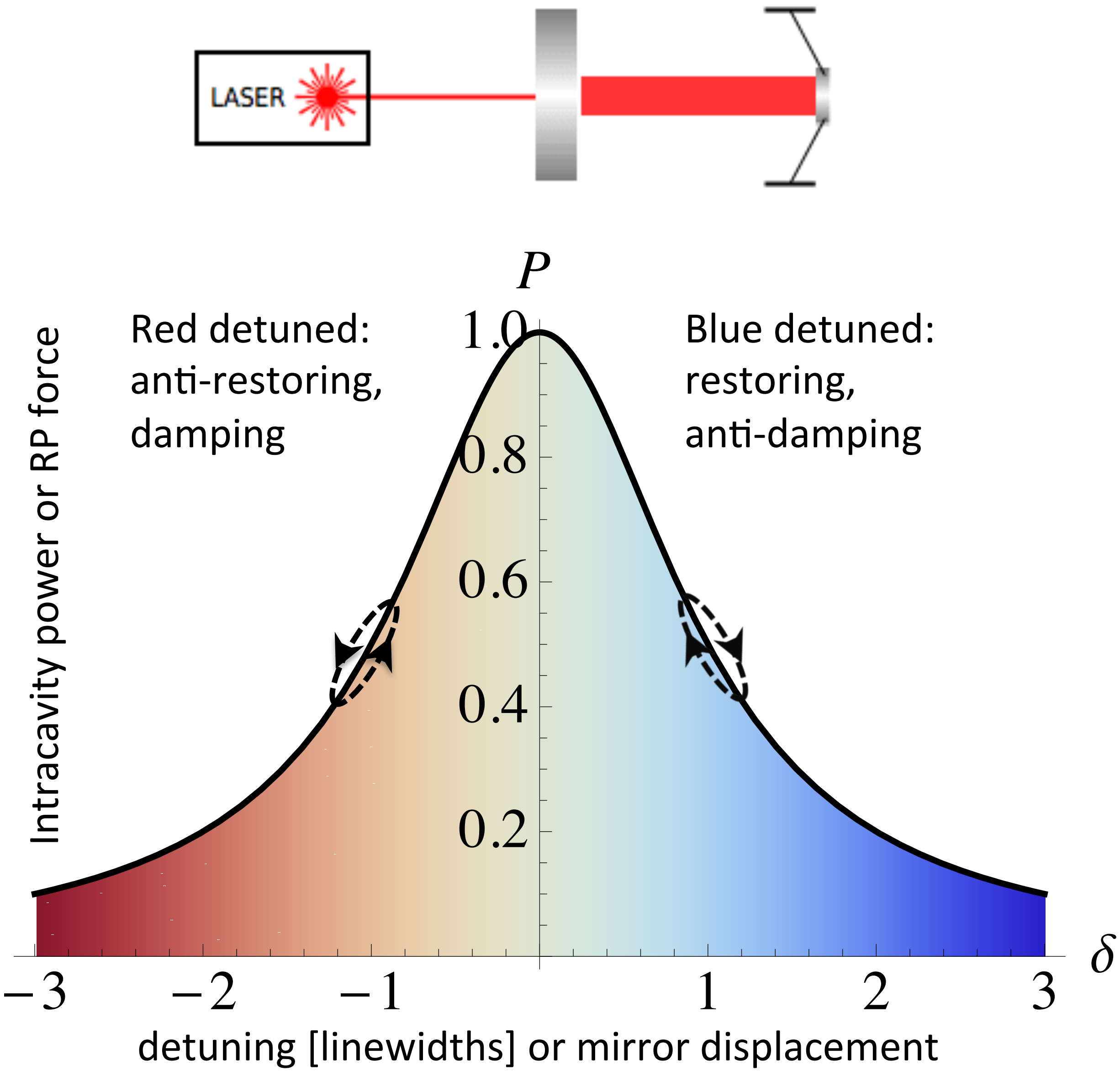


Radiation Pressure in a Cavity

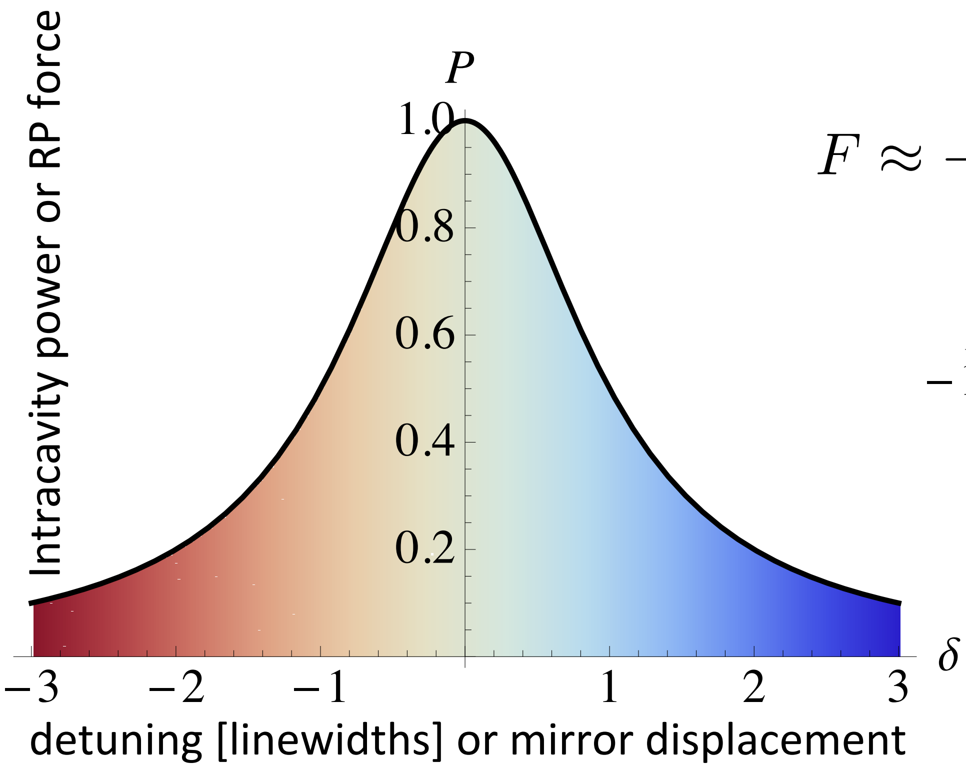


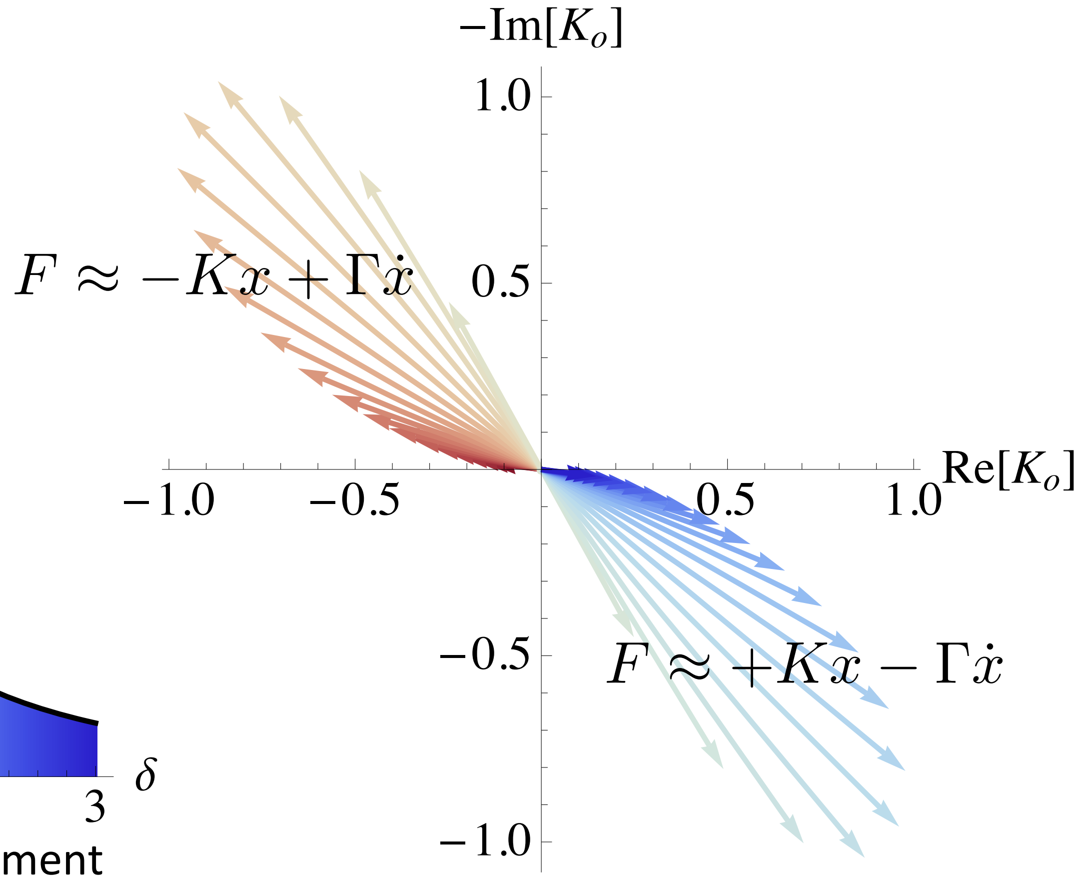


Radiation Pressure in a Cavity



Radiation Pressure in a Cavity





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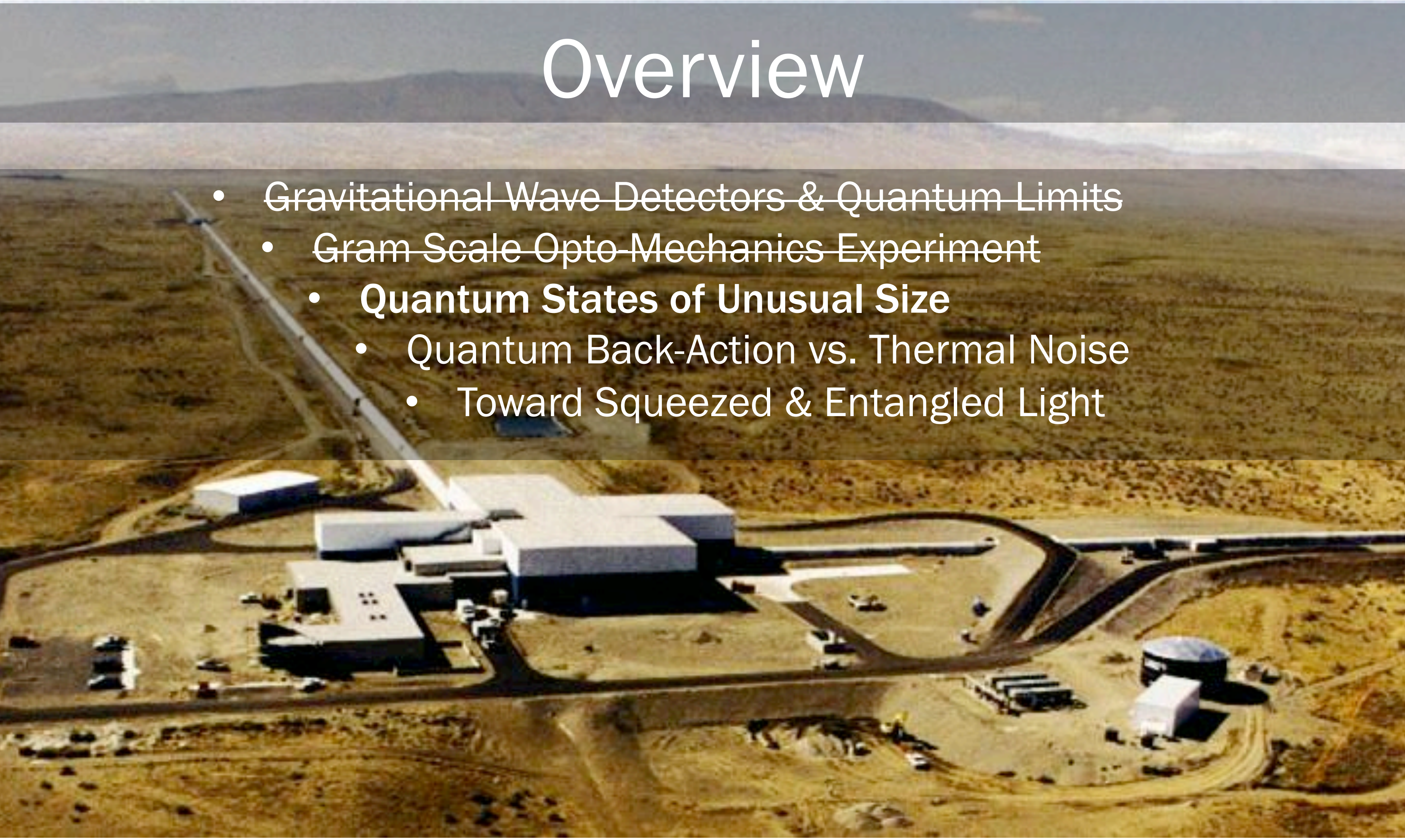
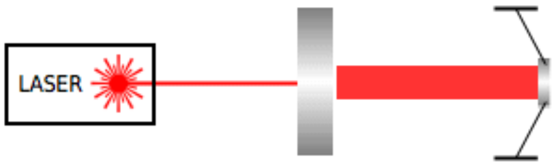


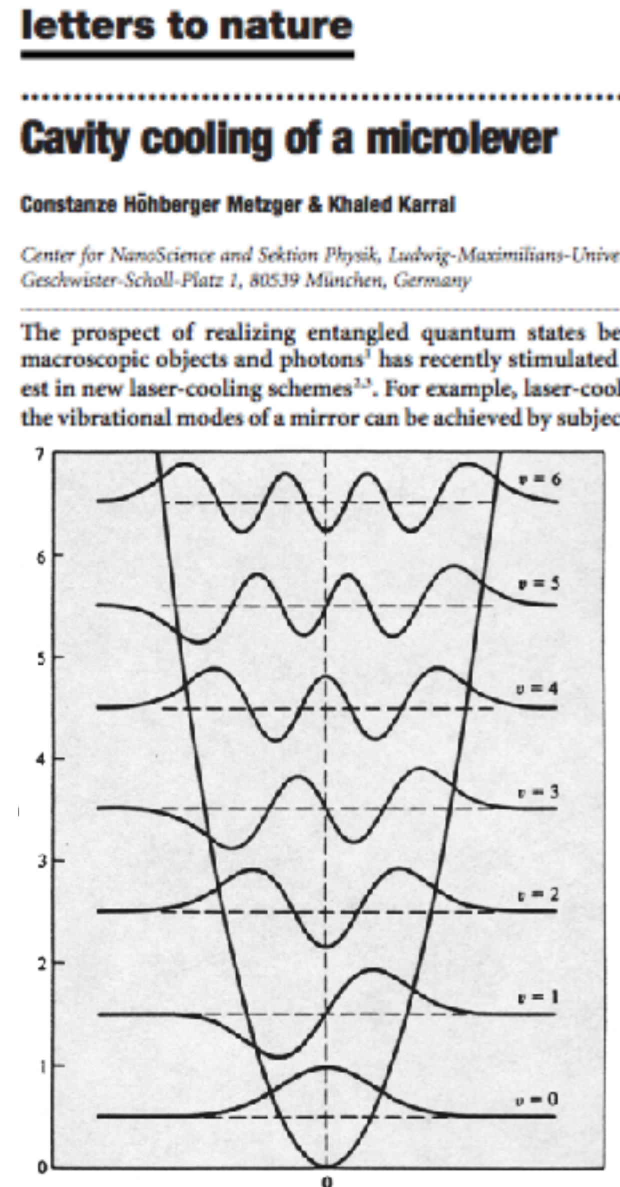
Opportunity for Macroscopic Quantum Mechanics

- Model system: Optical cavity with a movable mirror



- Quantum mechanics of mirror are normally swamped by thermal noise
  - Thermal energy $k_b T$ vastly exceeds the ground state energy $\frac{1}{2}\hbar\Omega$
  - Occupation number $N = \frac{k_b T}{\hbar\Omega} \sim 10^{12}$ for LIGO

- Can we use novel, non-cryogenic cooling techniques to approach the quantum ground state?


letters to nature

Cavity cooling of a microlever

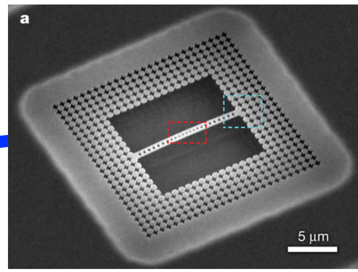
Constanze Höhberger Metzger & Khaled Karrai

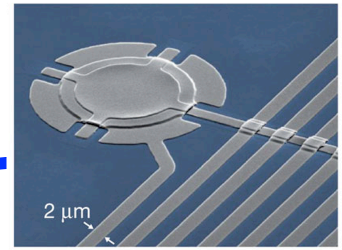
Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Unive
Geschwister-Scholl-Platz 1, 80539 München, Germany

The prospect of realizing entangled quantum states be macroscopic objects and photons[1] has recently stimulated est in new laser-cooling schemes[2,3]. For example, laser-cool the vibrational modes of a mirror can be achieved by subjec

Mechanical Resonators
Race to the Ground State

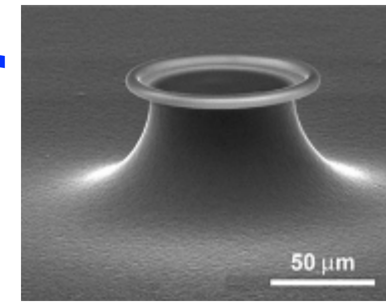
Photonic crystal nanobeam → 10^{-13} g



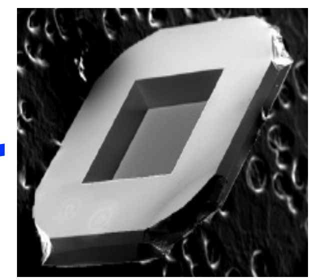


NEMS → 10^{-11} g

Toroidal microcavity → 10^{-11} g

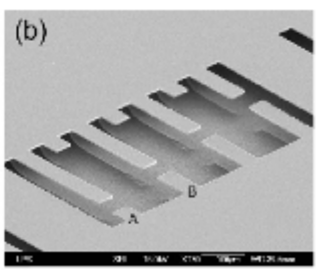


AFM cantilevers → 10^{-8} g

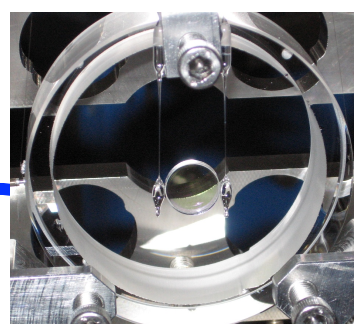


SiN_3 membrane → 10^{-8} g

Micro mirrors → 10^{-7} g

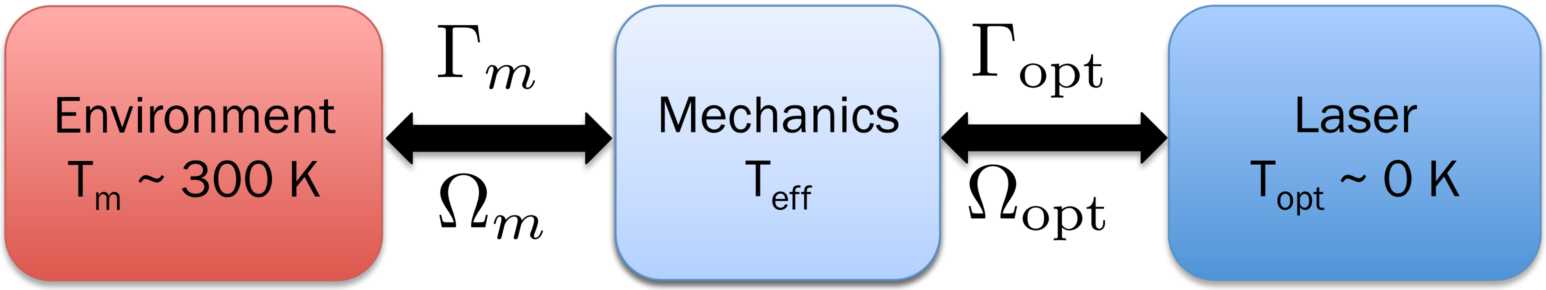


Mini mirror → 1 g



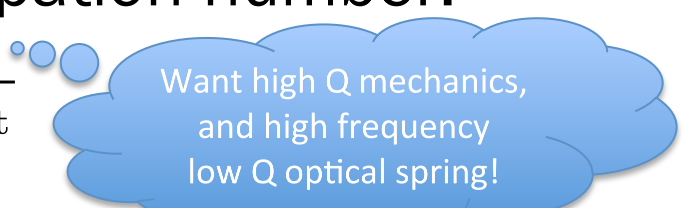
LIGO → 10^3 g

Optical Cooling of Mechanical Structures



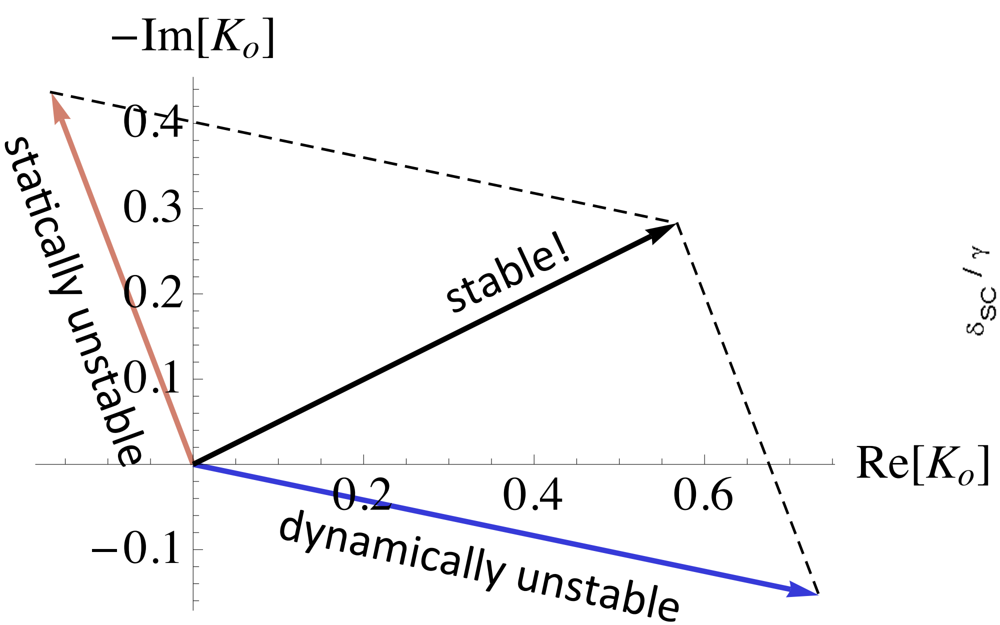
- Fluctuation Dissipation Thm => thermal noise $\sim T_m, \Gamma_m$
- Add an optical damping force:
  (can be quantum limited with $T_{\text{opt}} \sim 0$)
  New effective damping rate is $\Gamma_{\text{eff}} = \Gamma_m + \Gamma_{\text{opt}}$
  Cold force drains energy from the mechanics,
  without adding thermal noise
- Add an optical restoring force:
  New effective resonant frequency is $\Omega_{\text{eff}}^2 = \Omega_m^2 + \Omega_{\text{opt}}^2$
  New effective occupation number:

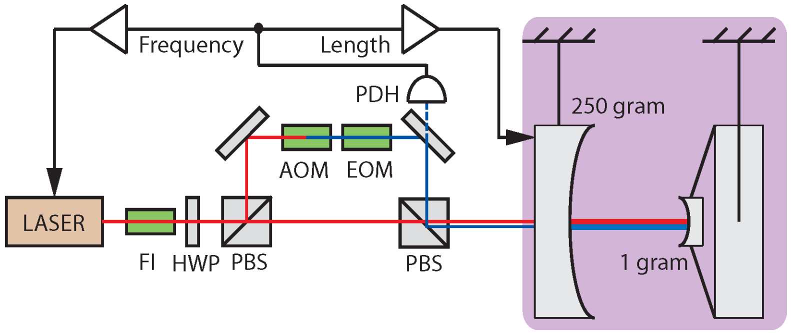
$$N \approx \frac{k_b T_m}{\hbar \Omega_m} \frac{\Omega_m}{\Omega_{\text{opt}}} \frac{\Gamma_m}{\Gamma_{\text{opt}}}$$



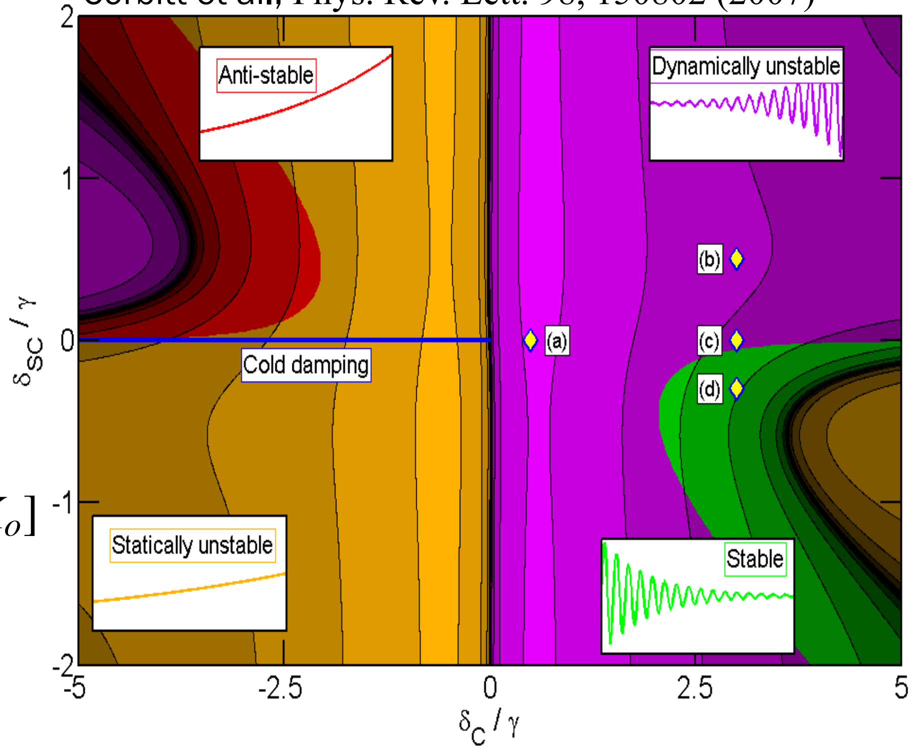
Double Optical Spring

- Combining the RP of two fields may lead to a stable configuration (if the power and detuning of each is well chosen)

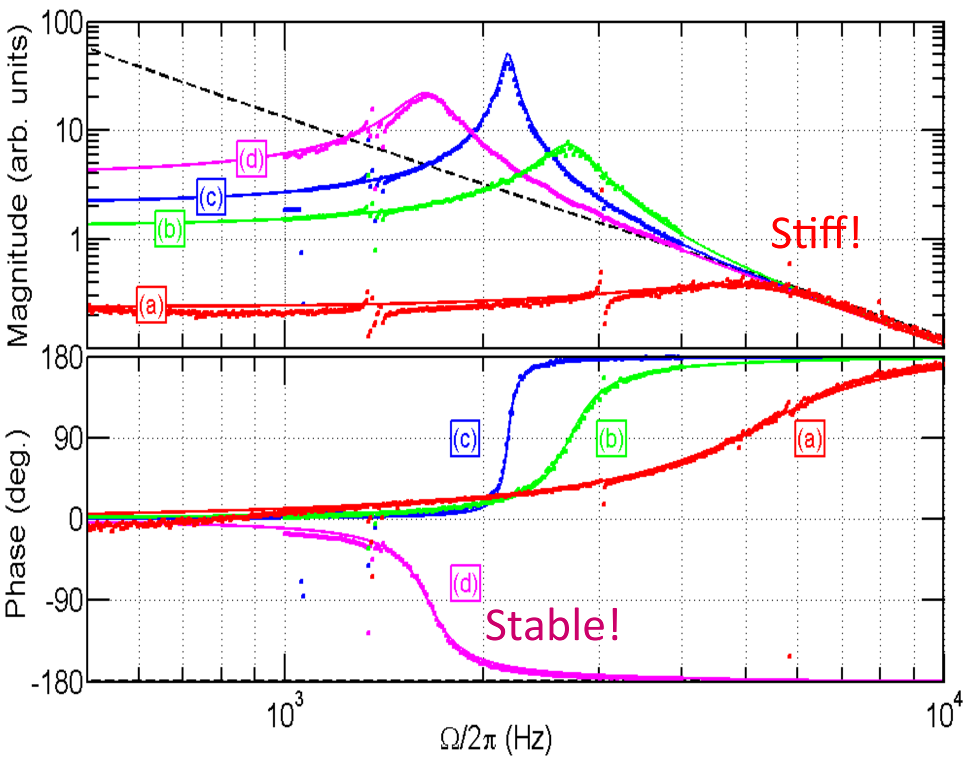


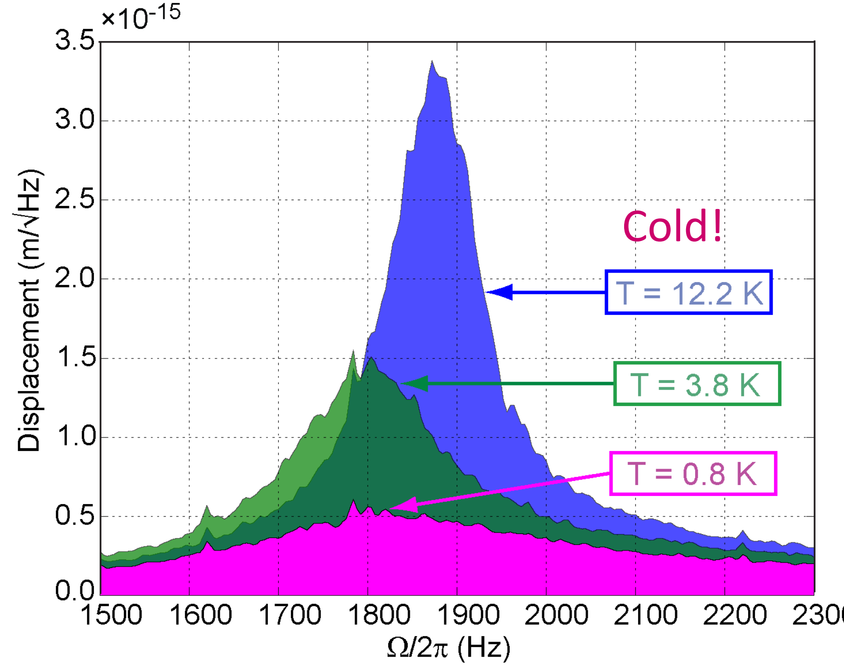


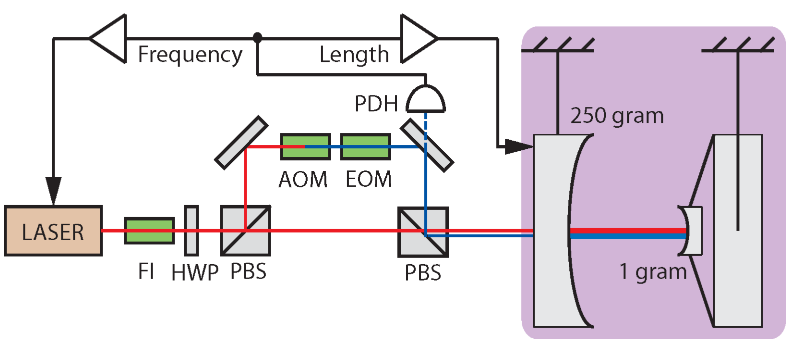
Corbitt et al., Phys. Rev. Lett. 98, 150802 (2007)



All-Optical Trap for a 1 Gram Mirror







- Stiff optical springs!
  Cavity mode => diamond rod
- Stable optical trap using two light fields, opposite detuning
- Cooling limited by laser noise

Corbitt et al., Phys. Rev. Lett. 98, 150802 (2007)

Quantum Limit of Cavity Cooling

- Mirror oscillator is heated by quantum radiation pressure fluctuations
- Limiting occupation number is

$$N \approx \frac{1}{2}\frac{\gamma_c}{\Omega_{\rm eff}} \quad (\Omega_{\rm eff} \lesssim \gamma_c)$$

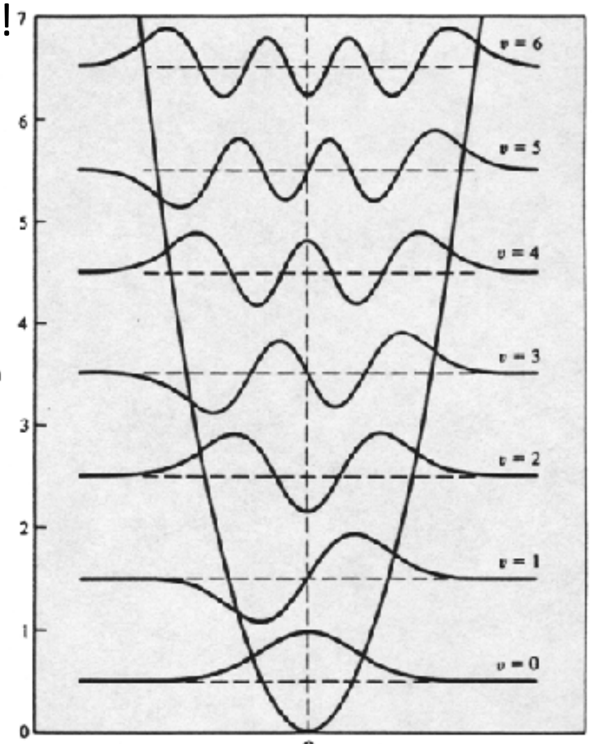
~~"bad cavity"~~
good measurement!

$$N \approx \frac{1}{4}\frac{\gamma_c^2}{\Omega_{\rm eff}^2} \quad (\Omega_{\rm eff} \gtrsim \gamma_c)$$

~~"good cavity"~~
bad measurement!

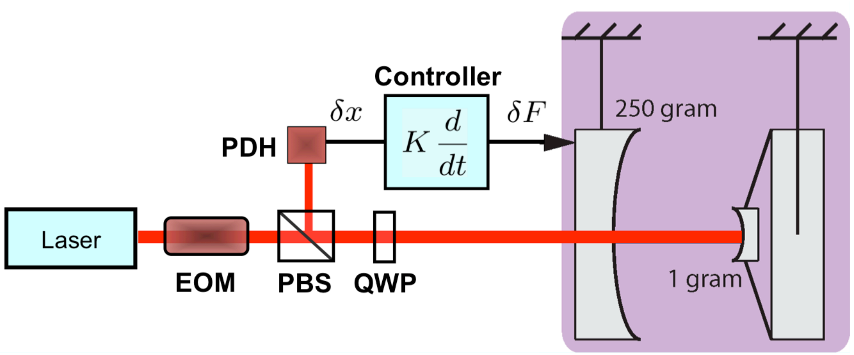
(with coherent state input)

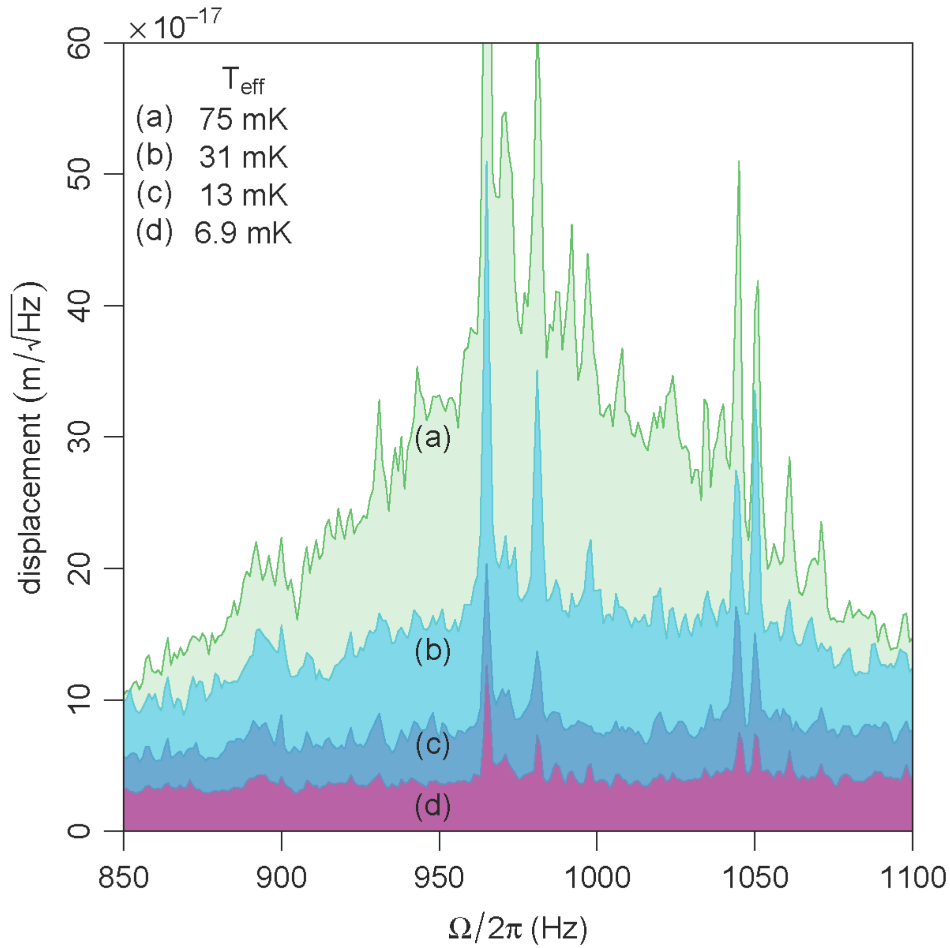
- Powerful cooling technique for micro-mechanics --- not optimal for the gram-scale system



Optical Trapping, Feedback Cooling

- Shortened cavity for reduced laser noise
- Electronic feedback of mirror displacement signal
  - Damps and stabilizes the optical spring
  - Plays to the strength of a "good measurement" cavity
  - Variant of previously known "cold damping" techniques
- Still limited by laser noise!

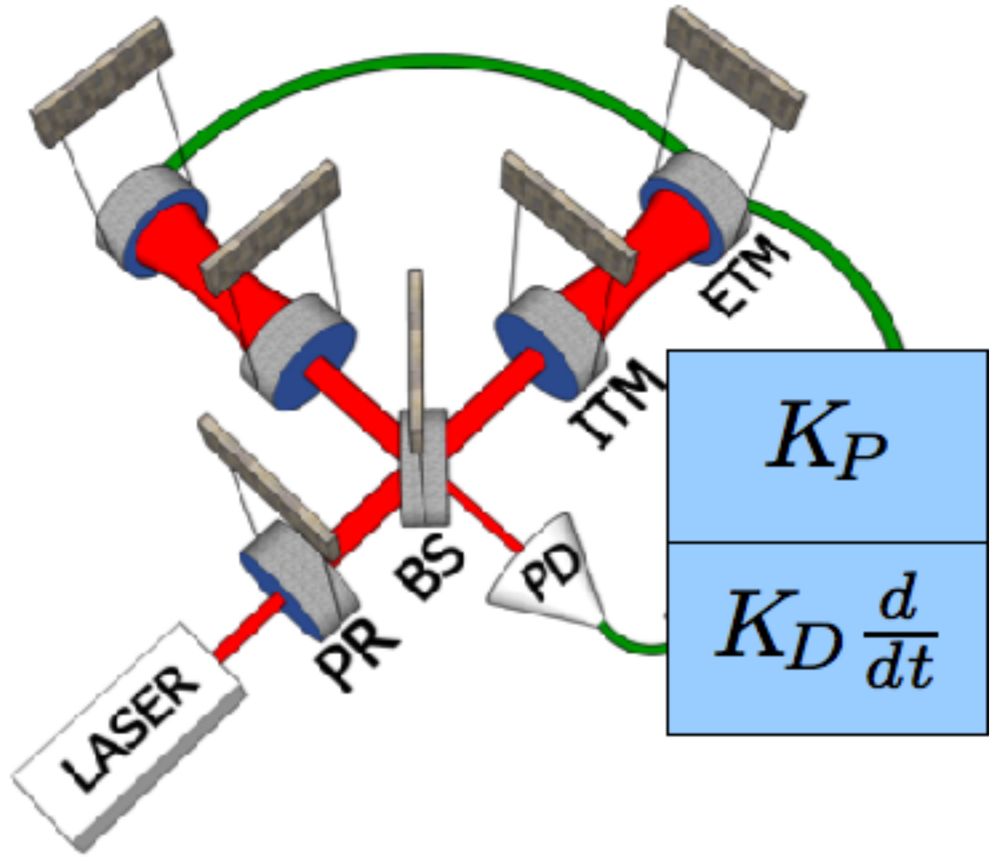




Corbitt et al., Phys. Rev. Lett. 99, 160801 (2007)

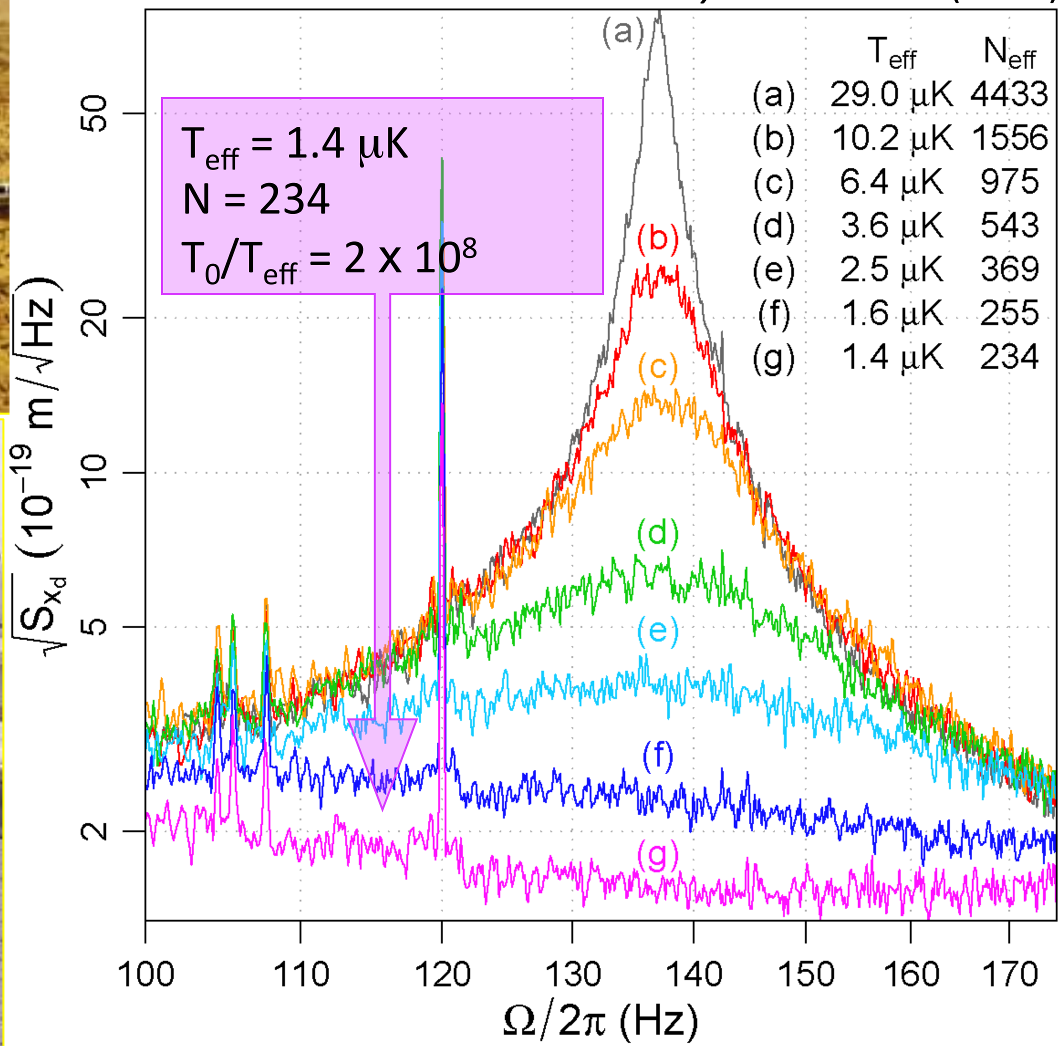
Electro-Optical Trap

- Strong optical damping/restoring forces not available in Initial LIGO
- Instead, damping and restoring forces may be synthesized via feedback
  - Derivative feedback => cold damping
  - Proportional feedback => servo spring



Cooling of LIGO Mirrors

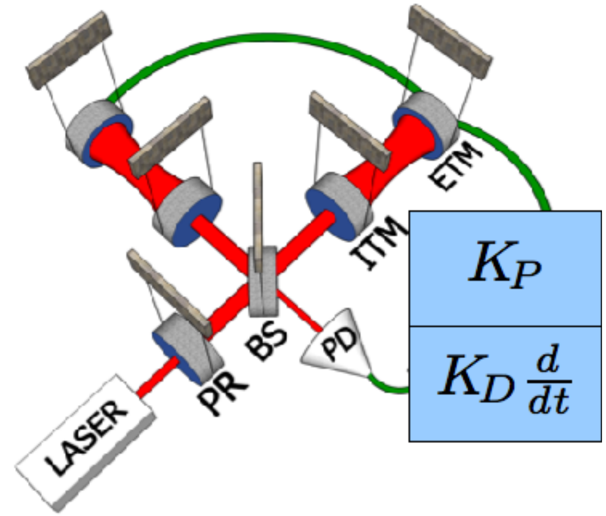
New J. Phys. **11** 073032 (2009)

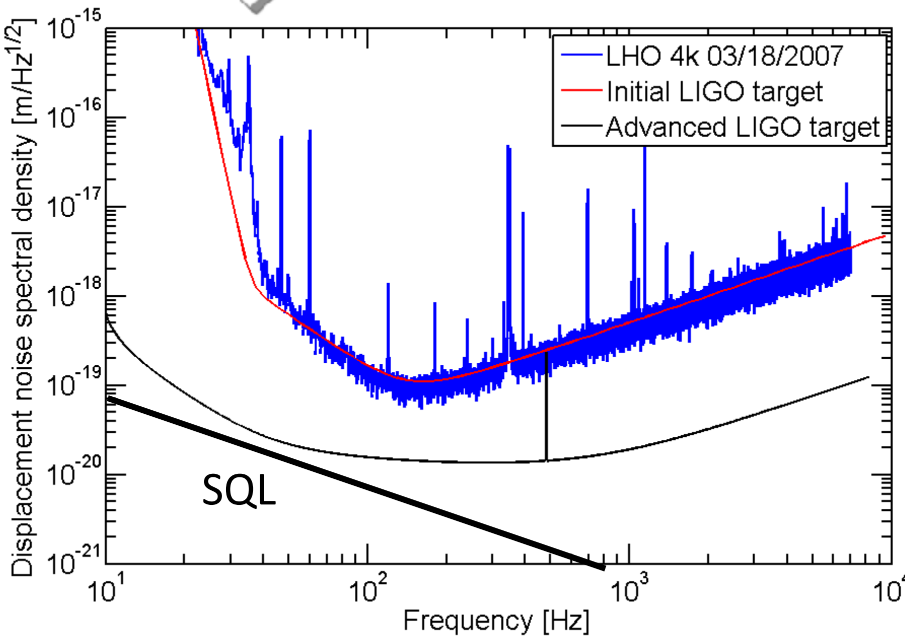


Reaching the SQL Enables Ground State Cooling

- Optimal feedback strategy has two parts
  - Shift the oscillator to the frequency of closest approach to the SQL
  - Subtract energy with a cold damping force
- Resulting occupation:

$$N_{\rm opt} = \frac{k_B T_{\rm eff}}{\hbar \Omega_{\rm eff}} \approx \frac{S_x(\Omega_{\rm eff})}{S_x^{\rm (SQL)}(\Omega_{\rm eff})}$$





Danilishin et al., arXiv:0809.2024

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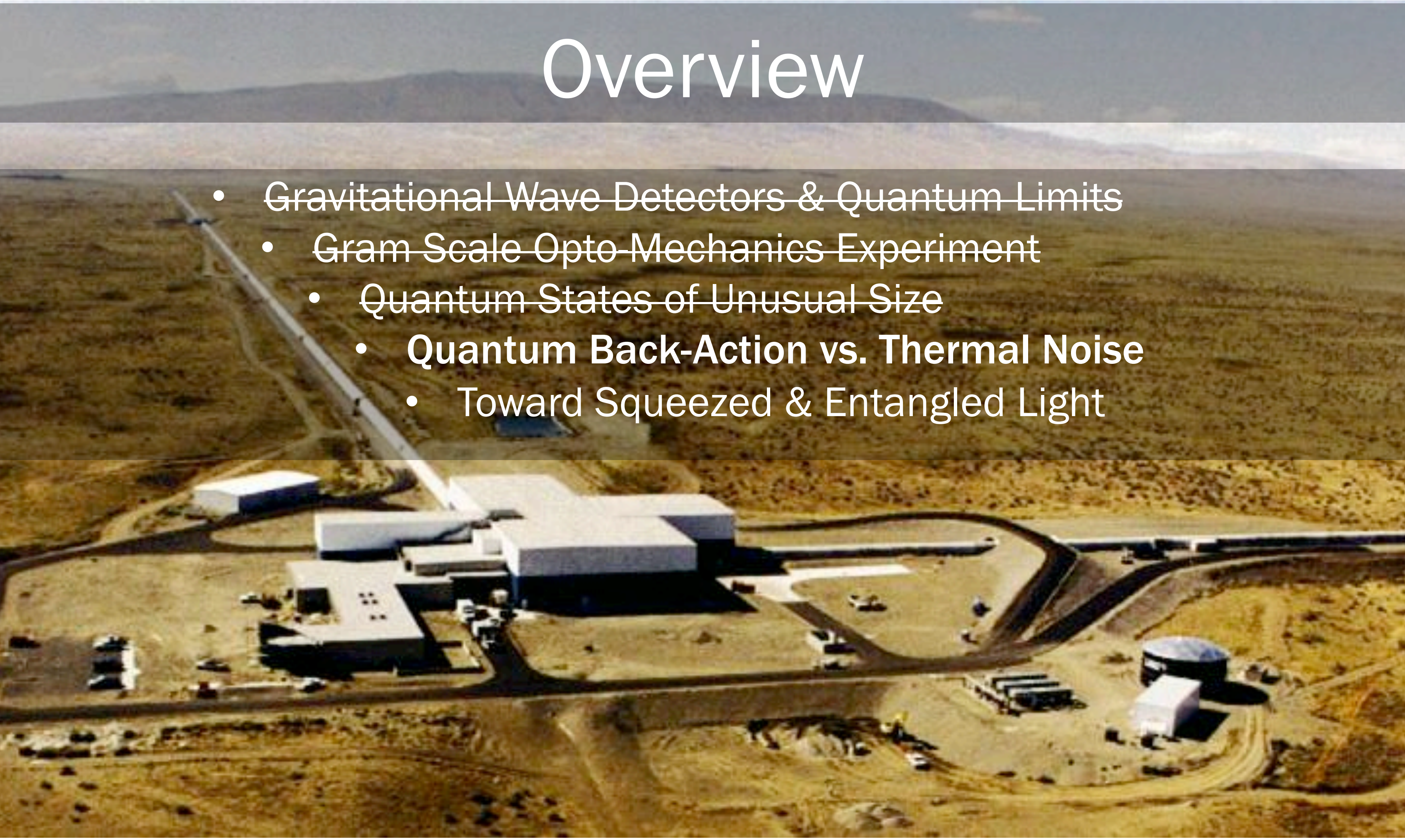
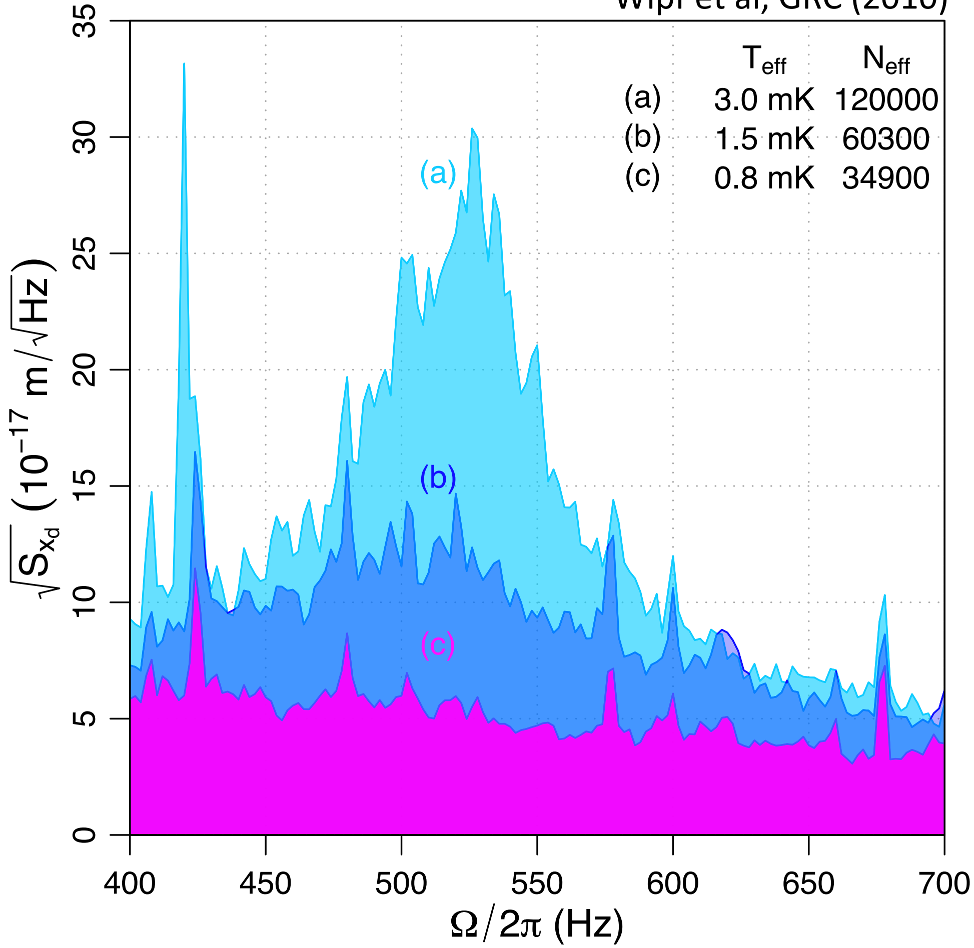


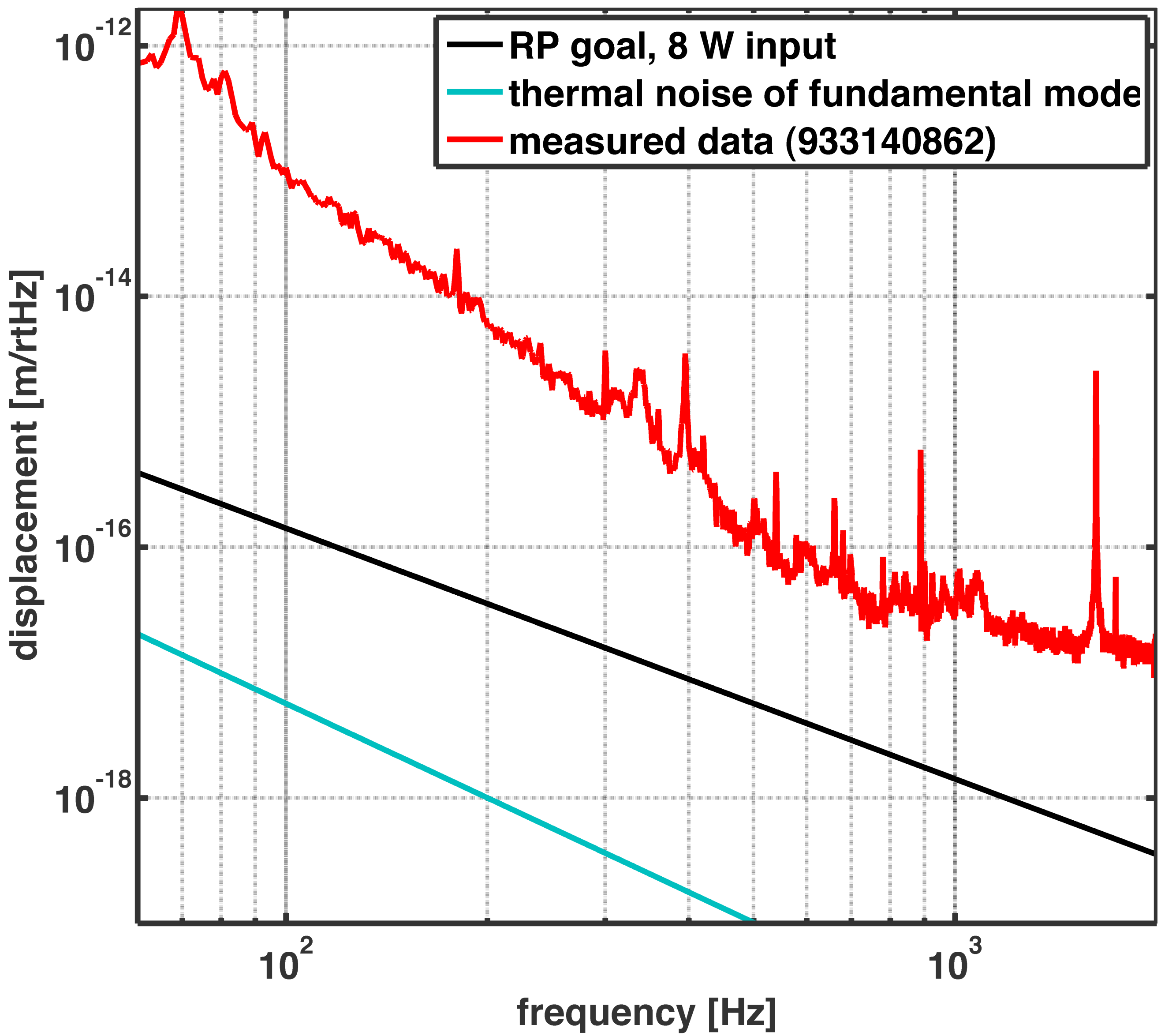
Benchmark Cooling Run

- Early experiment with the completed testbed interferometer
- Another demonstration of feedback cooling and trapping technique
- Michelson subtraction of laser noise in the differential readout
- ~10x colder than single-cavity feedback cooling result
- Noise floor = ???

Wipf et al, GRC (2010)



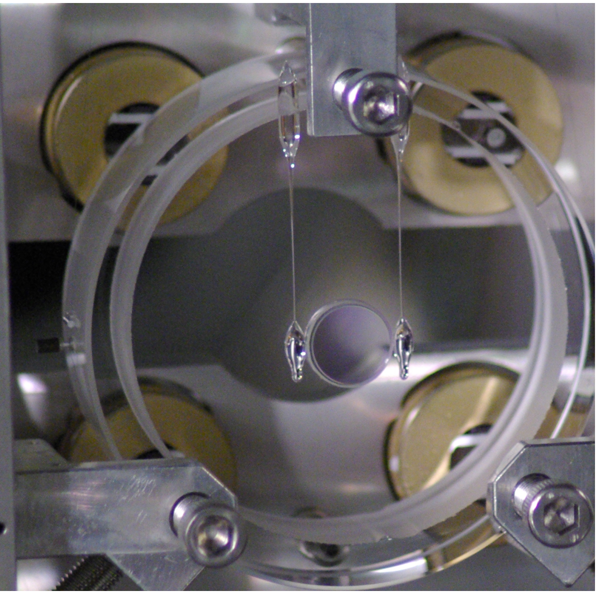
Initial Situation

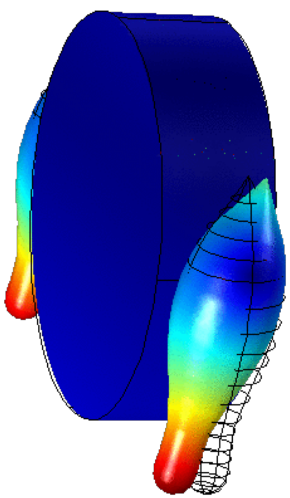


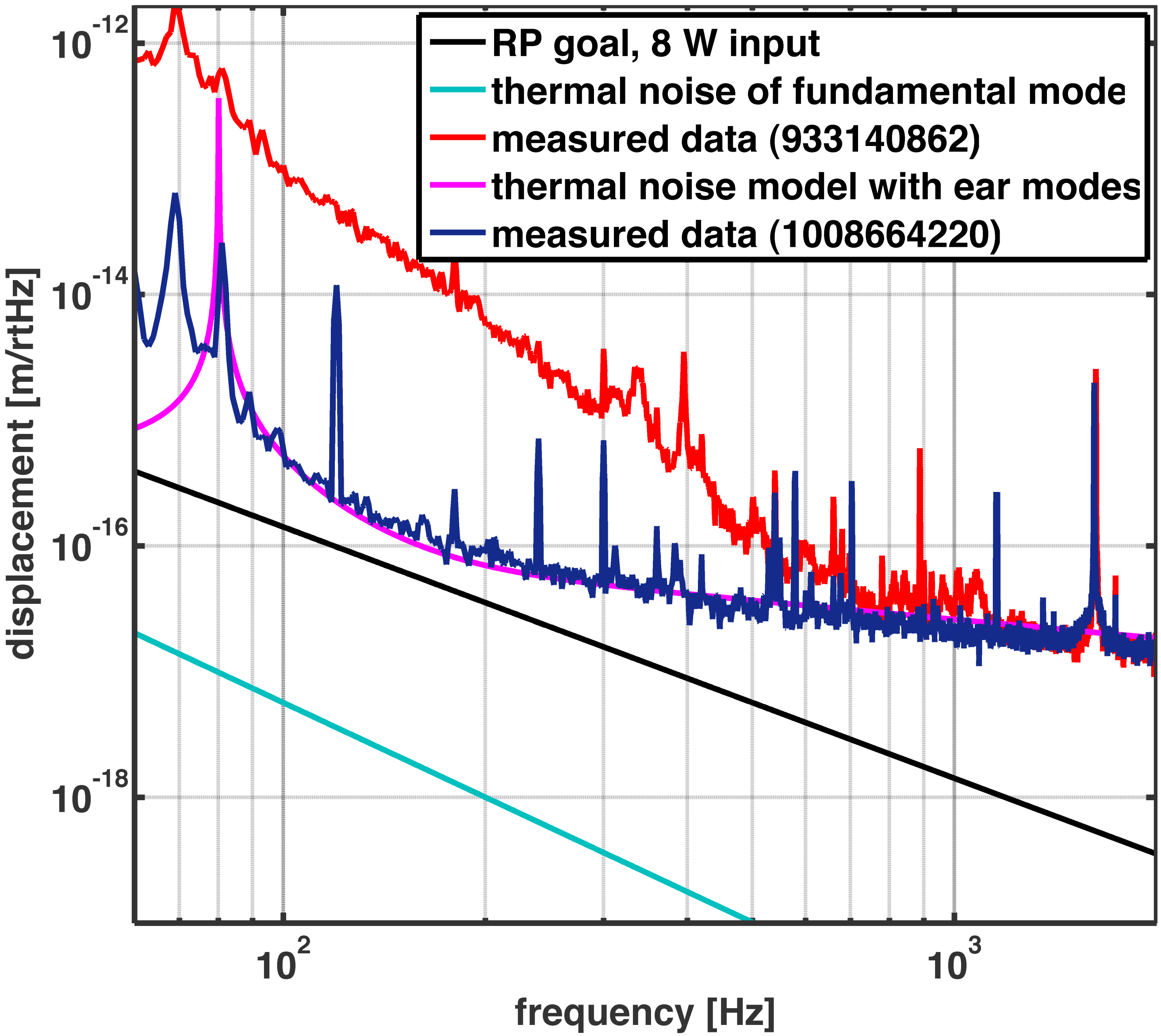
Debugging


Quake Term
dacOut[jj][ii] = -limit;
overflowDac[jj][ii] ++;
// pLocalEpics->epicsOutput.ovAccum ++;
overflowAcc ++;
diagWord |= 0x1000 * (jj+1);
}
#ifdef DAC_NOISE_SHAPING
dacOutState[jj][ii] += 65536 * dacOut[jj][ii];
int dac_out = dacOutState[jj][ii] >> 16;
dacOutState[jj][ii] -= dac_out << 16;
#else
int dac_out = dacOut[jj][ii];
#endif
dac_out += offset;
// if ((ii == 0) && (jj == 2) && (clock16K == 0)) printf("%d
*pDacData = (unsigned int)(dac_out & mask);
pDacData ++;
}
#ifdef OVERSAMPLE_DAC
}
#endif
// DMA out dac values
gsaDacDma2(jj,cdsPciModules.dacType[jj]);
controller.c lines 1126-1148/1702 65%
CCD
N50

Achieving the Thermal Noise Limit

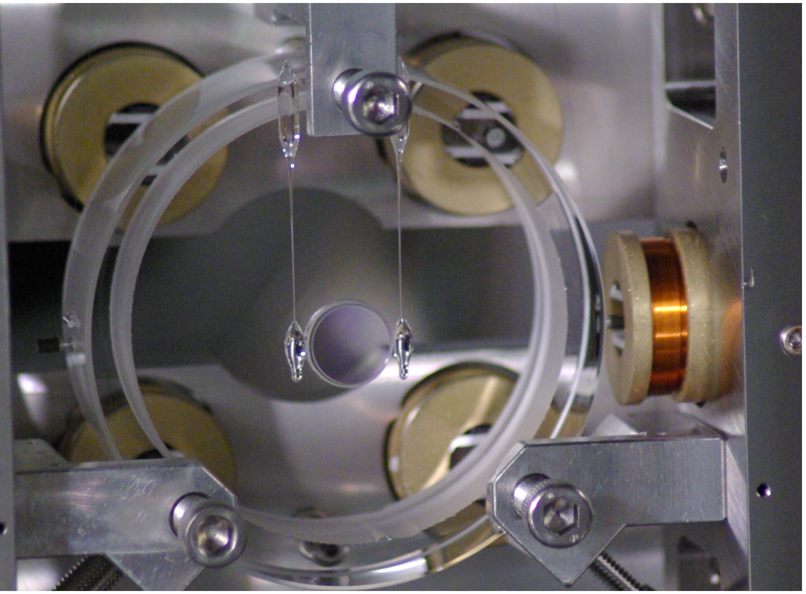


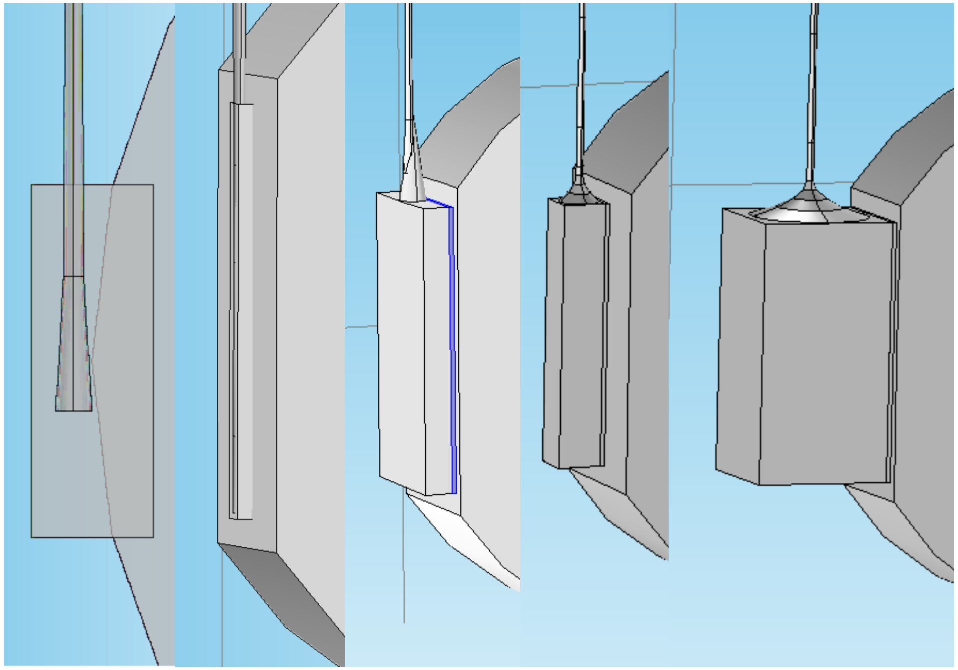


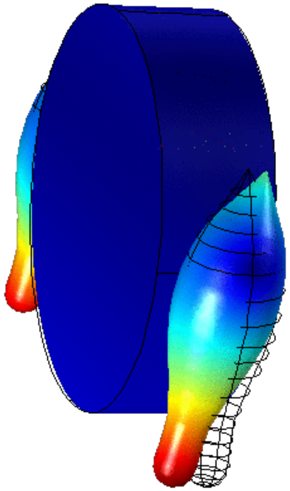


A. Neben et al, New J. Phys **14** 115008

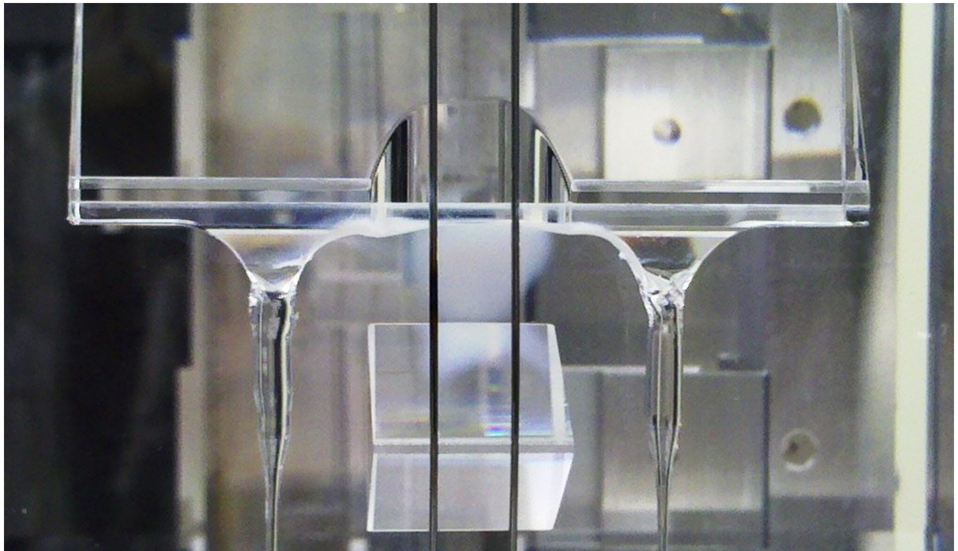
New Suspensions



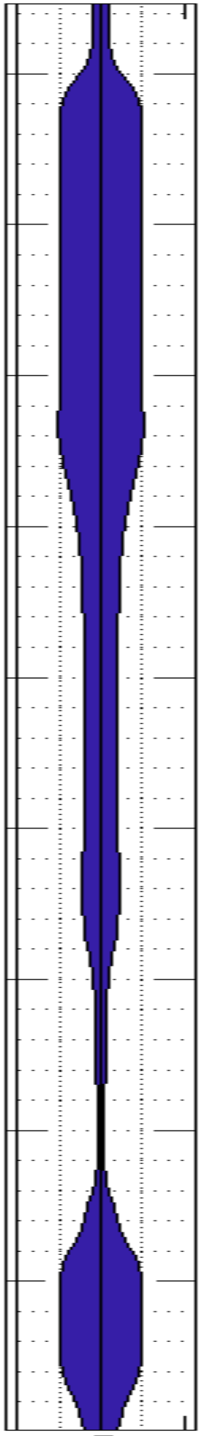


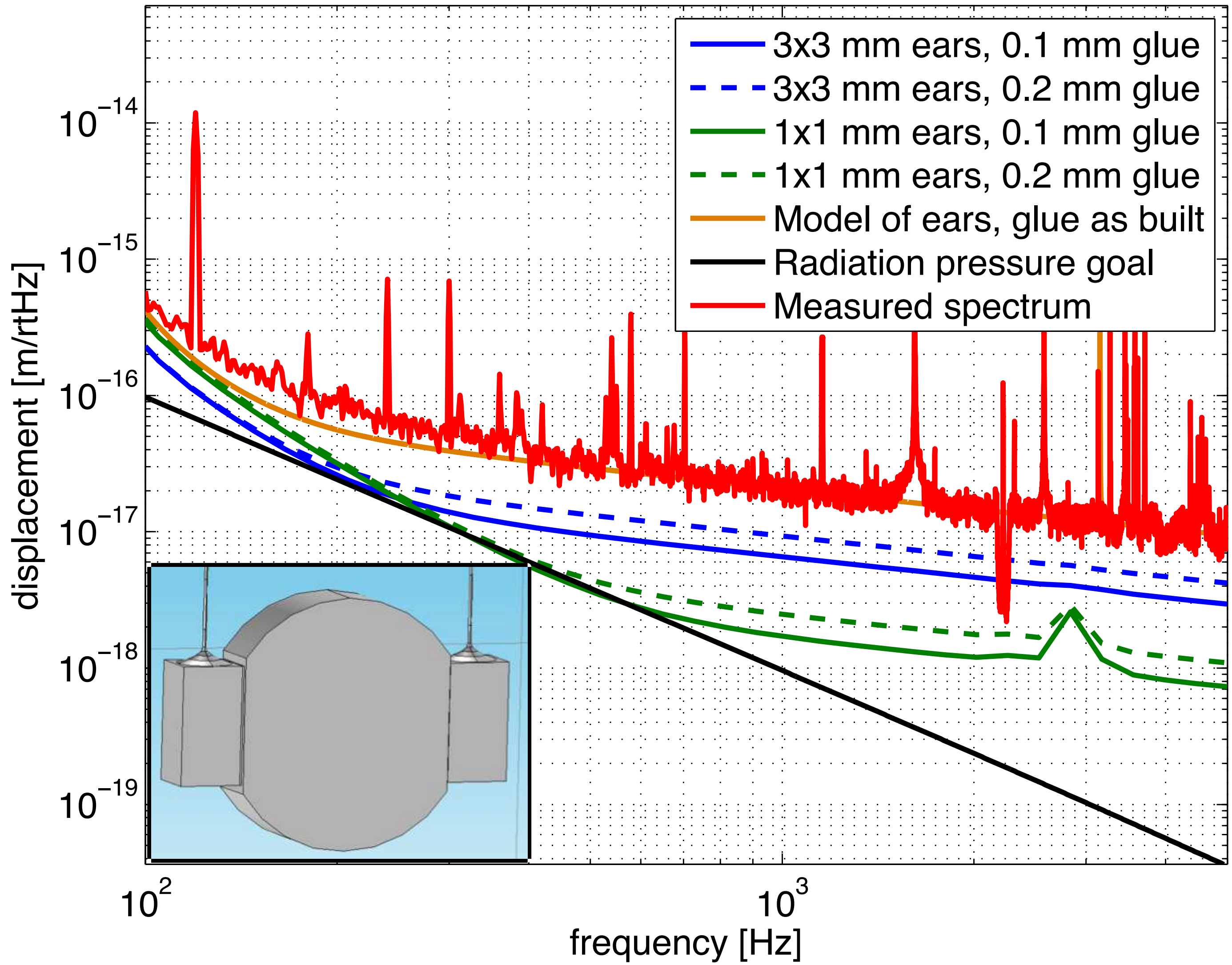


A. Neben et al, New J. Phys **14** 115008



New Suspensions





T. Bodiya ilog 12/2012

A. Neben et al, New J. Phys **14** 115008

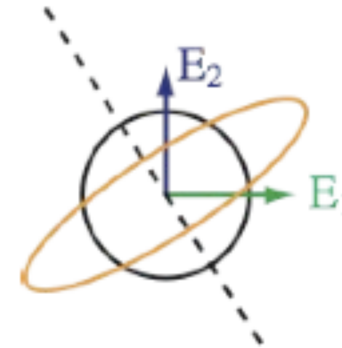
Overview

- ~~Gravitational Wave Detectors & Quantum Limits~~
  - ~~Gram Scale Opto-Mechanics Experiment~~
    - ~~Quantum States of Unusual Size~~
      - ~~Quantum Back-Action vs. Thermal Noise~~
        - **Toward Squeezed & Entangled Light**

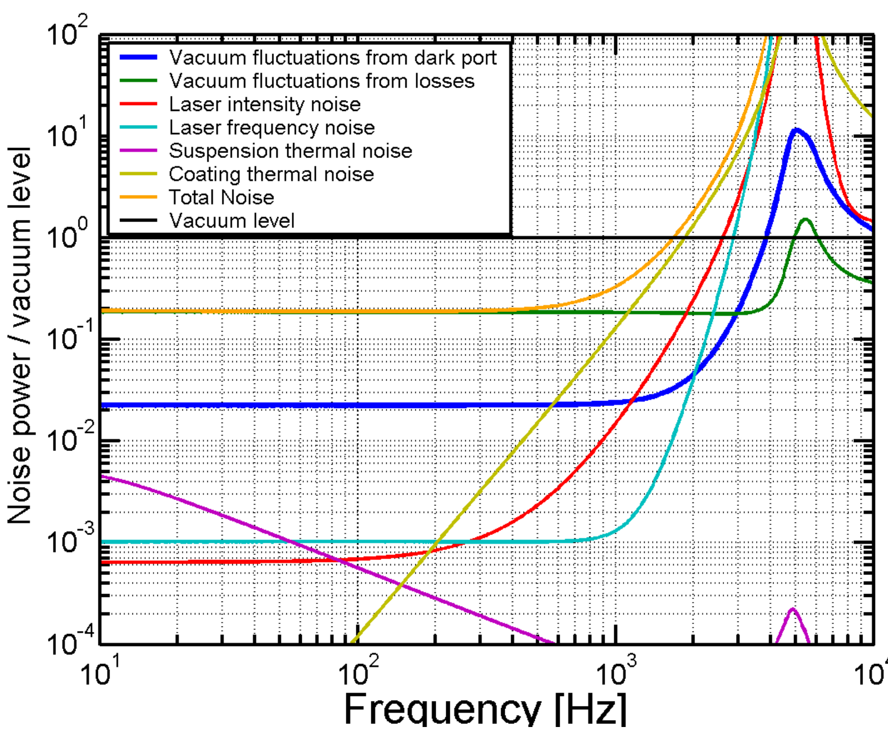
Optical Spring Assisted Squeezing

- Radiation pressure correlates amplitude and phase quadratures

$$E_1^{\text{out}} = E_1^{\text{in}}$$
$$E_2^{\text{out}} = E_2^{\text{in}} - \frac{I}{M\Omega^2} E_1^{\text{in}}$$



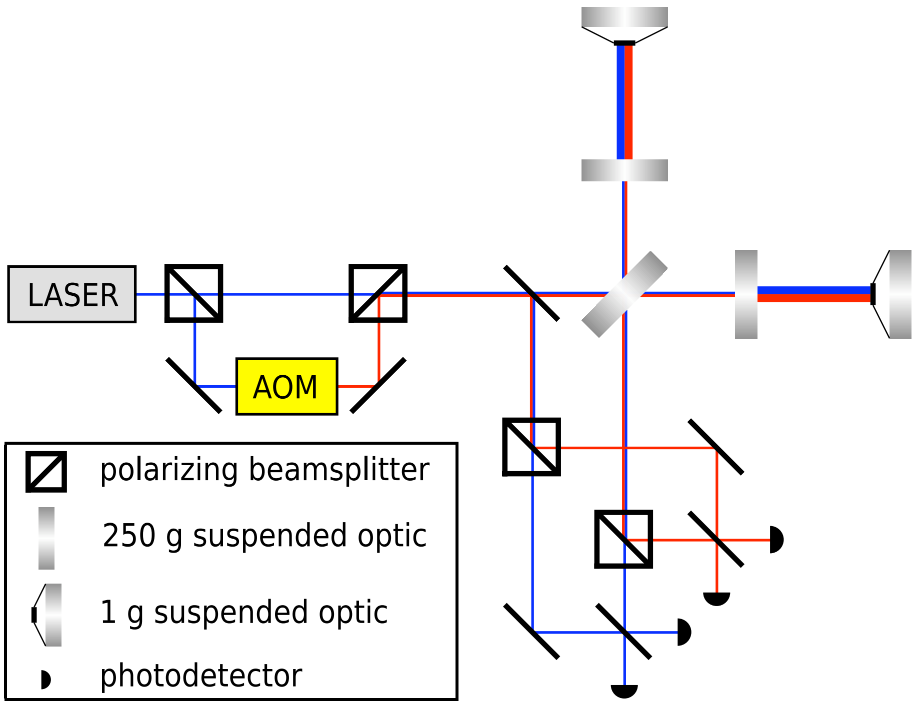
- Stiff optical spring enables broadband, frequency independent squeezing
- 7 dB squeezing predicted (if thermal noise requirements are met)



Corbitt et al., Phys. Rev. A 73, 023801 (2006)

Quantum Correlations in the Double Spring Optical Trap

- Mirror driven by RP of two optical fields should generate quantum correlations linking both
- Quadrature Squeezing => Quadrature Entanglement
- Need to read out multiple quadratures of both fields to verify the entanglement (homodyne tomography)



Entanglement

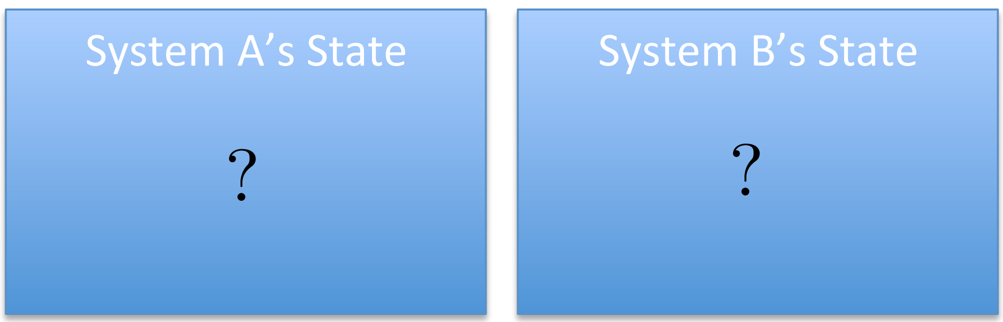
- Simplest case: two discrete systems
  Joint state: $|\psi\rangle_A|\psi\rangle_B = |0\rangle_A|1\rangle_B$

System A's State	System B's State
$|\psi\rangle_A = |0\rangle$	$|\psi\rangle_B = |1\rangle$

- We have complete knowledge of the system and can write down the state of each part separately

Entanglement

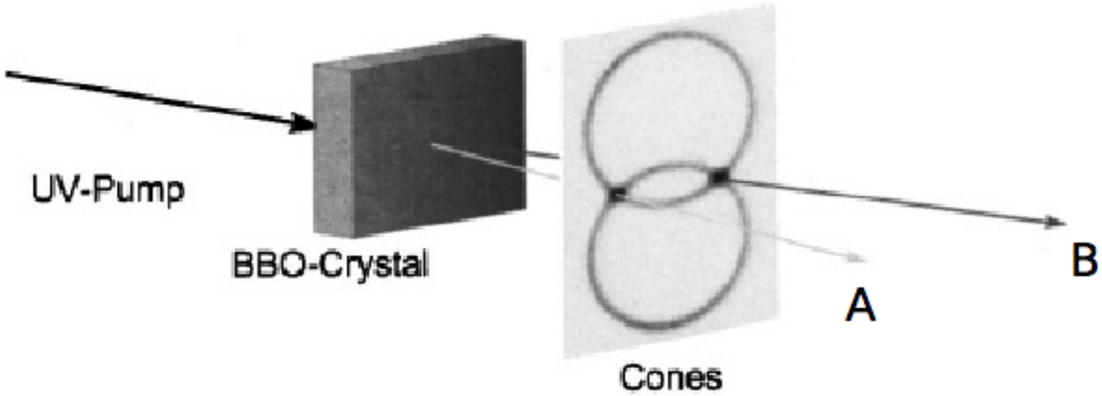
- Simplest case: two discrete systems
  Joint state: $|\psi\rangle_A|\psi\rangle_B = \frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)$



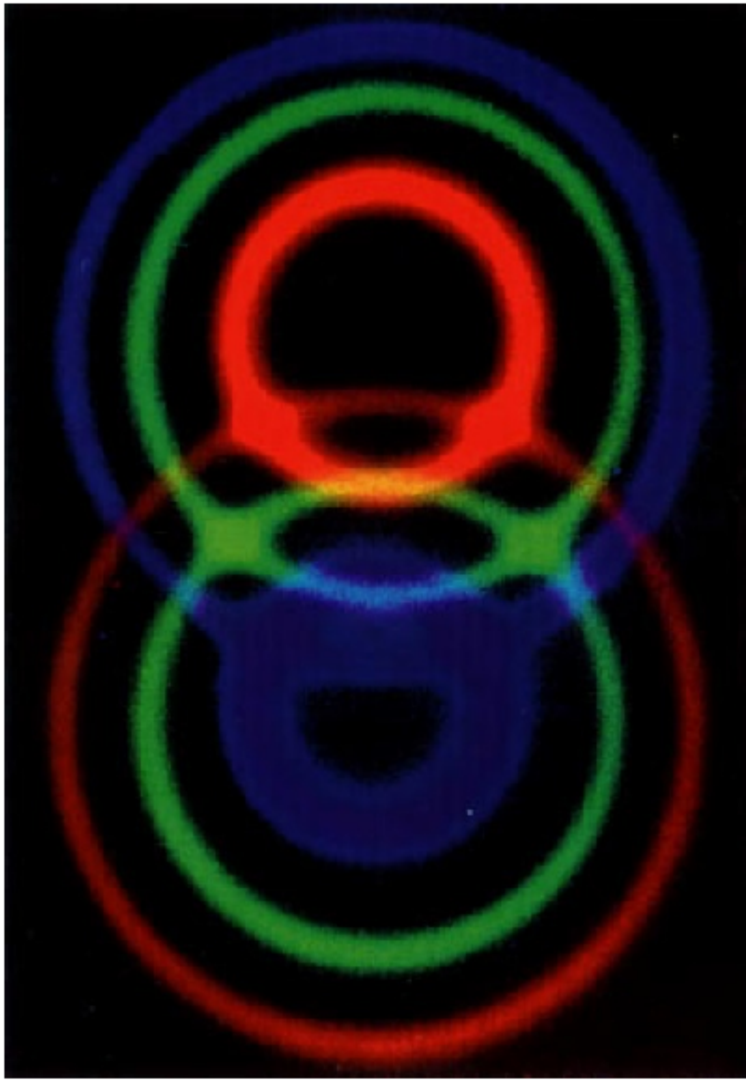
- This joint state is *entangled*: the state of A can no longer be described on its own (without reference to B)

Optical Realization of Entanglement

Photon polarization

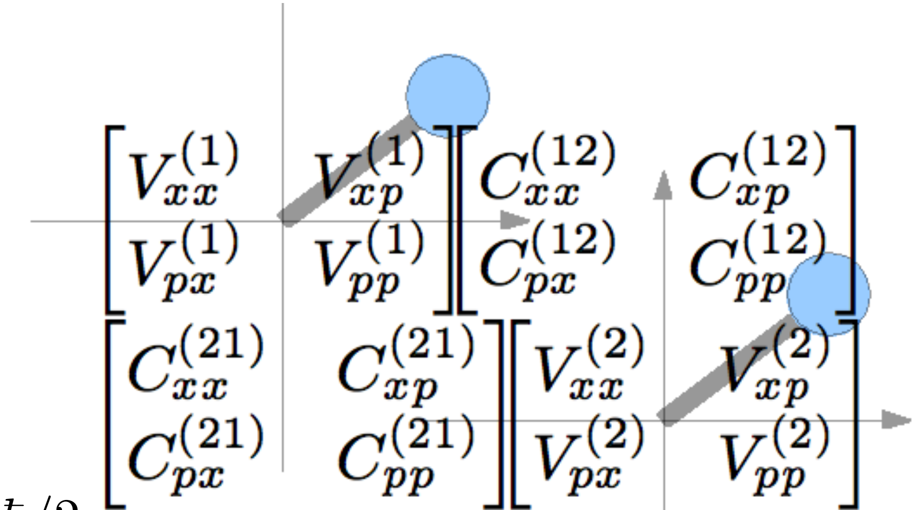


$$|\psi\rangle_{\text{joint}} = \frac{1}{\sqrt{2}}\left(|H\rangle_A|V\rangle_B + |V\rangle_A|H\rangle_B\right)$$



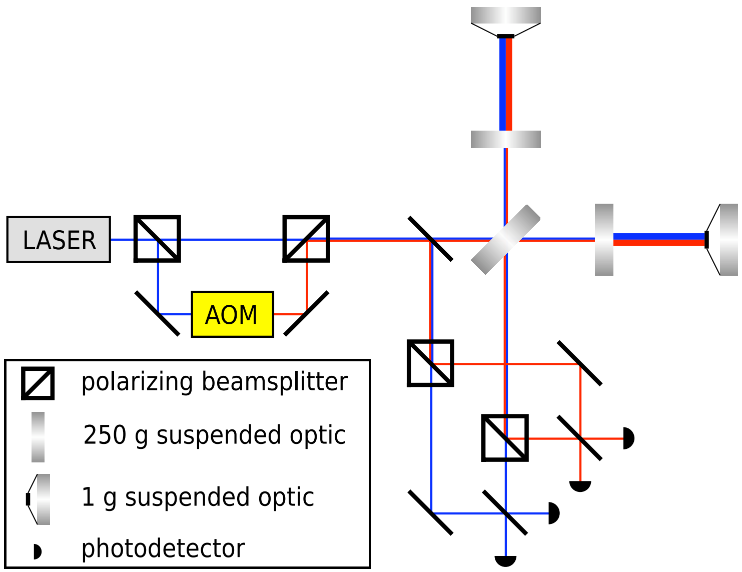
Zeilinger, RMP **71** S288, 1999

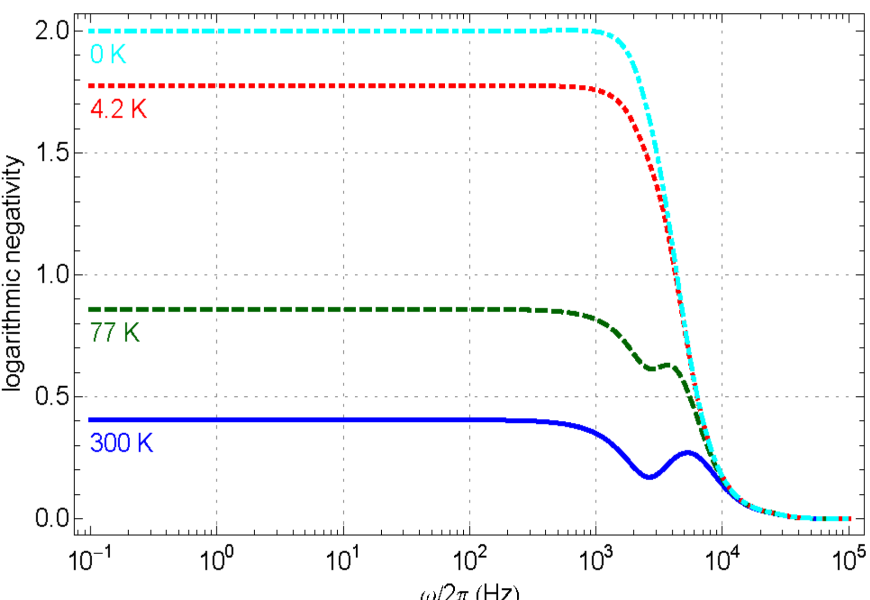
Quantification of Entanglement



- Ensemble of homodyne detector measurements gives us a variance matrix.
  Is it entangled?
- Variance matrix is constrained by an uncertainty principle, the matrix generalization of $\Delta x \Delta p \geq \hbar/2$
- The time reversed (*p* => -*p*) variance matrix must also satisfy the same constraint
- Simon's entanglement criterion
  - Apply time reversal to *one subsystem only*
  - If the state is entangled, this operation is unphysical, so there may be a violation of the uncertainty principle
- "Logarithmic Negativity" entanglement measure is based on quantifying this violation

Double Spring Assisted Entanglement





- Mirror driven by quantum RP of multiple optical fields generates quantum entanglement
- Exploits advantages of the optical trap configuration
  - High power stability permits strong coupling via the mirror
  - Optical entanglement becomes robust against thermal noise
  - Possible to entangle fields of different wavelengths

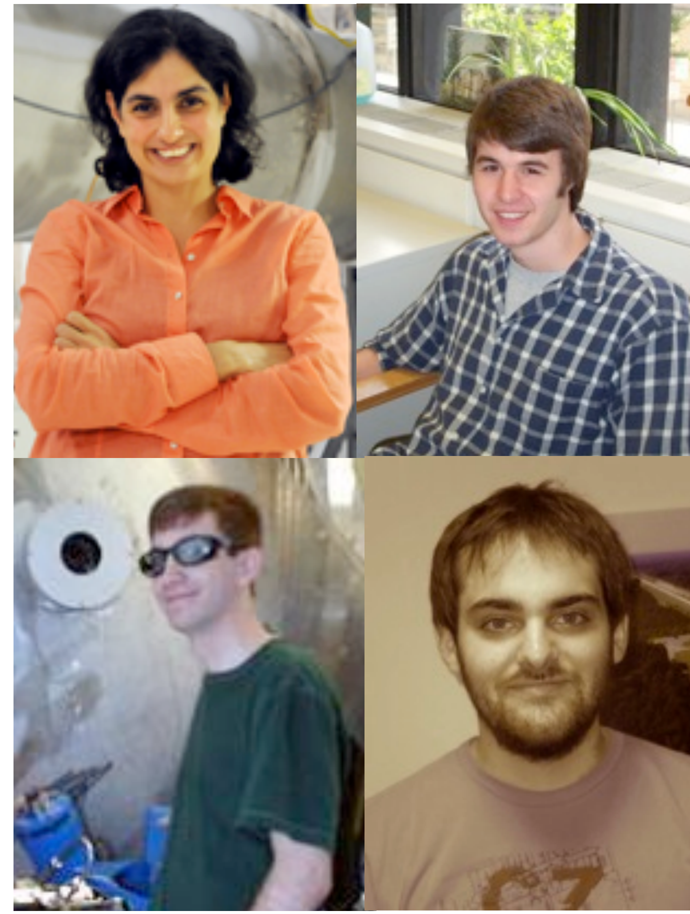
Wipf et al, New J. Phys 10, 095017 (2008)

Summary

- GW detectors now being built will:
  - Attain the Standard Quantum Limit
  - Approach the ground state of motion of their kg-scale test masses
  - Detect gravitational waves
- Gram-scale experiment has demonstrated:
  - Classical radiation pressure forces that dominate over the mechanical forces
  - Trapping and cooling with RP and feedback, laser noise limited
  - Cancellation of laser noise in the Michelson configuration
  - Broadband sensitivity reaching the limit set by suspension thermal noise
- A suspension upgrade to mitigate the thermal noise should reveal:
  - Quantum radiation pressure
  - Squeezing and entanglement

Closing Credits

- Prof. Nergis Mavalvala
- Thomas Corbitt, Tim Bodiya, Eric Oelker, Abraham Neben
- Sarah Ackley, Nancy Aggarwal, Lisa Barsotti, Rolf Bork, Yanbei Chen, Fred Donovan, Sheila Dwyer, Matt Evans, Peter Fritschel, Edith Innerhofer, Tomoki Isogai, Alex Ivanov, Junghyun Lee, Myron MacInnis, Fabrice Matichard, Rich Mittleman, Helge Müller-Ebhardt, David Ottaway, Henning Rehbein, Daniel Sigg, Nicolás Smith-Lefebvre, Stan Whitcomb, Marie Woods, Mike Zucker
- LIGO Laboratory colleagues and the LIGO Scientific Collaboration



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