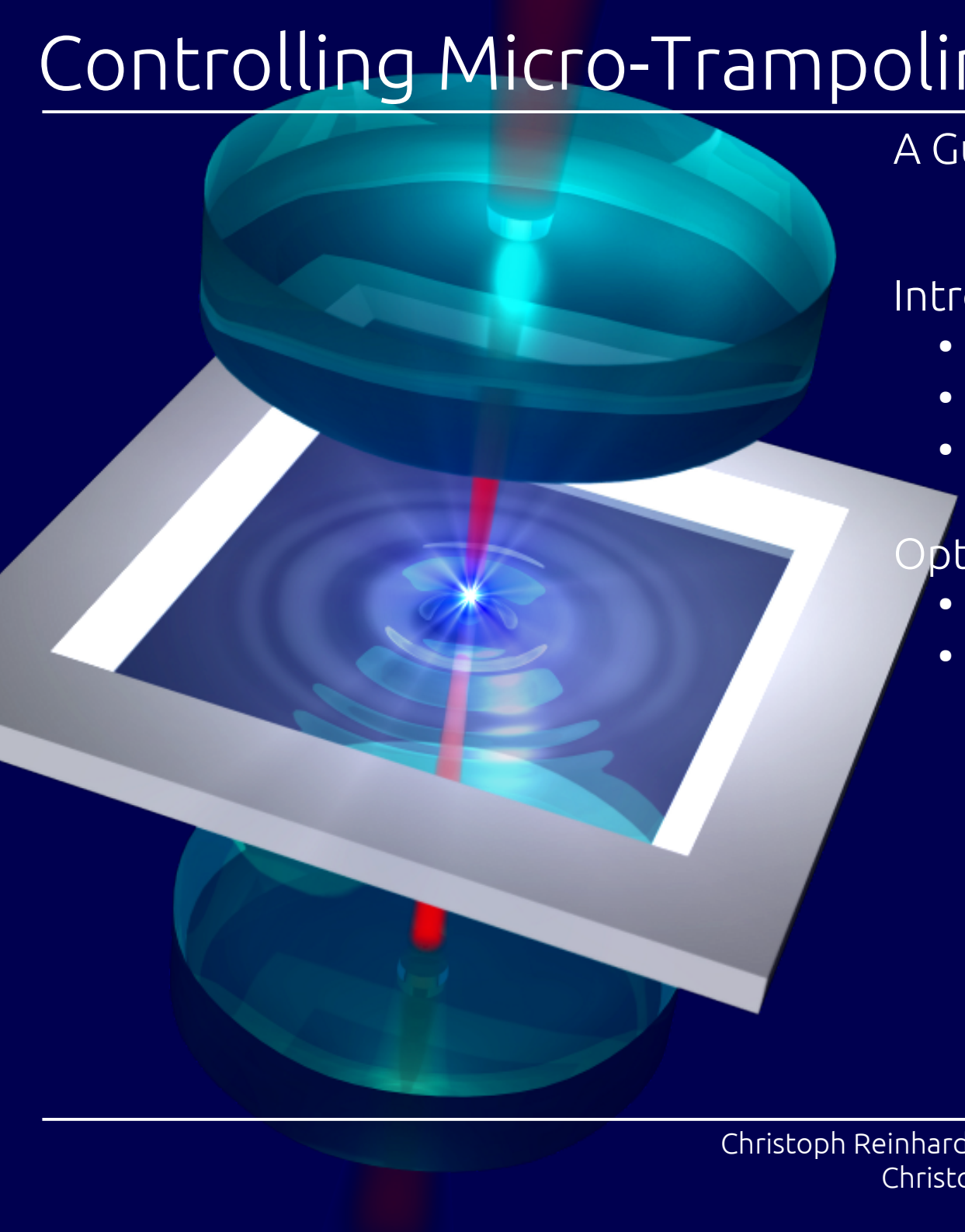
Controlling Micro-Trampolines with Light



A Guitarist's Guide to Optomechanics

Introduction

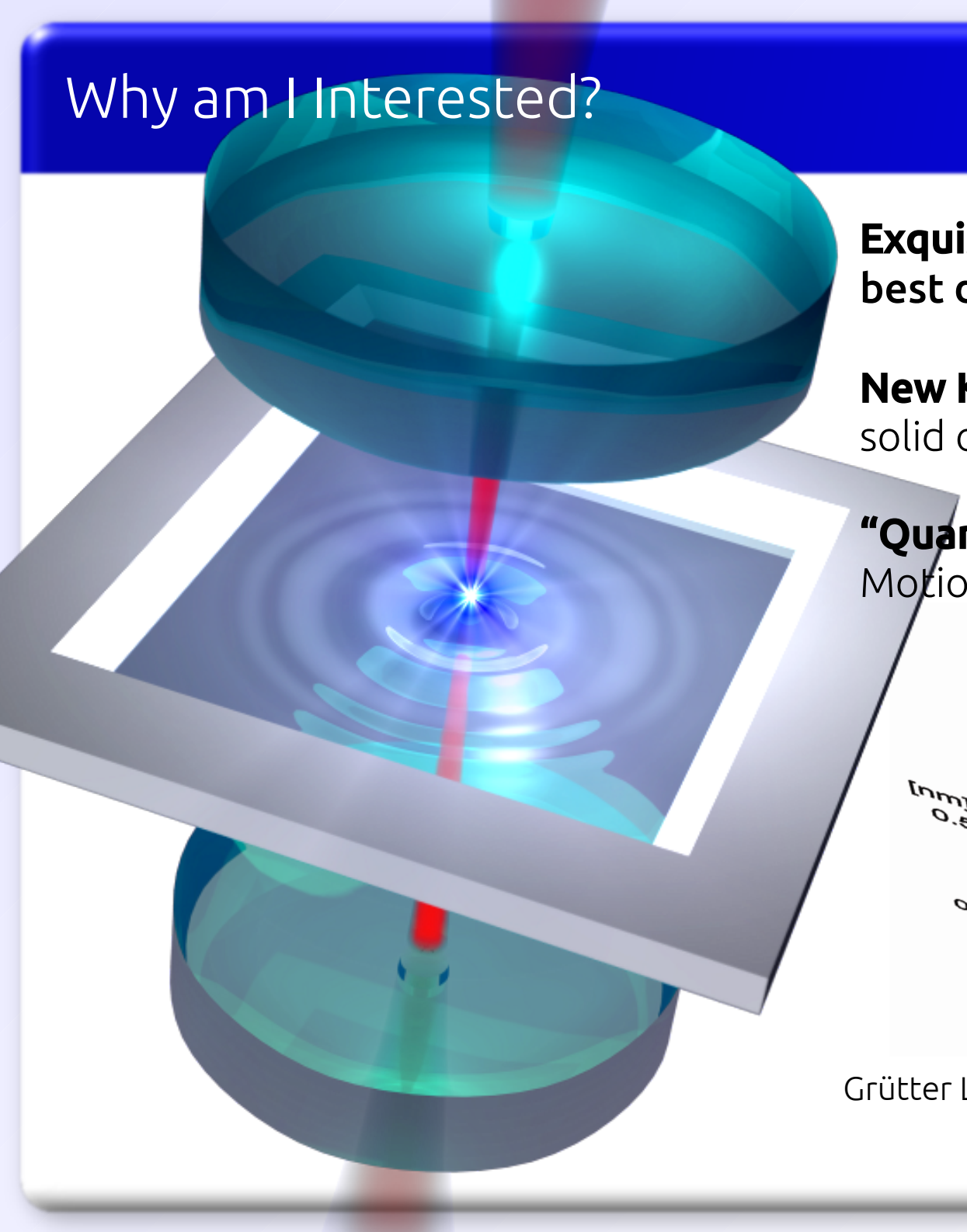
- Membranes are tuning forks
- Optical cavities are guitar strings
- Mechanical damping is annoying

Optomechanics Experiments

- Laser cooling
- Current goal: optically-levitated membranes, sorta

Christoph Reinhardt, Alexandre Bourassa, Xin Yuan Zhang, Julian Self
Christopher McNally, Perry Phillipopoulos & **Jack Sankey**

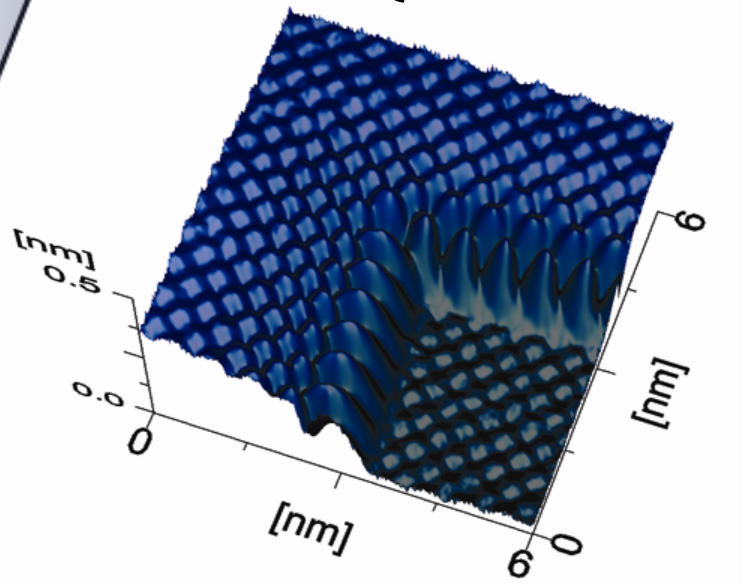
Why am I Interested?



Exquisite Force Detection (?): The best detectors see the best stuff.

New Knob to Turn: Optically tune a solid object's mechanical properties

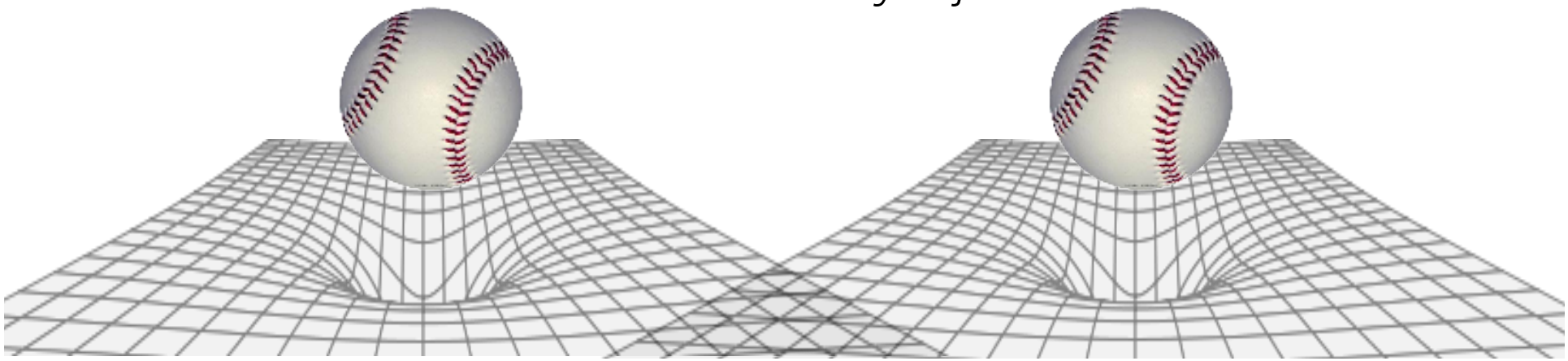
"Quantum" Stuff: Lasers Can Make Motion of Solids "Quantum"



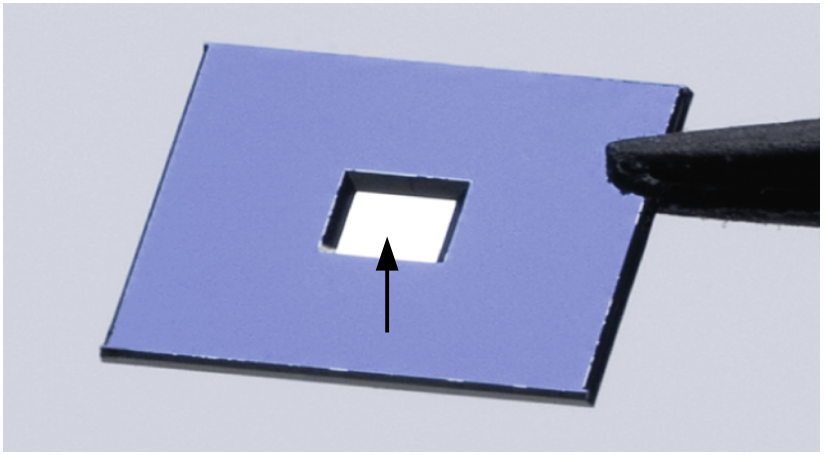
Grütter Lab measuring forces of individual atoms

Quantum Properties of Massive Objects?

Penrose: “Gravity might ruin quantum mechanics for heavy objects.”

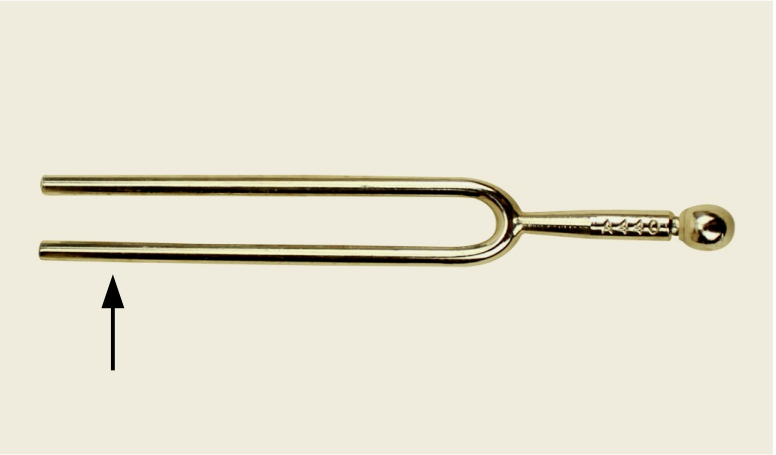


Membrane Basics: Frequency



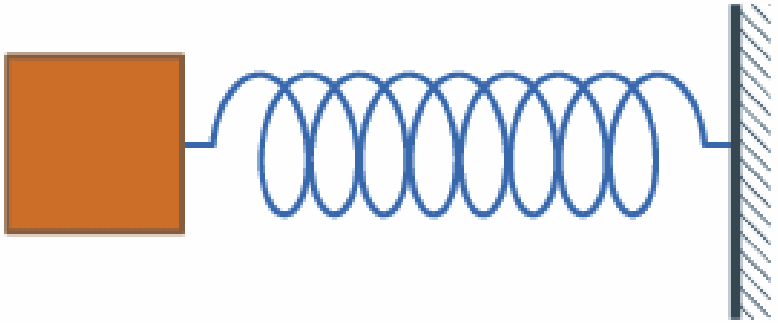
Mechanical Resonator: 1,000,000 Hz
0.00000005 grams (50 nm thick)

=

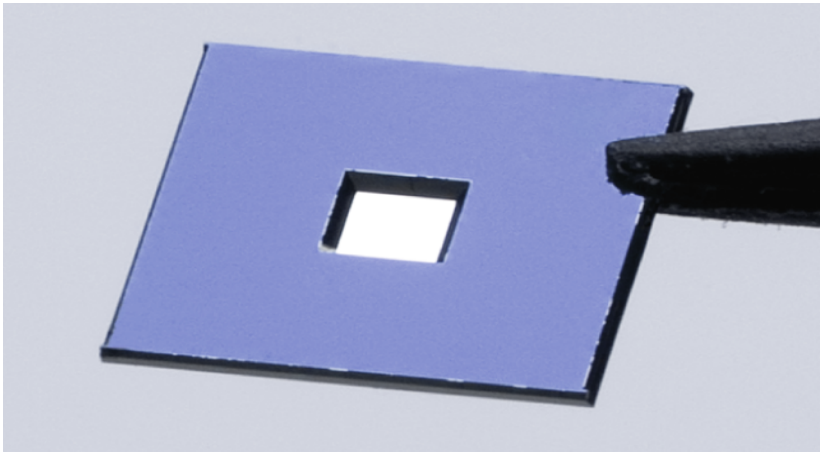


Mechanical Resonator: 440 Hz
about 50 grams

=

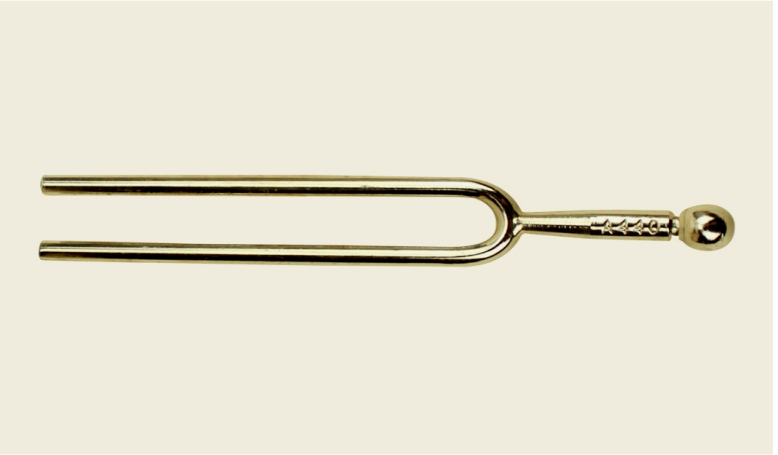


Membrane Basics: Damping



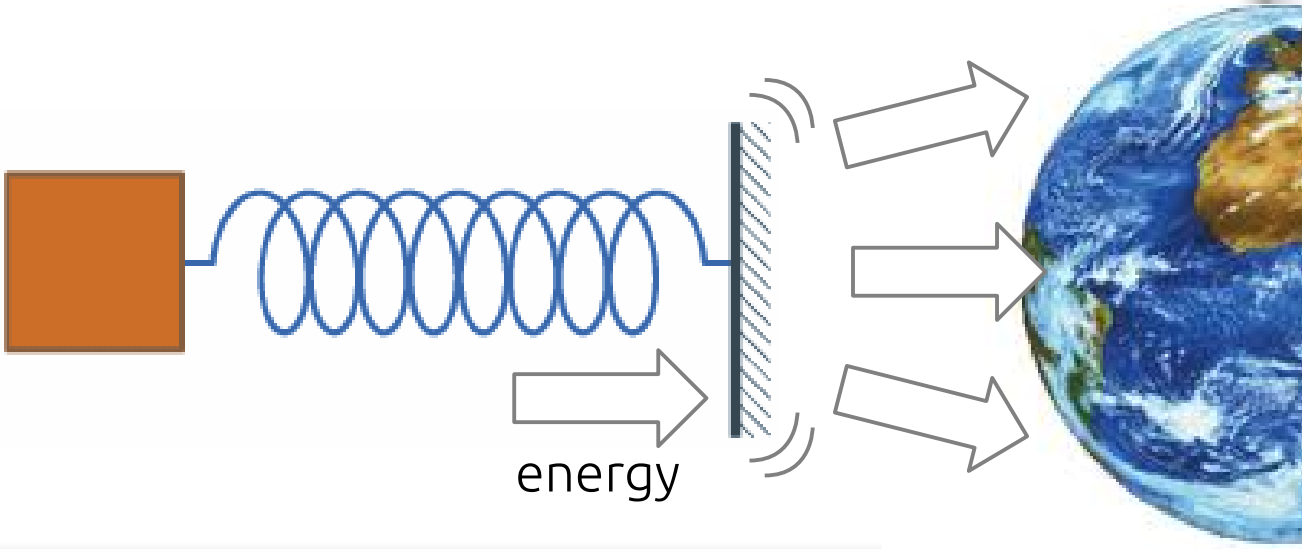
Rings for a few seconds
(about a million cycles)

=

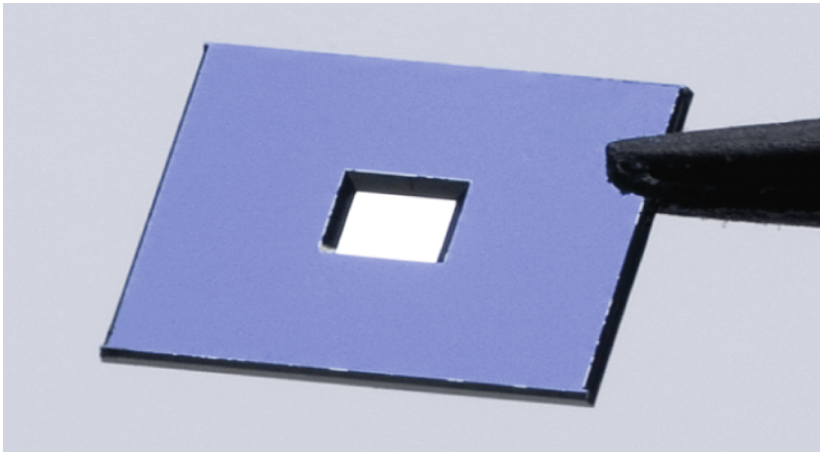


Rings for a few seconds
(about a thousand cycles)

=

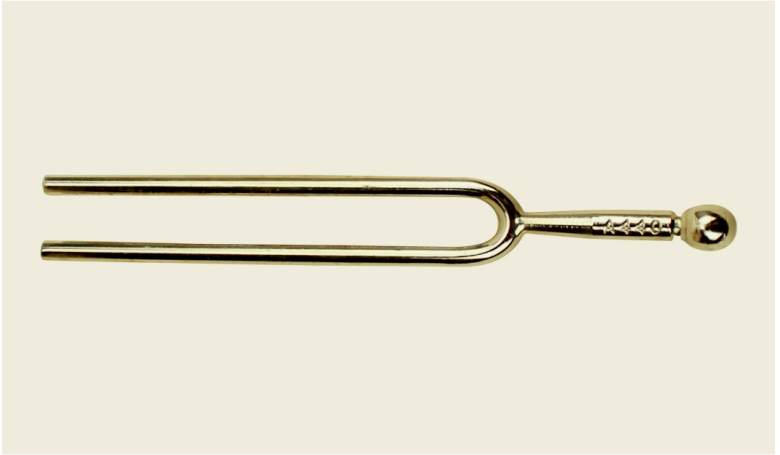


Membrane Basics: Damping



Rings for a few seconds
(about a million cycles)

=



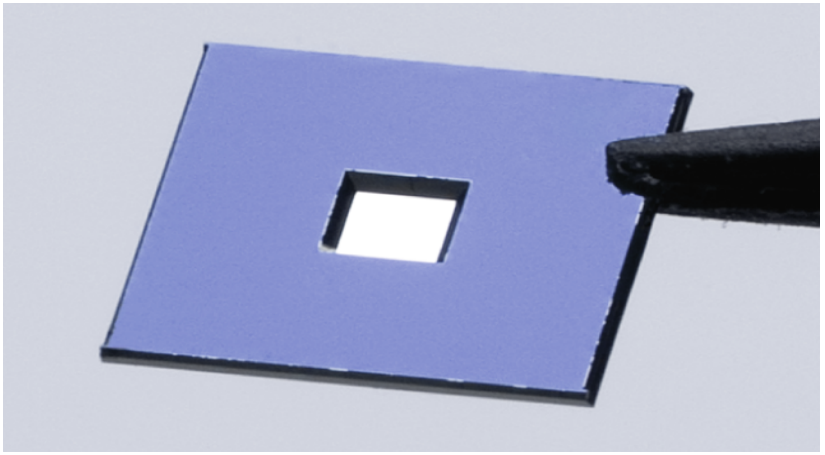
Rings for a few seconds
(about a thousand cycles)

=

LIES and HALF-TRUTHS

energy

“Thermal Fluctuations”: Damping is a Two-Way Street



Rings for a few seconds
(about a million cycles)

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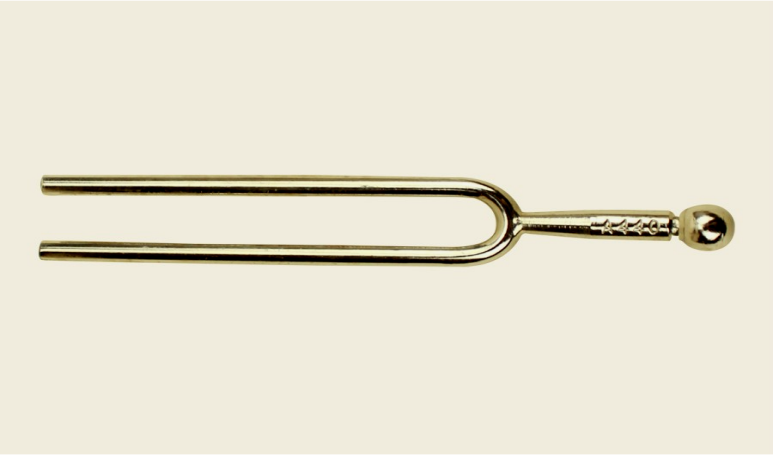

Rings for a few seconds
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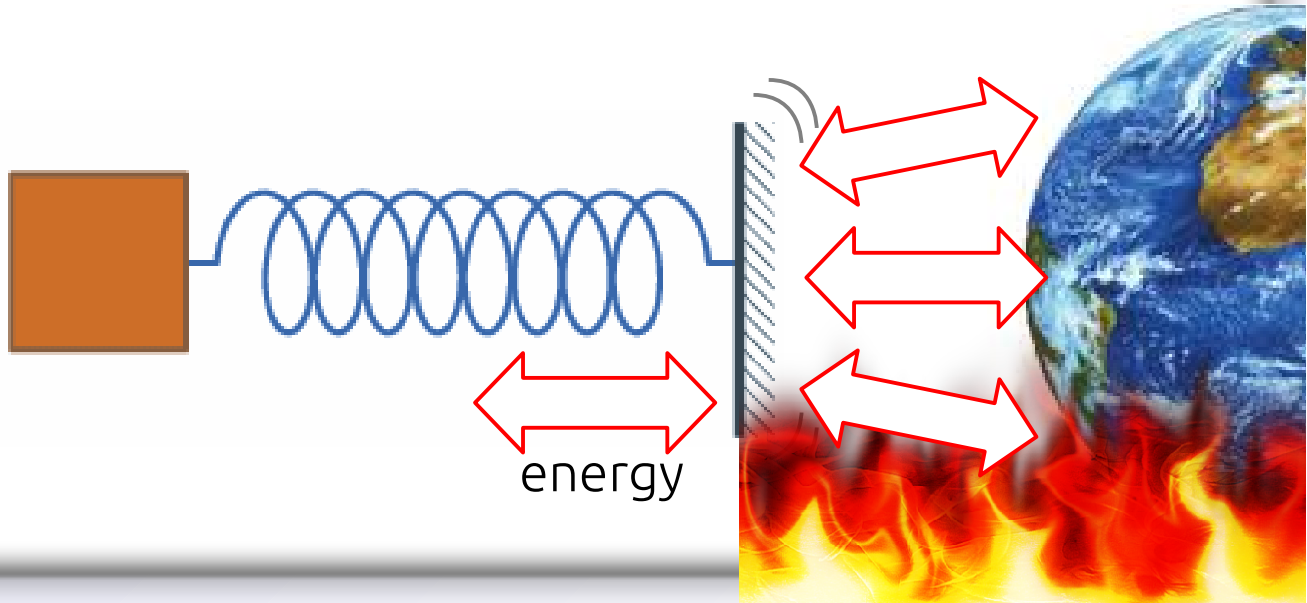
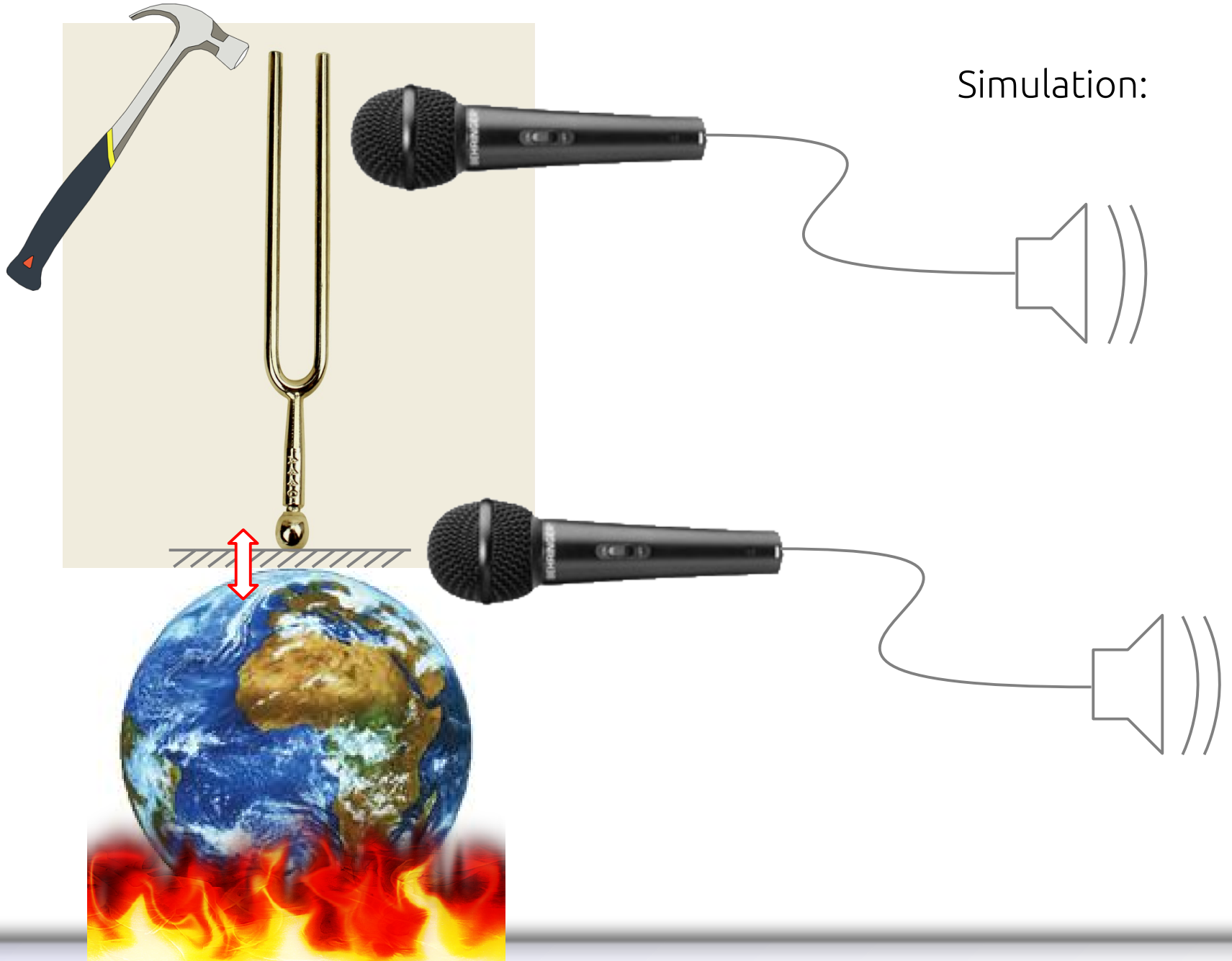
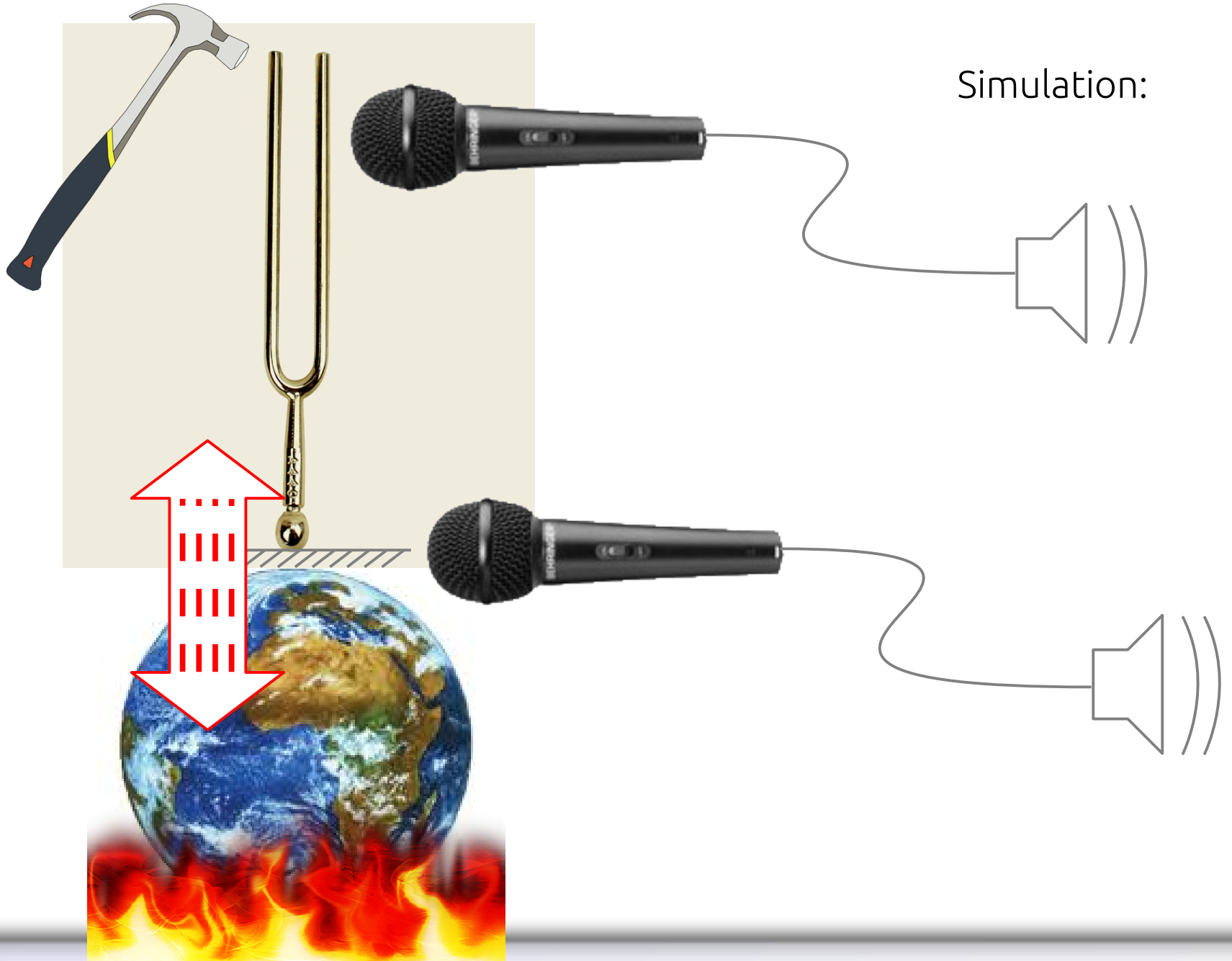


“Thermal Fluctuations”: Damping is a Two-Way Street

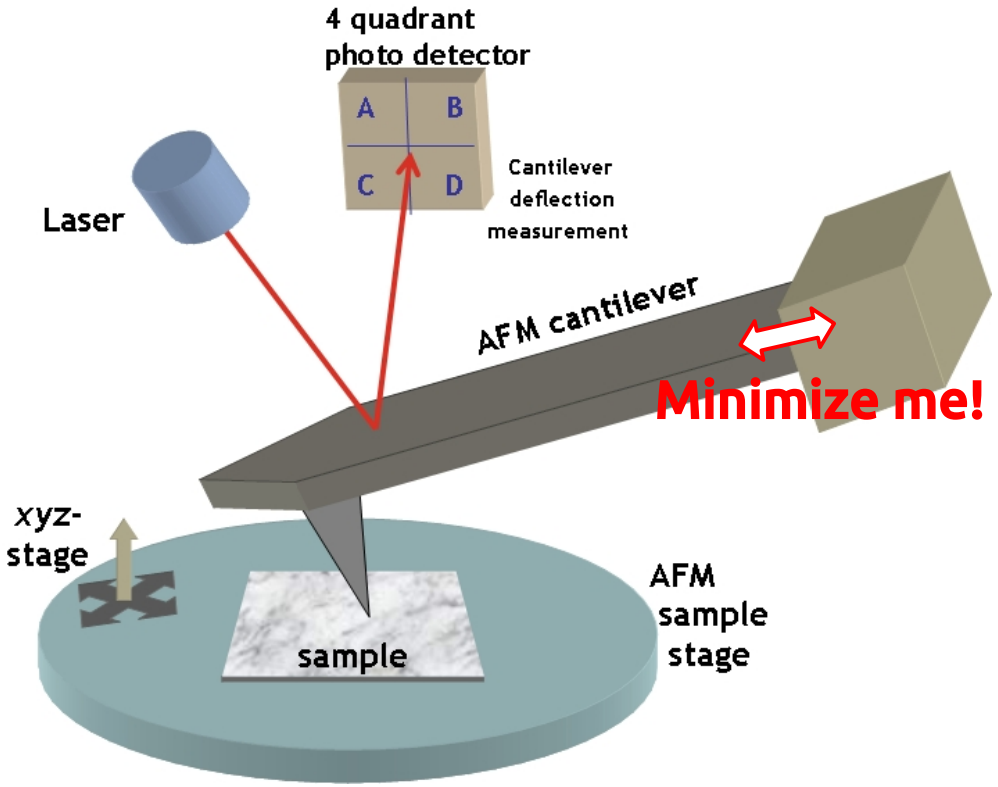


“Thermal Fluctuations”: Damping is a Two-Way Highway



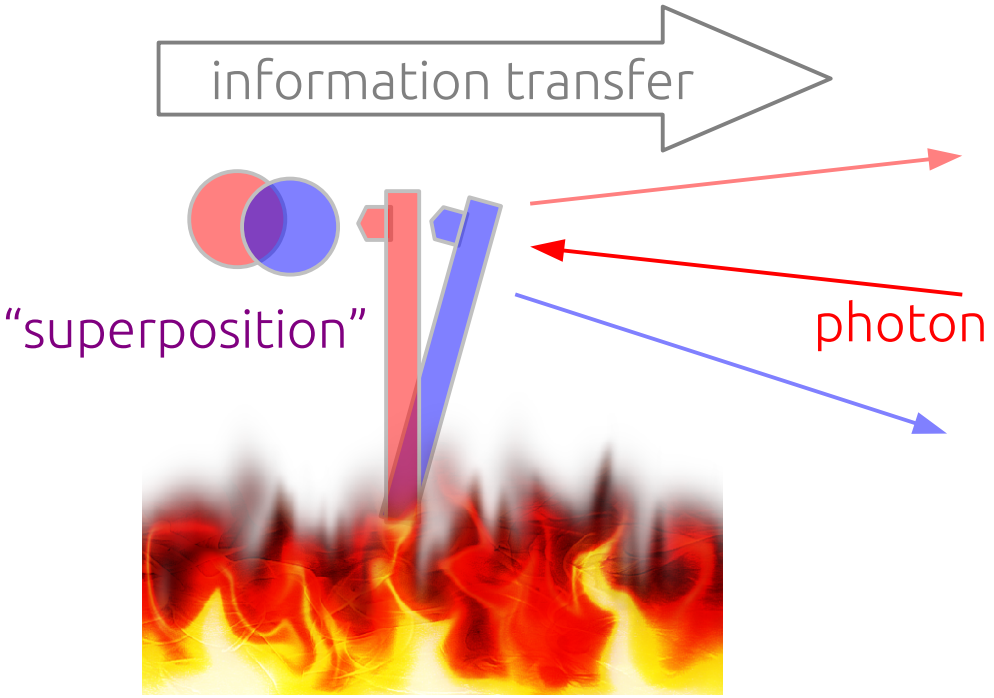
Implications for Technology

Mechanical Force Detectors: minimize noise from environment



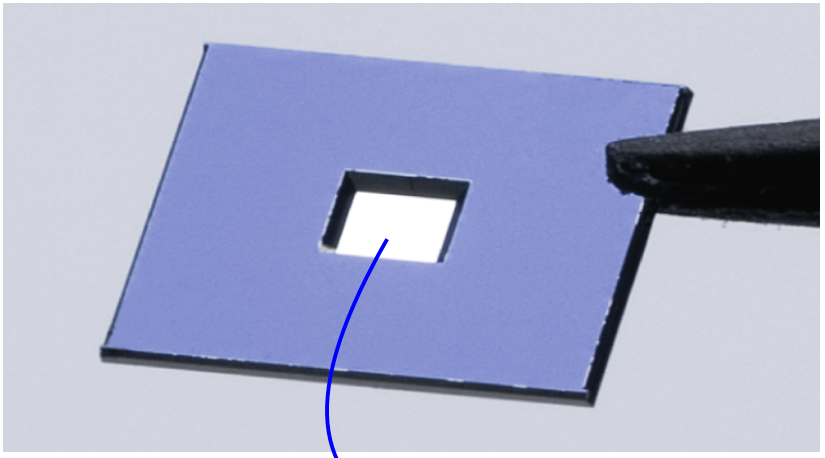
Implications for Technology

Quantum Information Storage: Minimize randomization from thermal noise



Problem

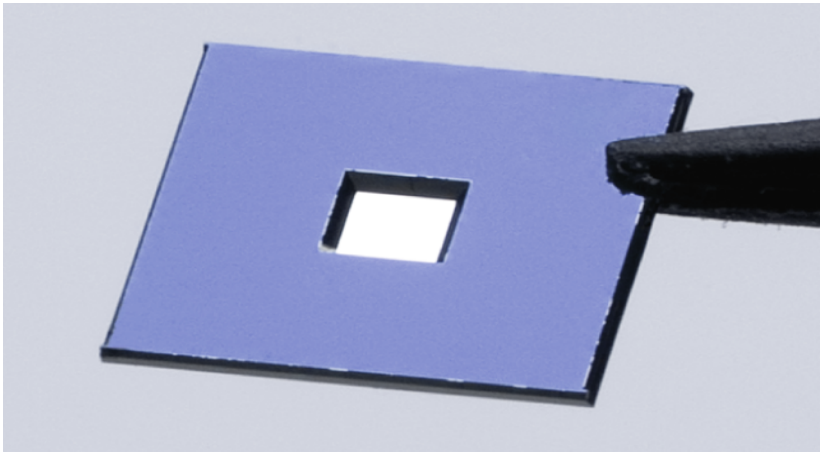
Why is There Damping?

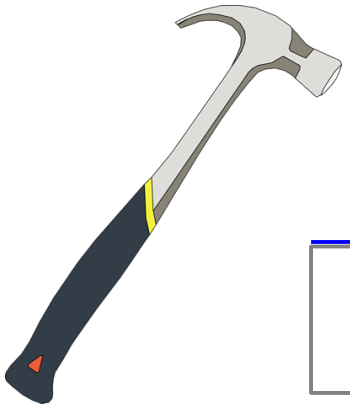


Limits of Mechanical Devices

- Connection to frame (& earth)
- Pushing air molecules (sound)
- Flexing materials generates heat

Solutions to Damping



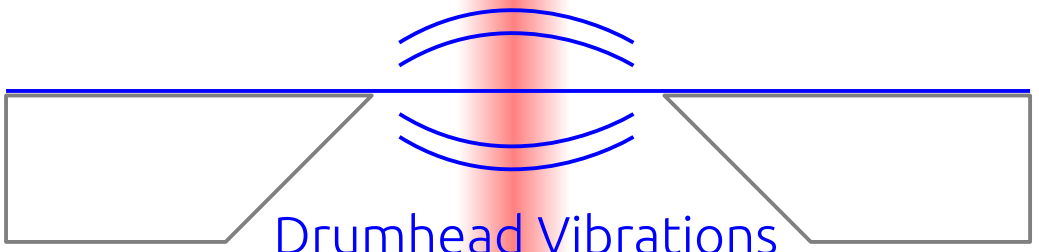


Connection to frame (& earth)
- Traditional engineering / black magic

Pushing air molecules (sound)
- Remove air (vacuum)

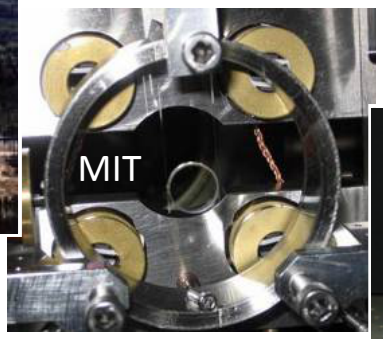
Flexing materials generates heat
- Traditional engineering / black magic
- Replace materials with laser light

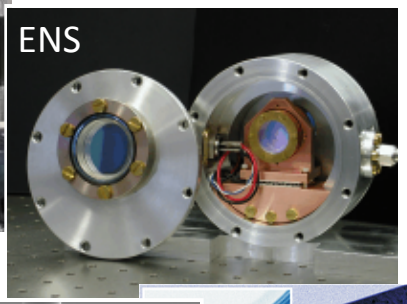
predicted to ring for *weeks!*

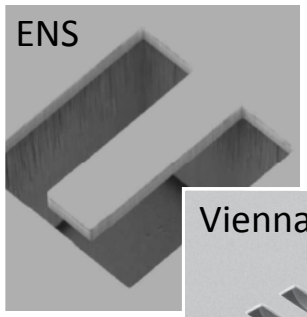


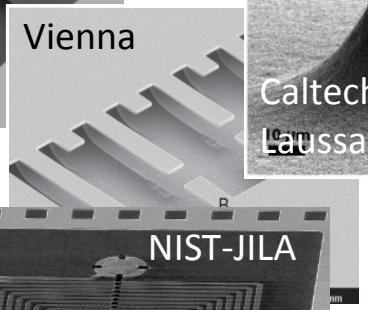
Drumhead Vibrations

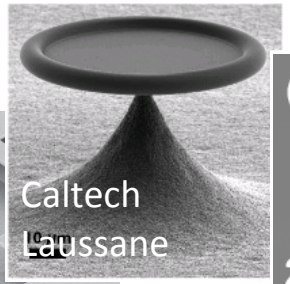
Solid Objects Controlled by Photons

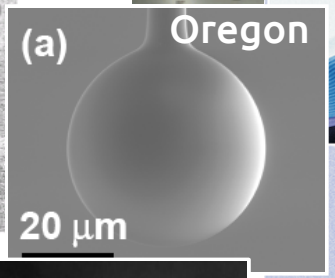


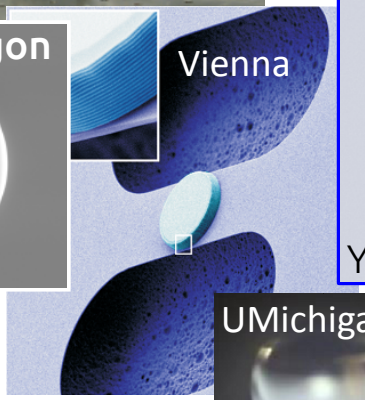


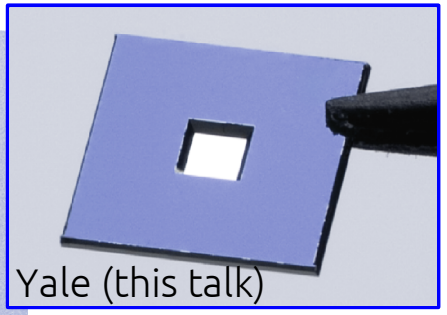


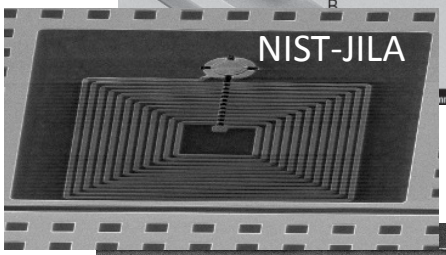


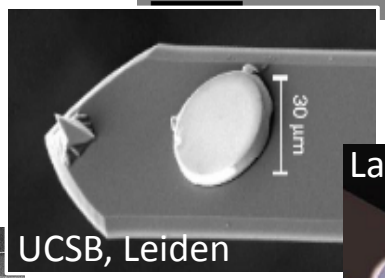


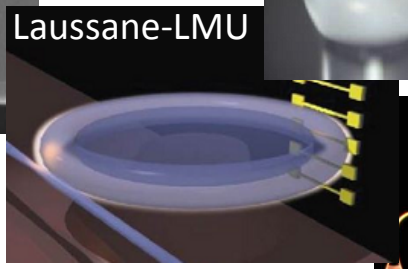


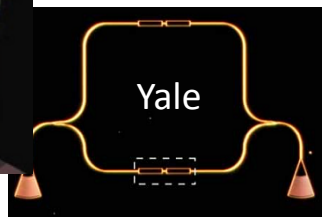


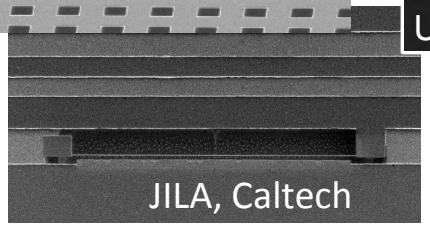






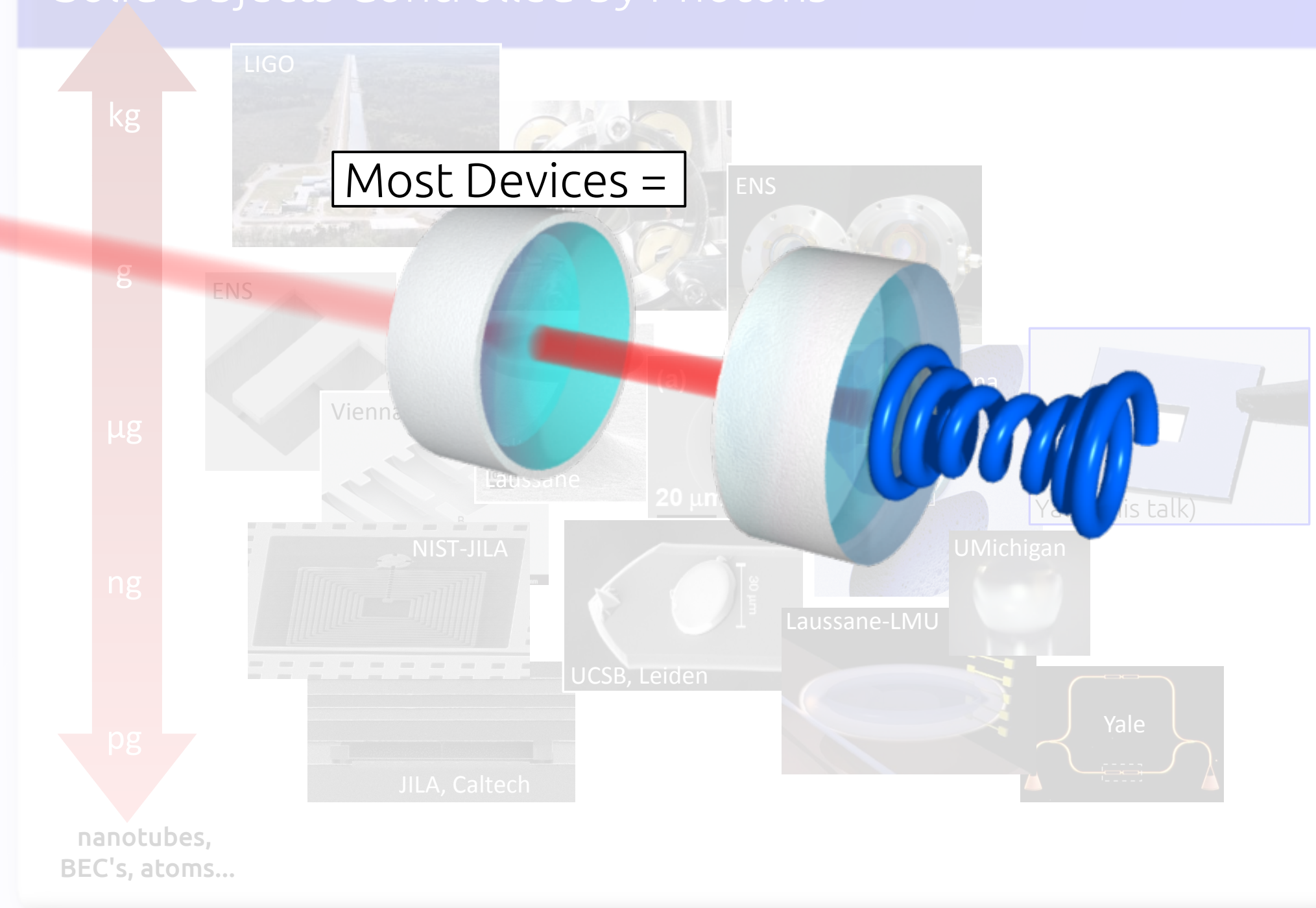




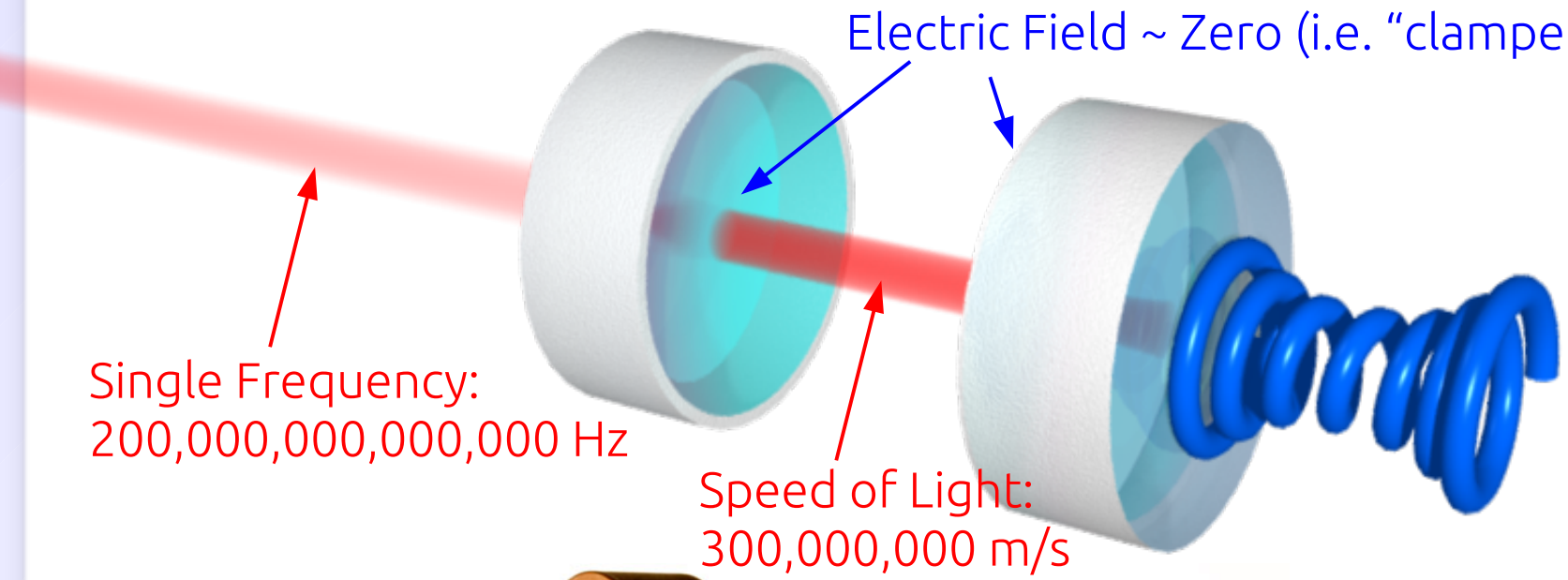


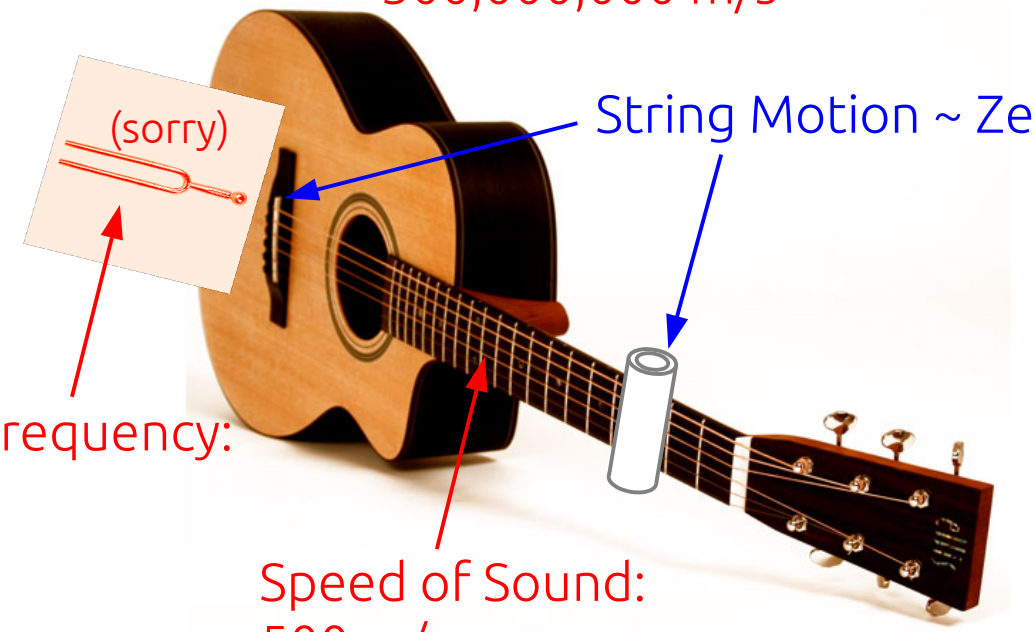
nanotubes, BEC's, atoms...

Solid Objects Controlled by Photons



Optomechanical Systems Are Guitars: Same Physics





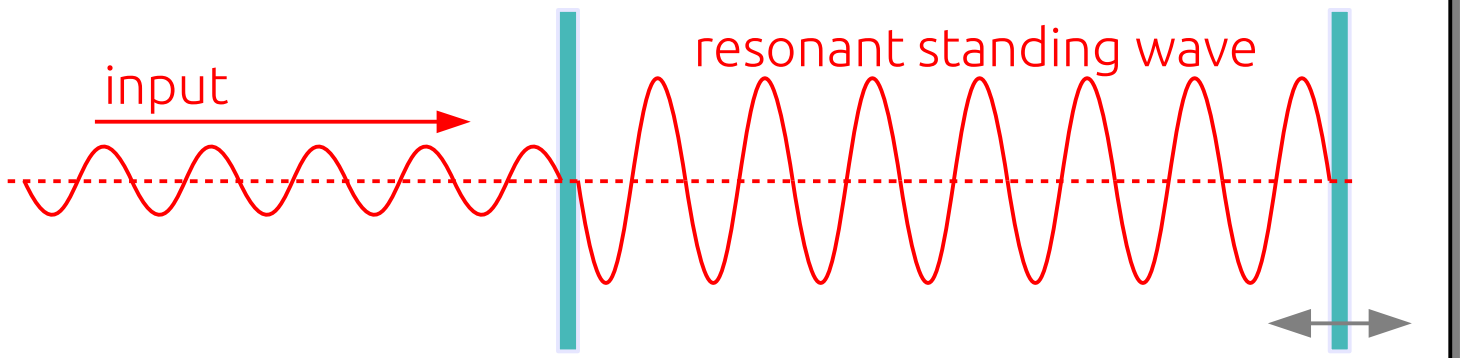
Embarrass self...

Optomechanical Systems Are Guitars: Same Physics

Electric Field ~ Zero (i.e. “clamped”)

Both “Cavity” Systems:

- mostly-clamped ends, one clamp's position can change
- resonant or “preferred” cavity frequency depends on length
- driven by single-frequency



Sing
200

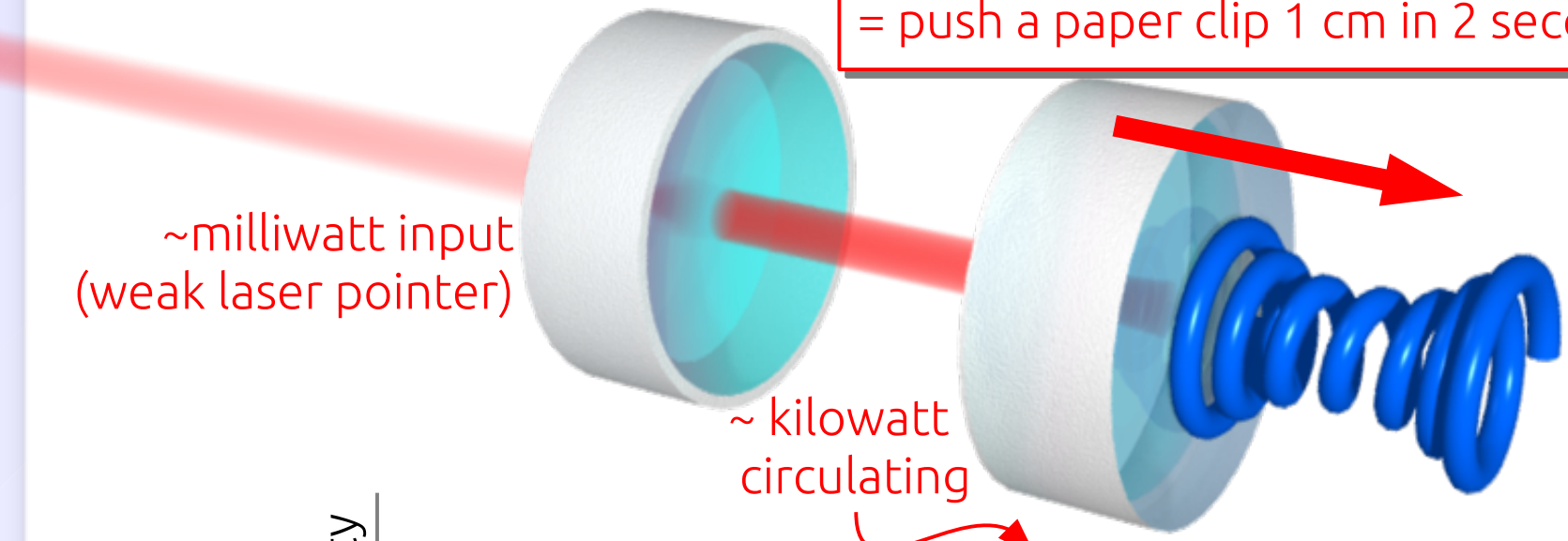
Single Frequency:
440 Hz

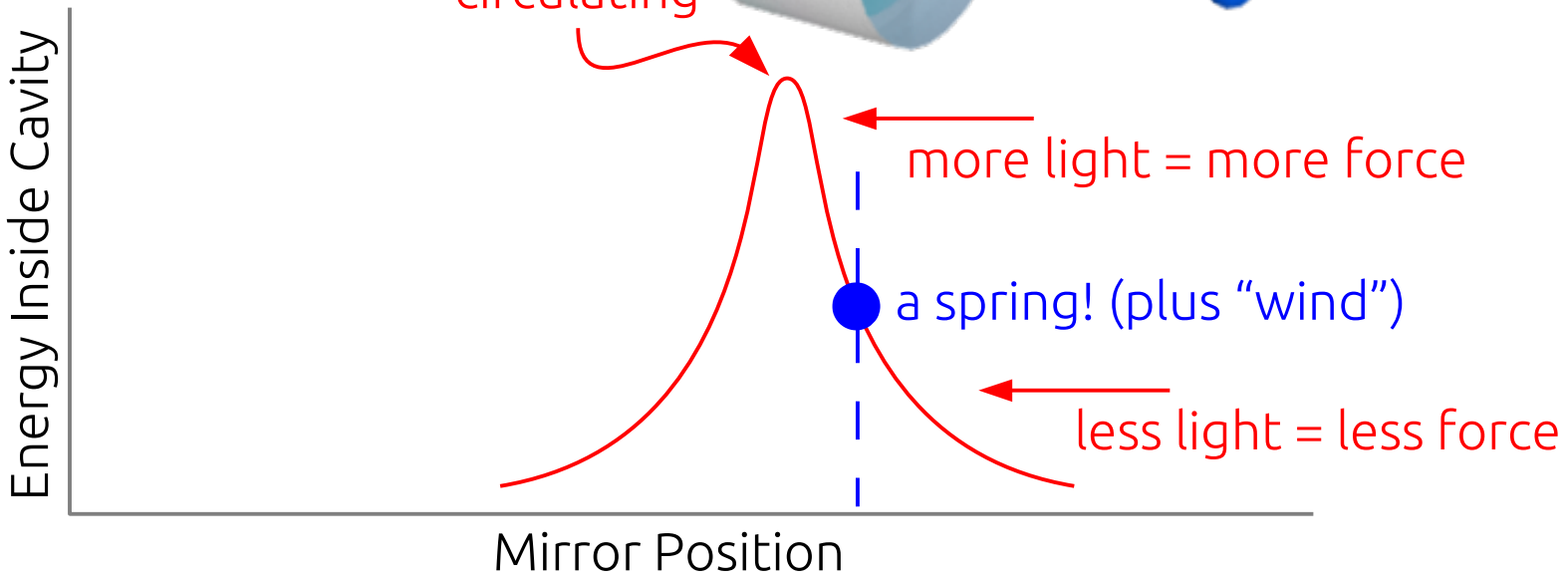
Speed of Sound:
500 m/s

Embarrass self...

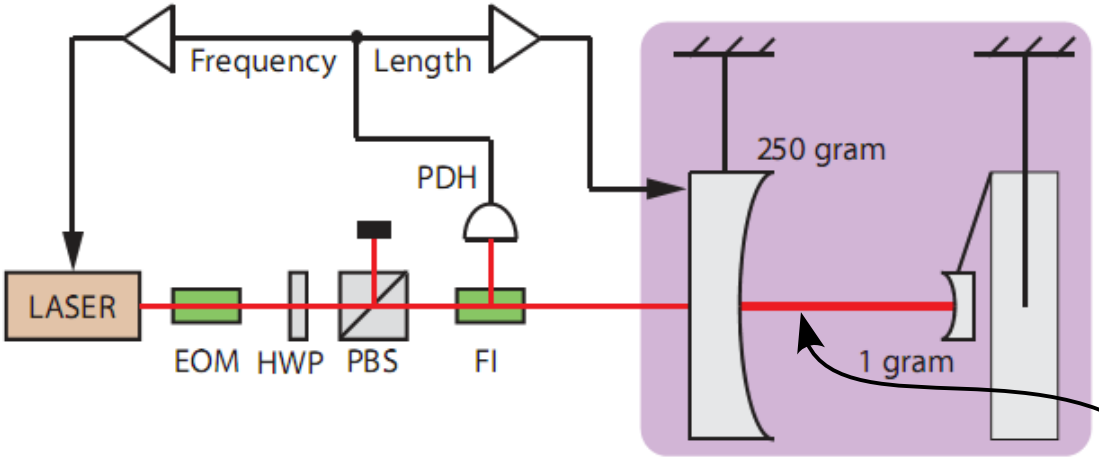
When the Input Frequency Matches the Cavity Frequency

= 5 micronewtons
= weight of 100 grains of salt
= push a paper clip 1 cm in 2 seconds (in space)

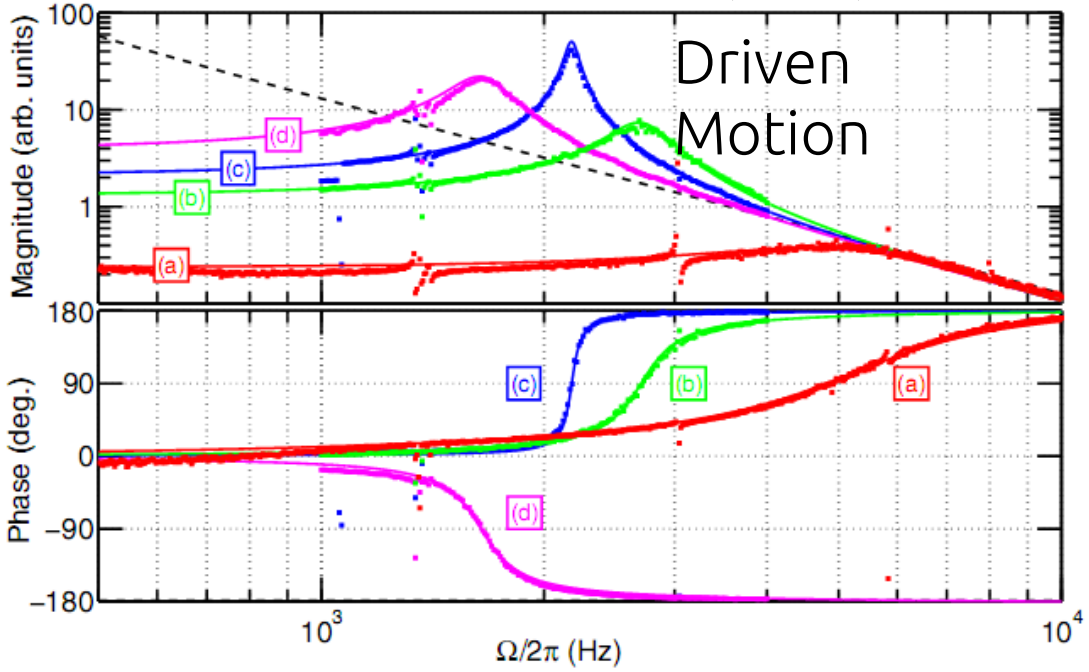




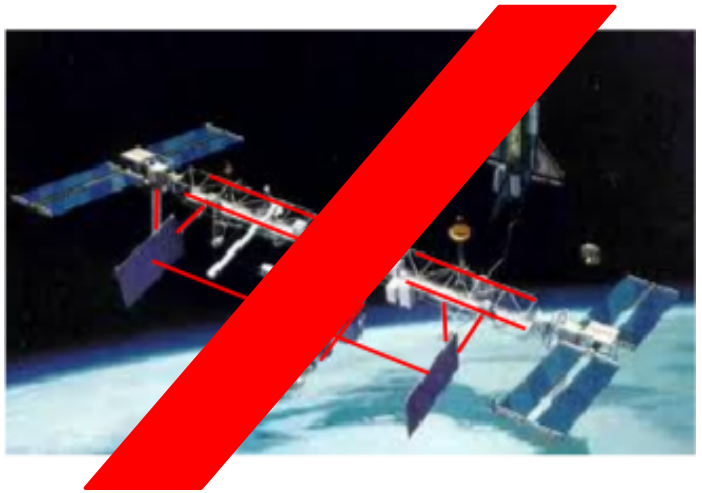
Surprisingly Stiff Photons



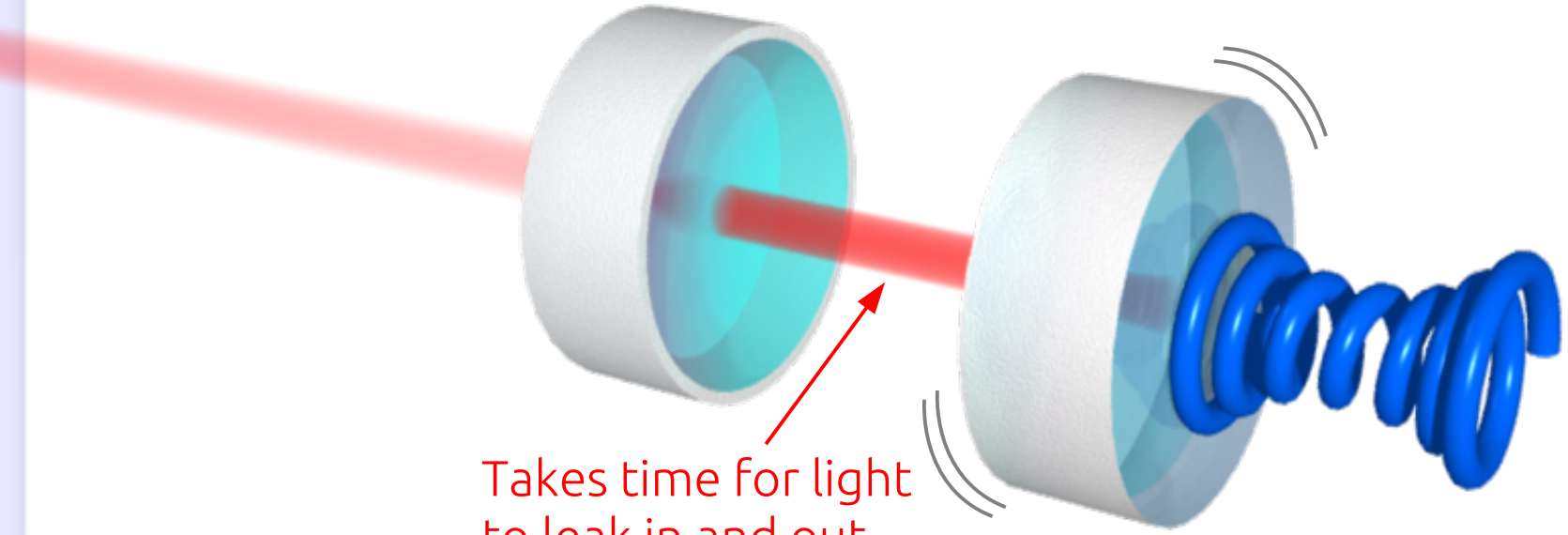
T. Corbitt *et. al.*, PRL (2007)



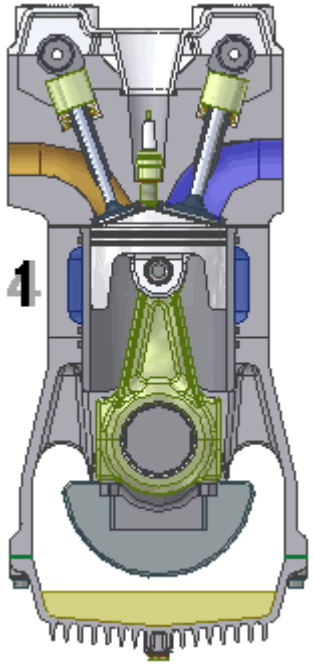
- Optical cavity
- One gram-scale mirror is free to swing (~170 Hz)
- "Optical spring" stiffens these vibrations to 5,000 Hz
- Column of light is stiffer than diamond (but brittle, "windy")

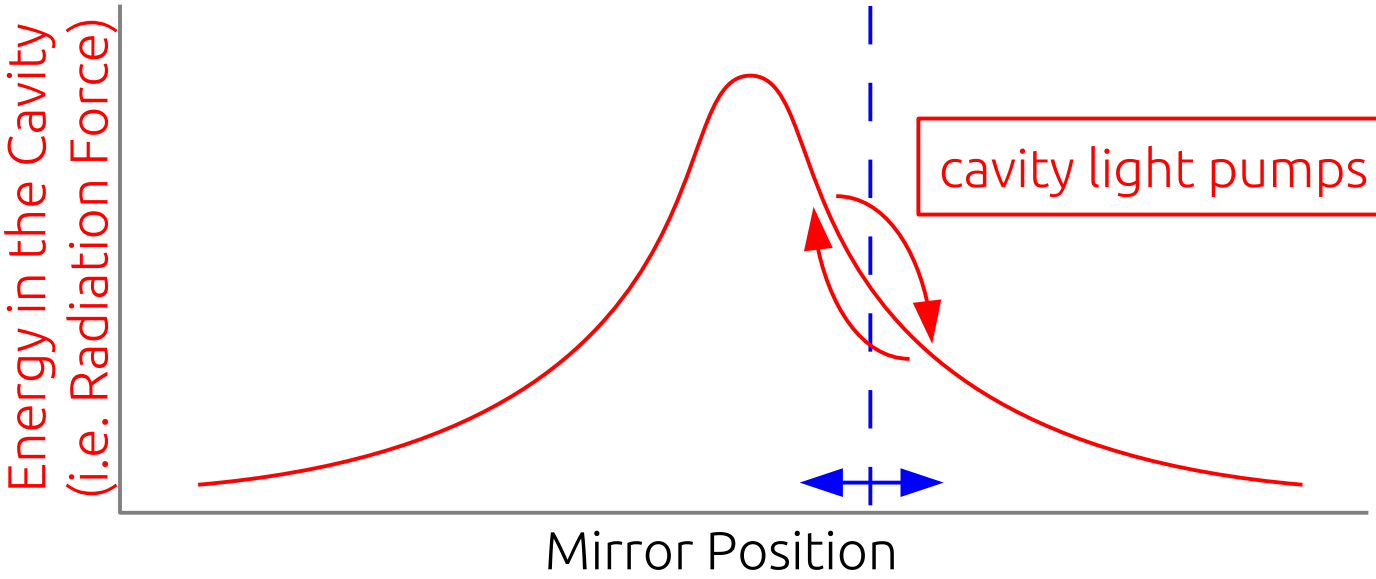


Laser Engines



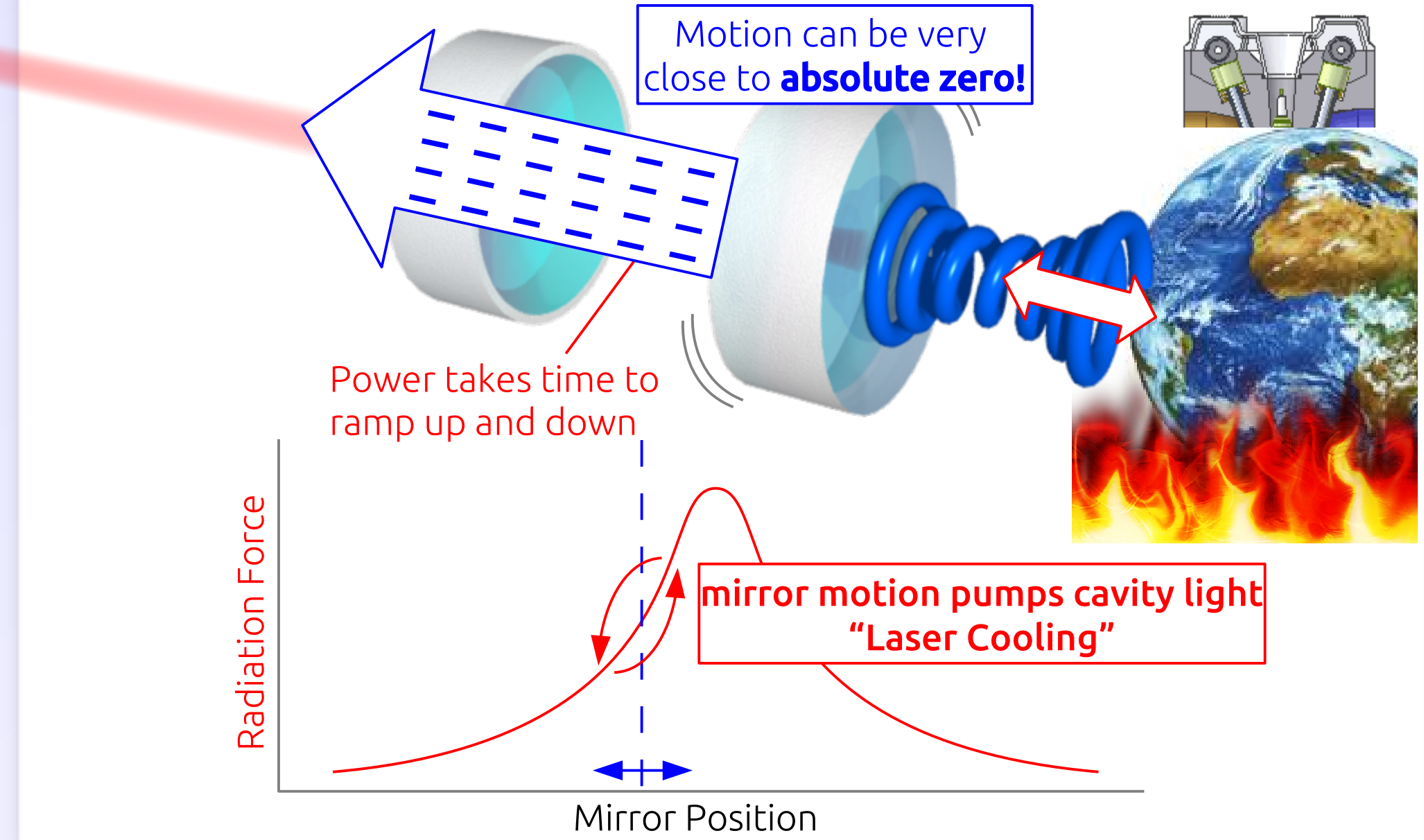
Takes time for light
to leak in and out



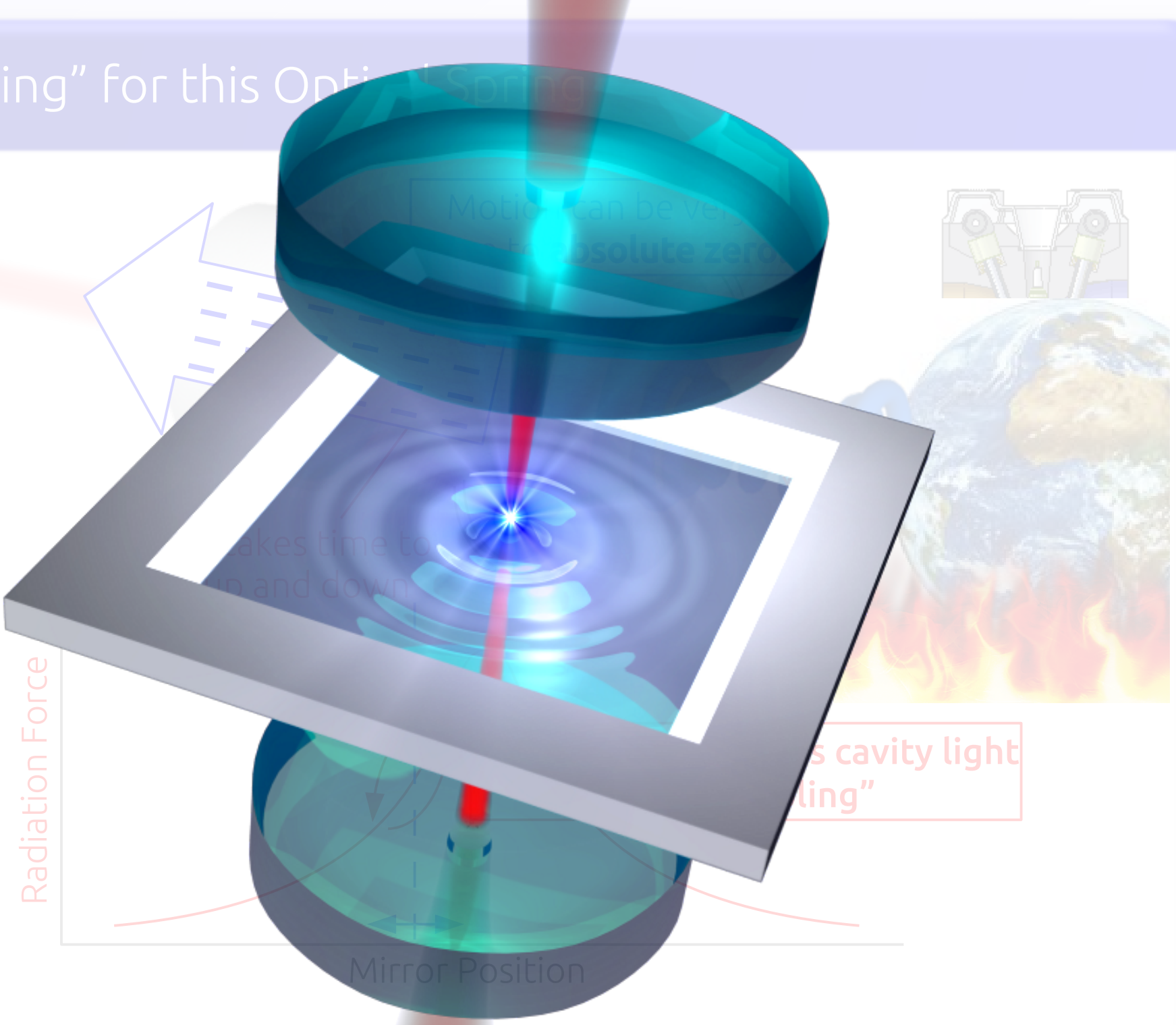


cavity light pumps mirror motion

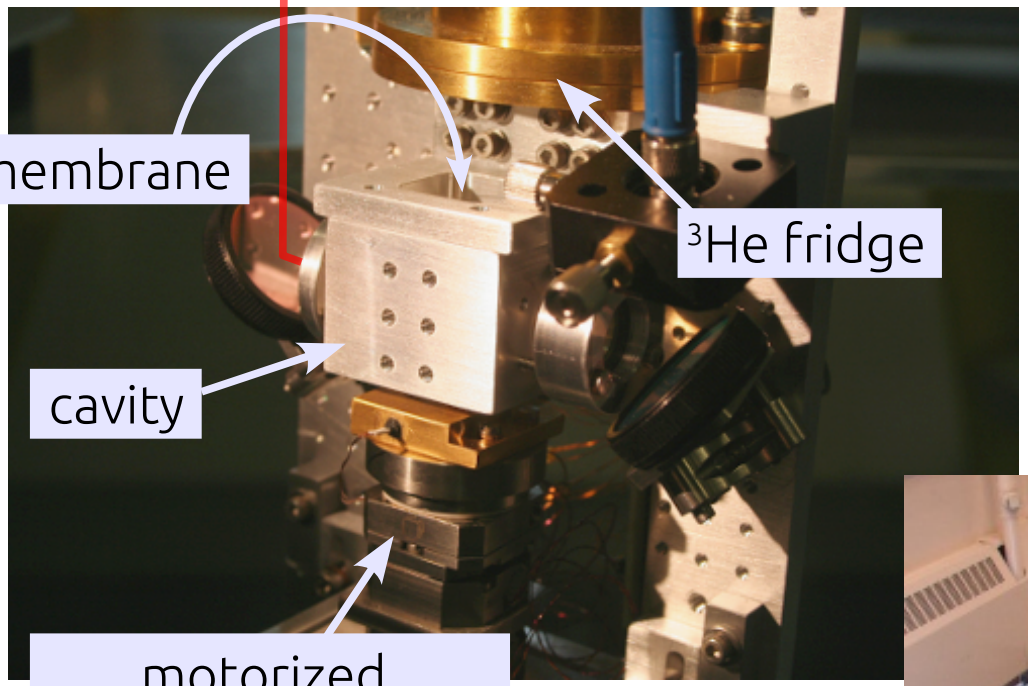
“Damping” for this Optical Spring



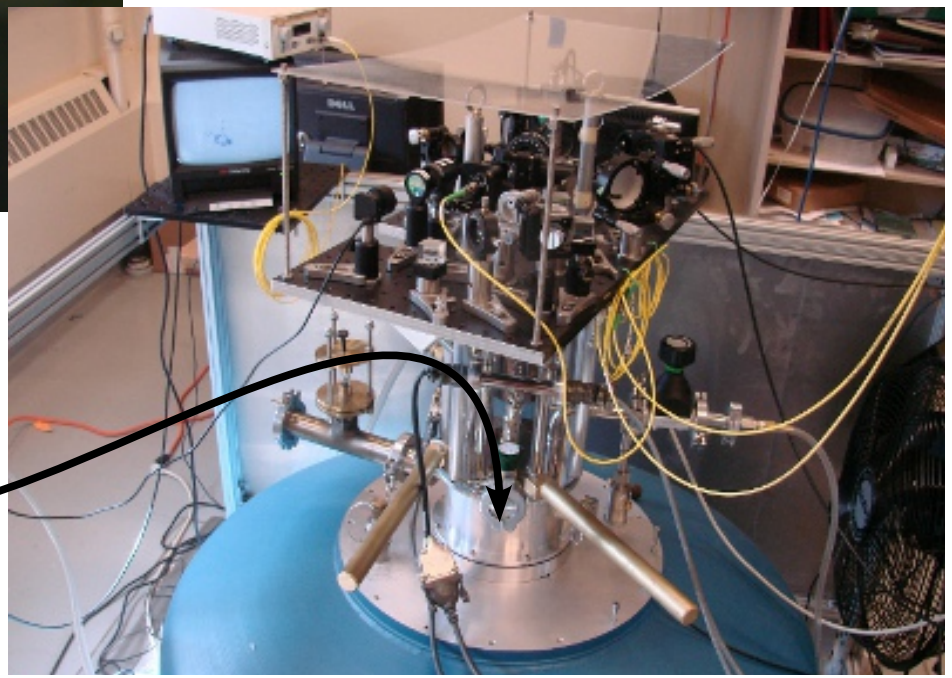
“Damping” for this Optical Spring



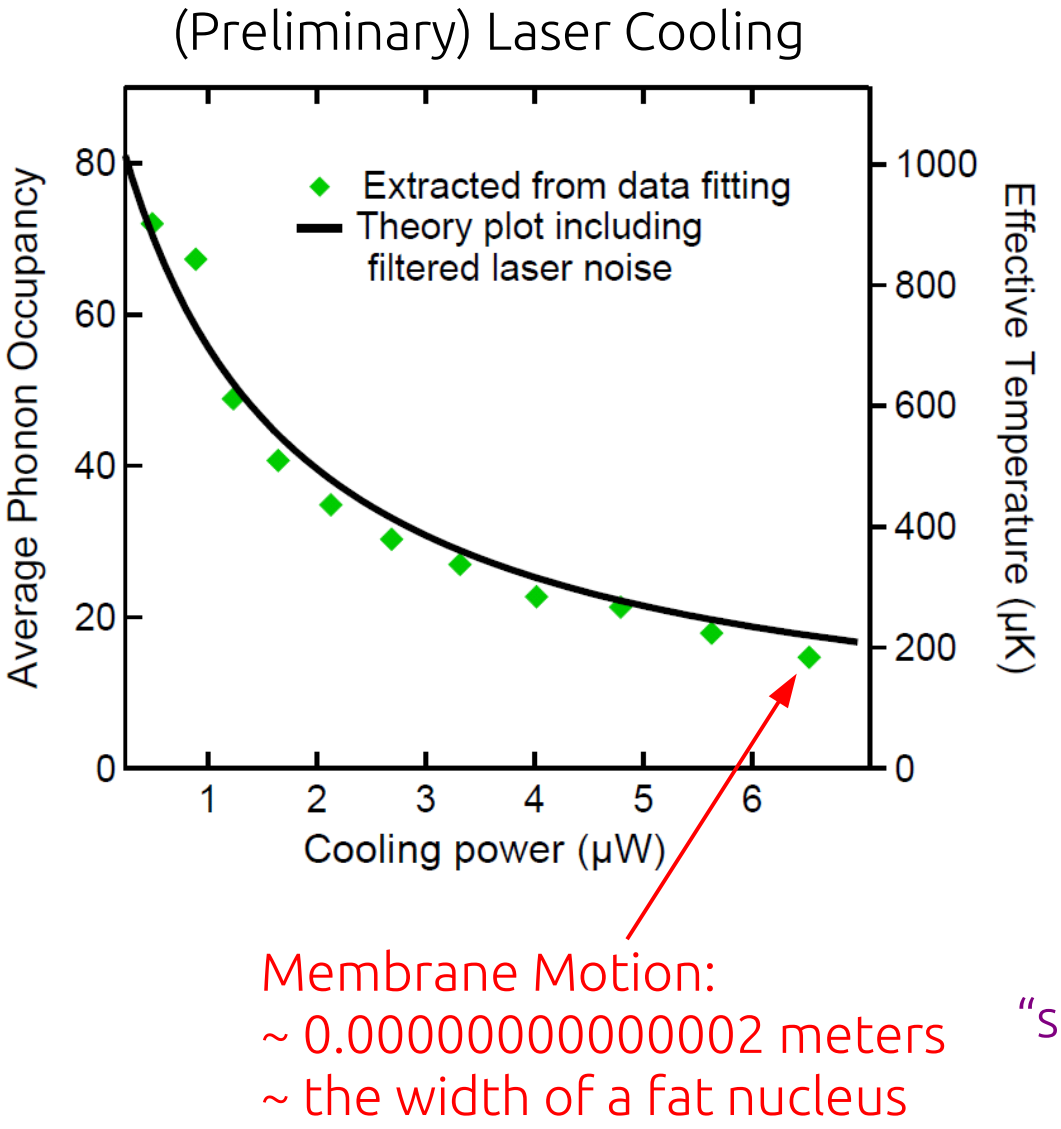
At Yale: Laser Cooling in Cryogenic Environment



- 50 nanometer thick membrane, 1.5 x 1.5 mm^2, 261 kHz drumhead, Q = 5 Million
- System starts at 0.4 °C above absolute zero (i.e. 0.4 “Kelvin”)
- Shoot laser down a tube.



Test: Laser Cooling to Very Low Temperature

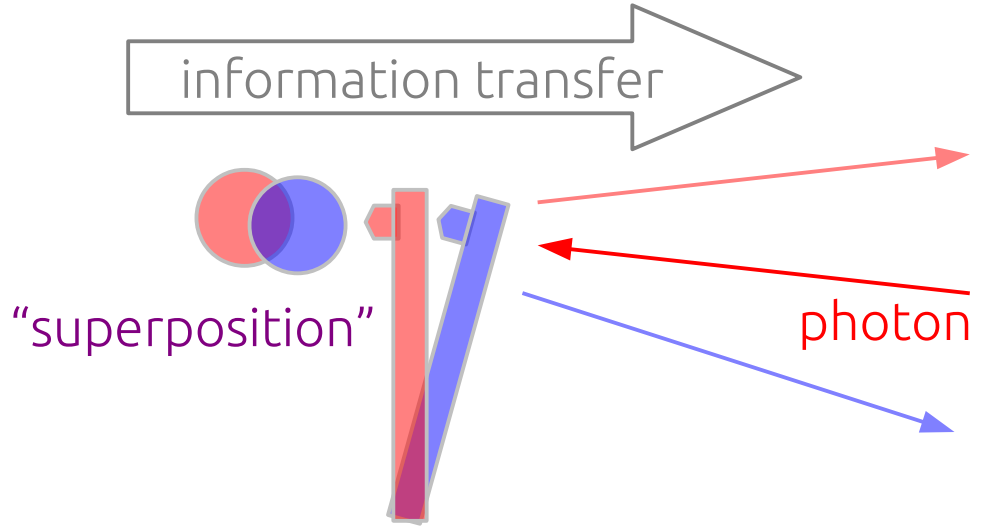


Membrane Motion:
~ 0.00000000000002 meters
~ the width of a fat nucleus

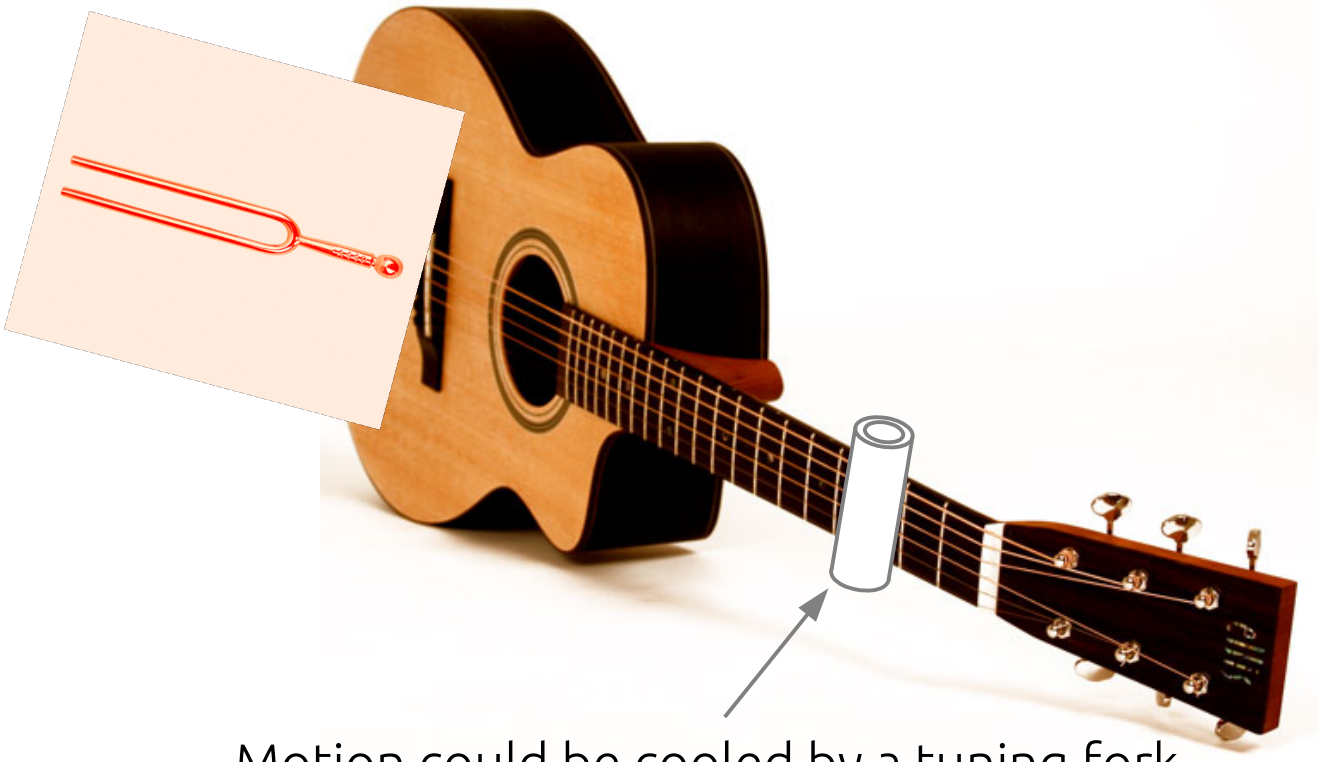
Laser cooling to 0.0002 K (~factor of 40 above quantum minimum energy)

Next: vibration isolation, smaller membrane

- Should achieve < 0.0000001 K: **motion limited by laws of quantum mechanics**
- "fun", also a milestone toward:



Complete Analogy: “Tuning Fork Cooling” of Fingers



Motion could be cooled by a tuning fork.

This does not change the thermal noise!

kg

LIGO

ENS

Not affected by laser cooling

Options:

- Continue Traditional Materials / Geometry Engineering
- **Replace material with photons (main goal in ERP B024)**

ng

UCSB, Leiden

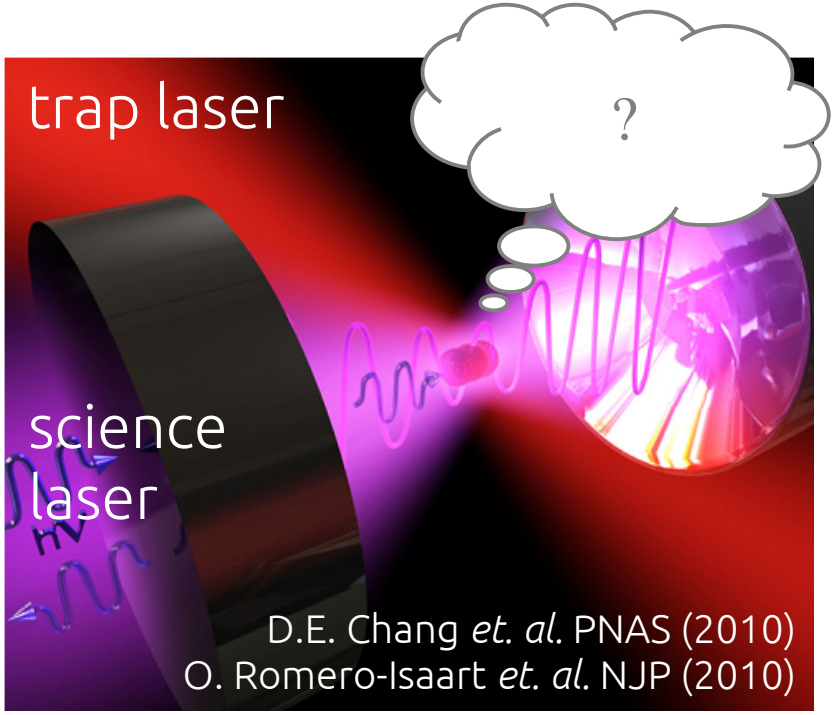
Caltech

pg

JILA, Caltech

nanotubes, BEC's, atoms...

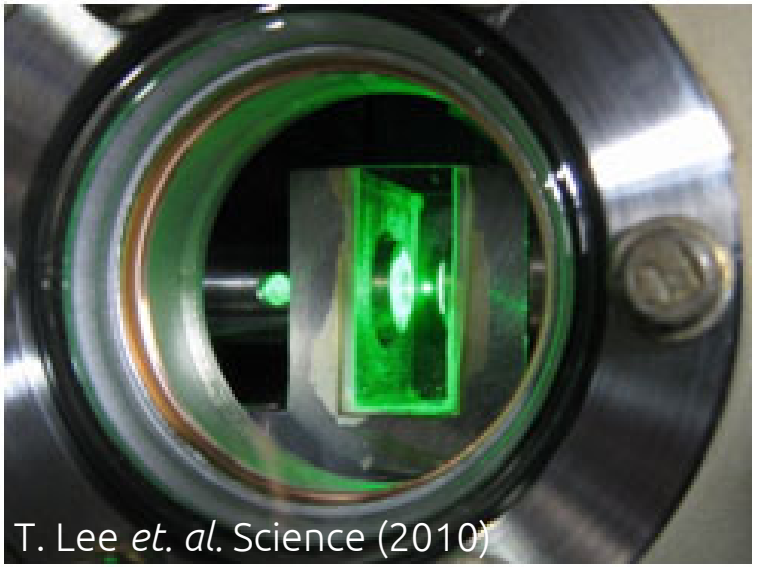
Direct Optical Levitation



Using light as a “material” support

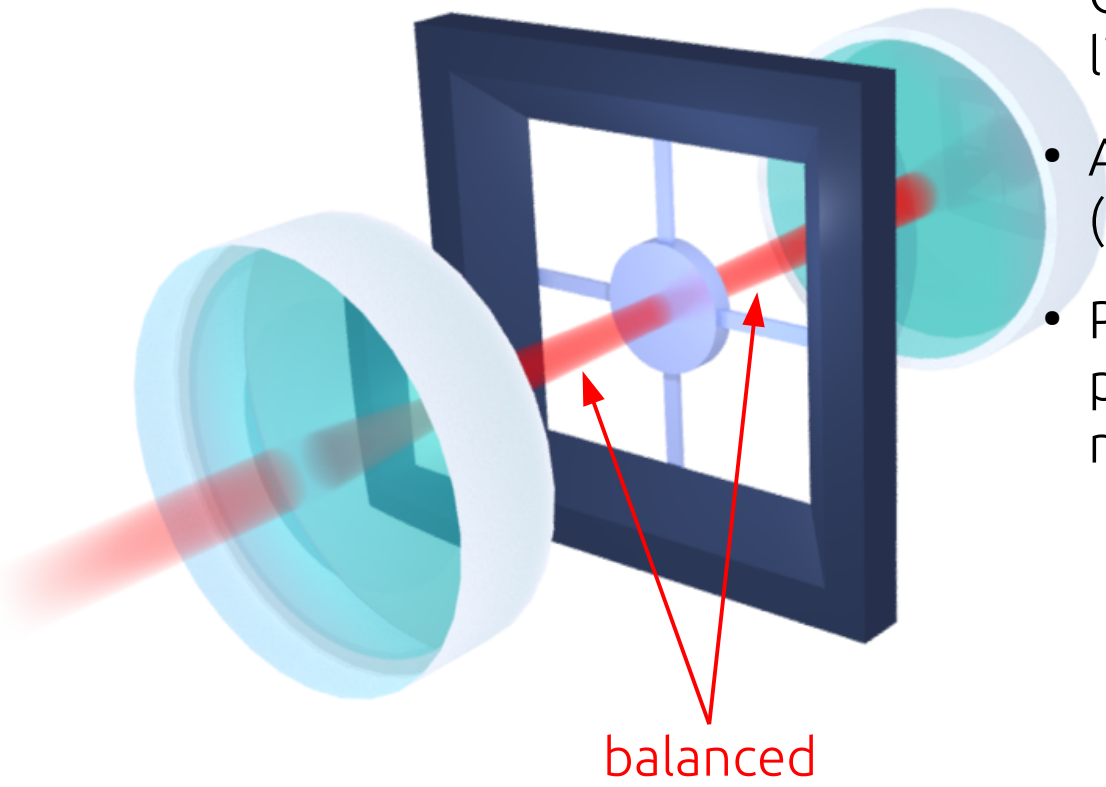
- Circumvents traditional material limitations
- Predicted to rings for *weeks* when struck.

proof-of-principle experiment



...also A. Ashkin (1976)

Another Solution: Make Radiation the Dominant Force



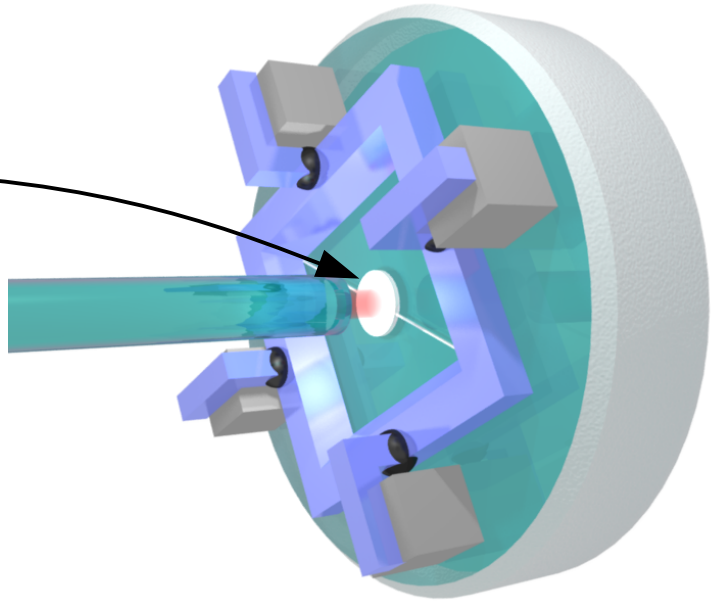
- Create weakly-tethered, lightweight, floppy trampolines
- Add a very strong optical spring (with no “wind” or engine problem)
- Predicted to achieve similar performance (but no launching required)

Optomechanics Lab at McGill

Goals that Fit in a Storage Closet

Christoph

- Design and fabricate lightweight, floppy objects
- Assemble new UHV optical trapping system

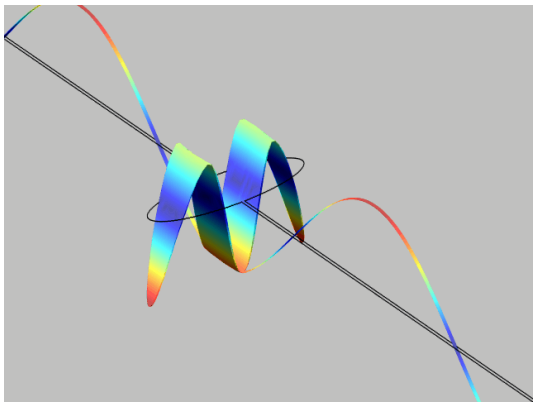


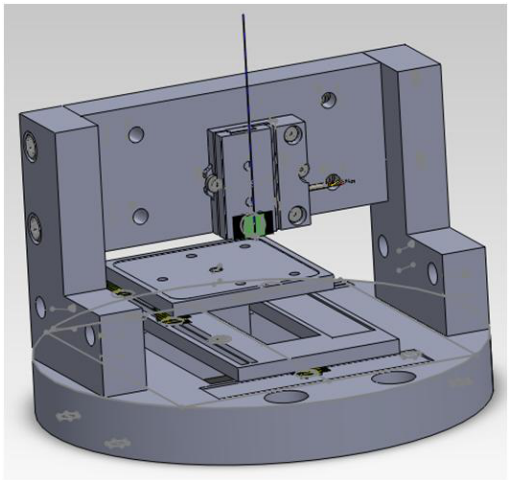
Alexandre, Chris, Perry

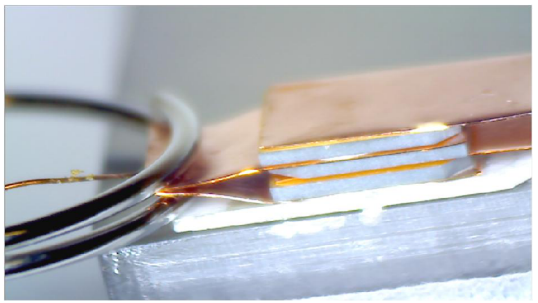
- UHV rapid device characterization interferometer

Xinyuan, Julian

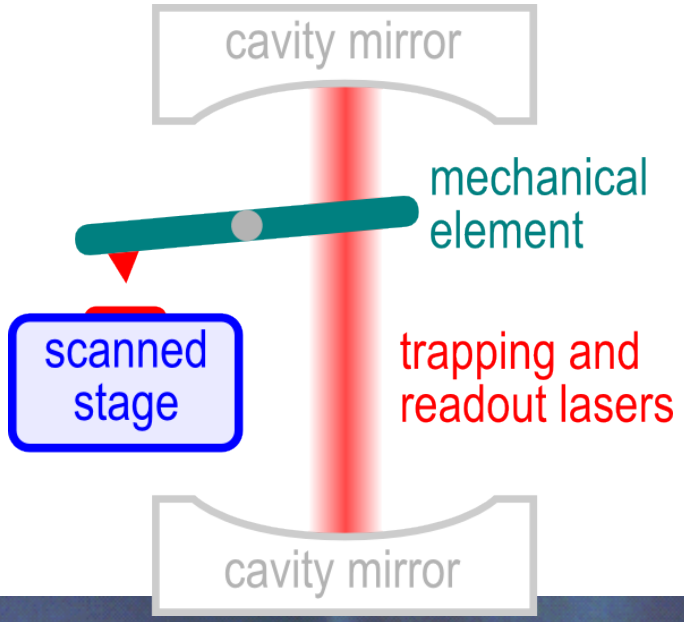
- Mechanical simulations
- Photonic crystal simulations







Additional Directions



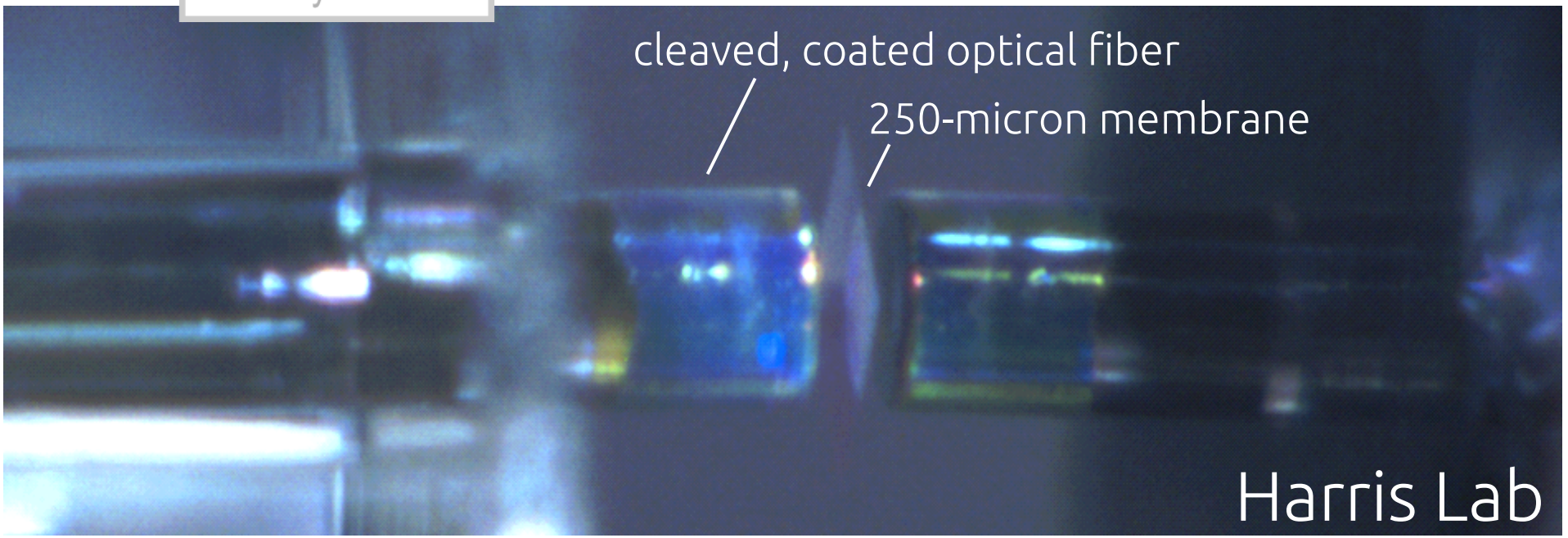
Develop Practical Force Sensors

Cryogenic System to Reduce Thermal Noise

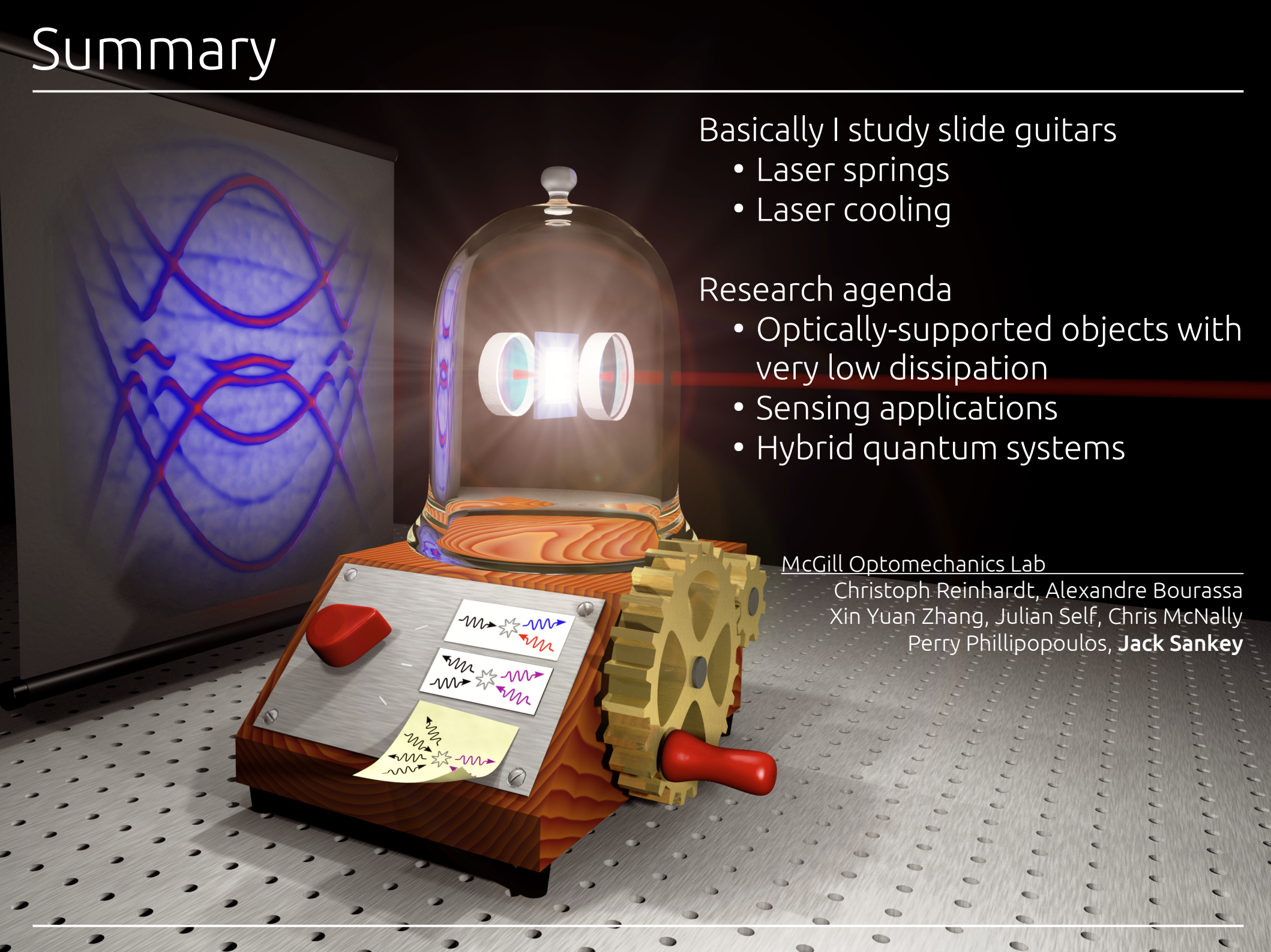
Compact Optical Fiber Packages

Diamond Mechanical Elements

Hybrid Quantum Systems



Summary



Basically I study slide guitars

- Laser springs
- Laser cooling

Research agenda

- Optically-supported objects with very low dissipation
- Sensing applications
- Hybrid quantum systems

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