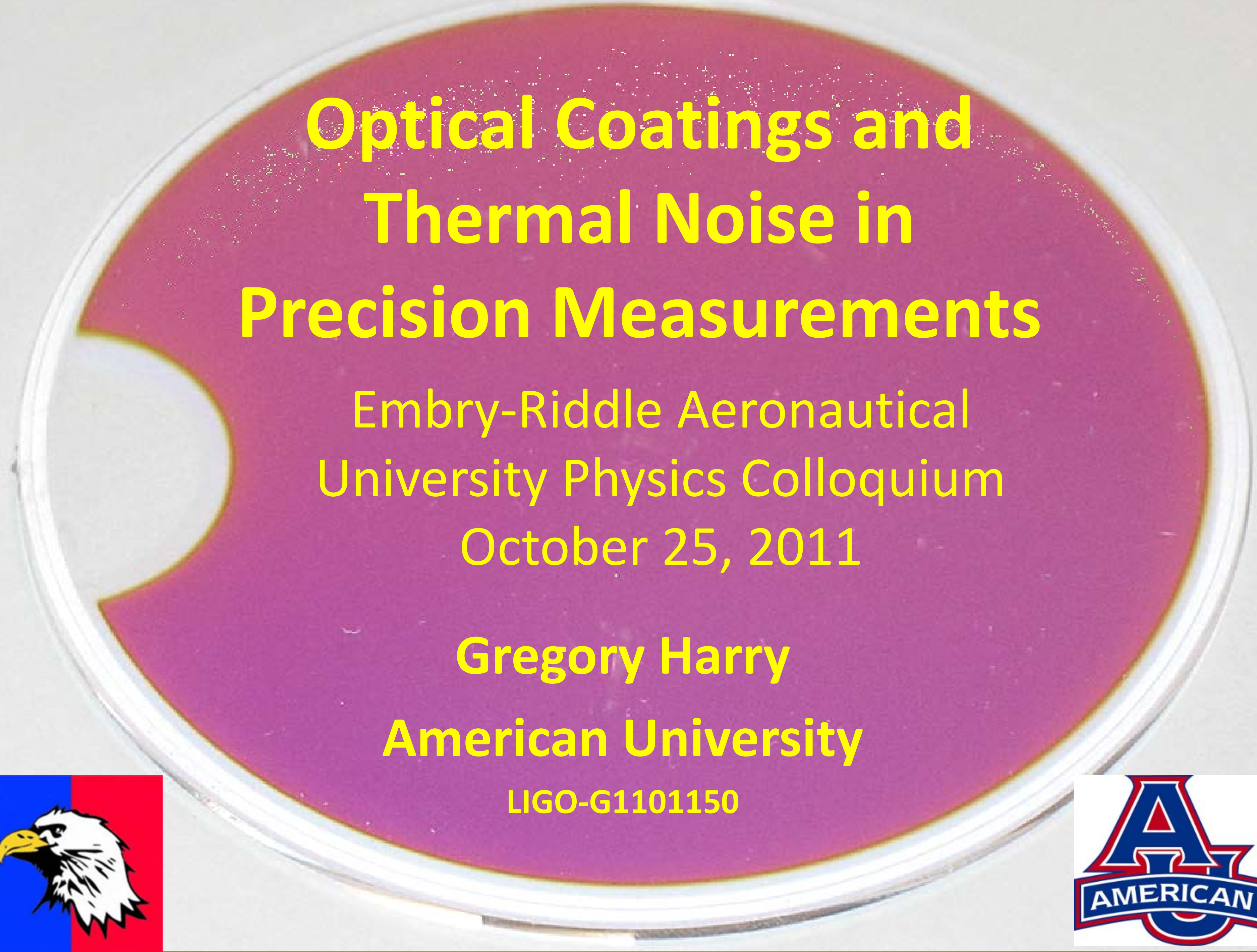

Optical Coatings and Thermal Noise in Precision Measurements

Embry-Riddle Aeronautical
University Physics Colloquium
October 25, 2011

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American University

LIGO-G1101150

Thermal Noise

- Random motion when not at 0 Kelvin
  - Can also appear as random voltage, force, pressure, optical properties, etc.
- Energy in thermal noise increases with temperature
  - Cooling is a way, but not the only way, to reduce these thermal fluctuations

Thermal Energy

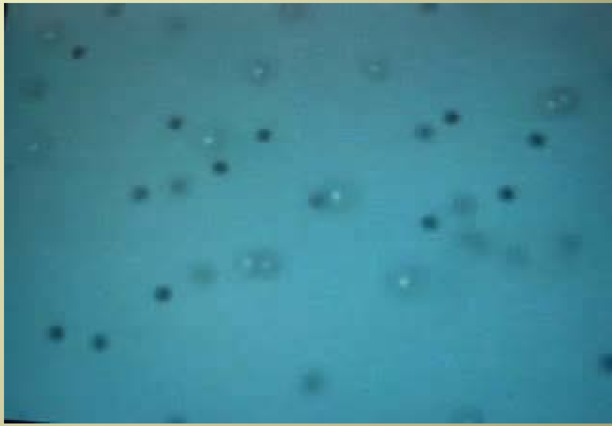
Cooling

- These random motions set a lower limit on measuring signals
  - This is the "noise" part of thermal noise
- Not random fluctuations in temperature
  - Although these can play a role in thermal noise (thermo-optic, thermoelastic, etc.)

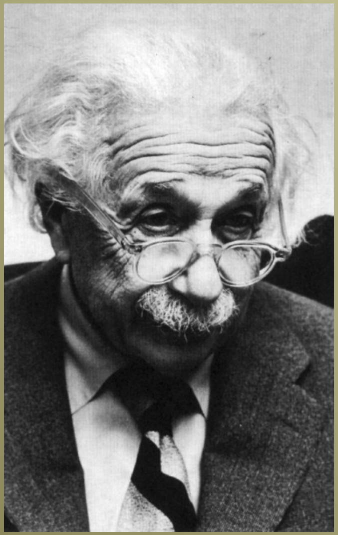
Brief History of Thermal Noise: I

Robert Brown: Botanist (1827)

- Microscope pioneer
- Observed pollen moving in water
- Saw dust from Sphinx moving as well



Brownian Motion



Einstein

Albert Einstein: Physicist (1905)

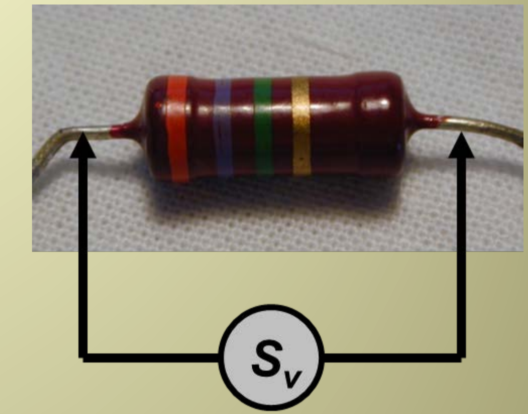
- Mathematics of Brownian motion
- Linked motion to fluid viscosity
- Most cited of Einstein's papers

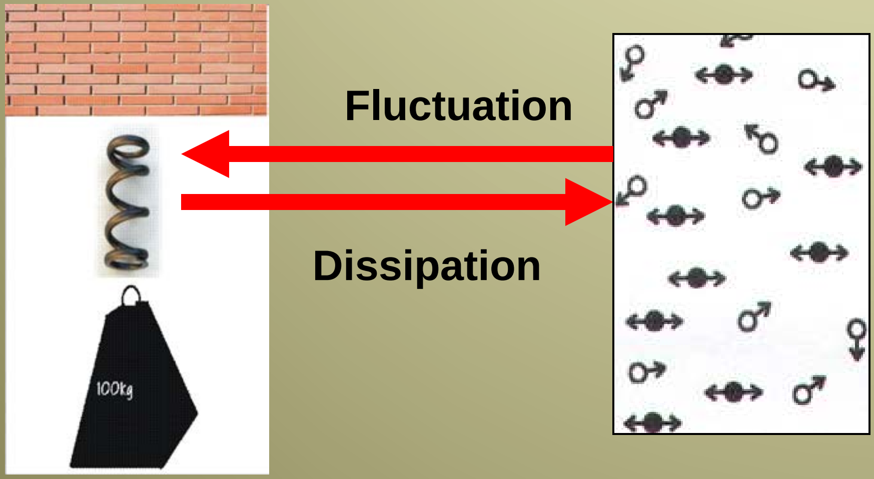
Brief History of Thermal Noise: II

Johnson and Nyquist (1926)

- Voltage noise around resistors
- Seemingly separate to Browns motion

Johnson Noise





Fluctuation-Dissipation Theorem

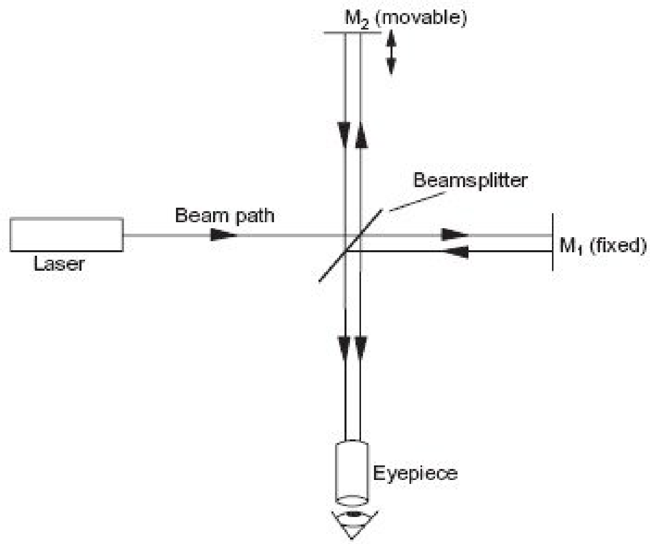
Callen, Welton, and Greene (1950s)

- Tie everything together
- Relates random motion to energy loss
- Fluctuation-Dissipation Theorem

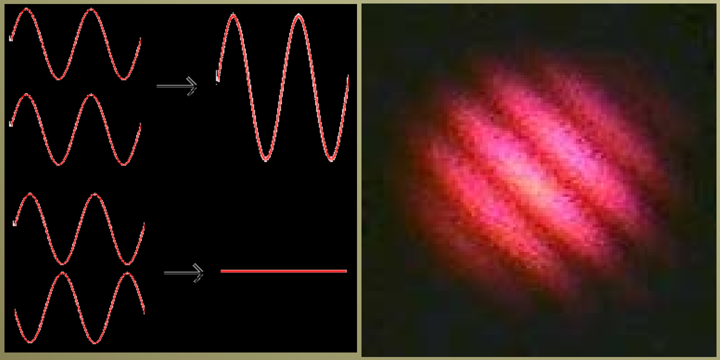
Interferometry

- High precision measurement
- Wavelength of light yardstick
  - Visible light 500 nm (5 X 10^{-7} m)
  - Can use even shorter waves
- Uses interference

Interferometer



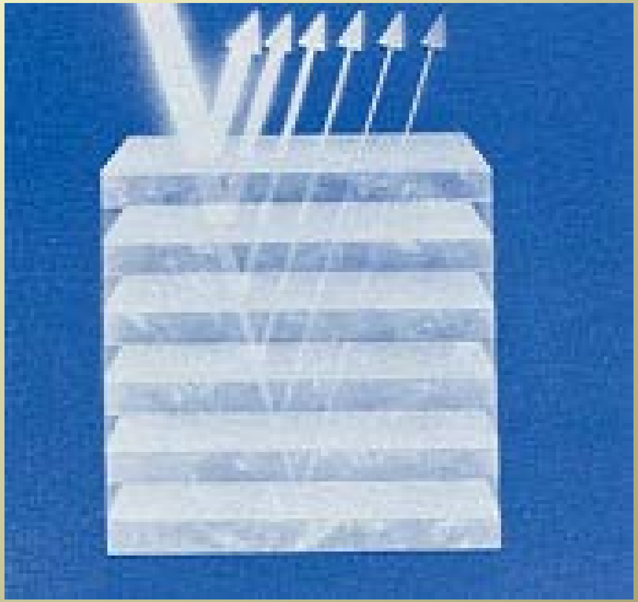
- Measures position of reflection
  - Want mirror center of mass
- Thermal noise in coatings on mirror limits sensitivity
  - Other limits may exist as well



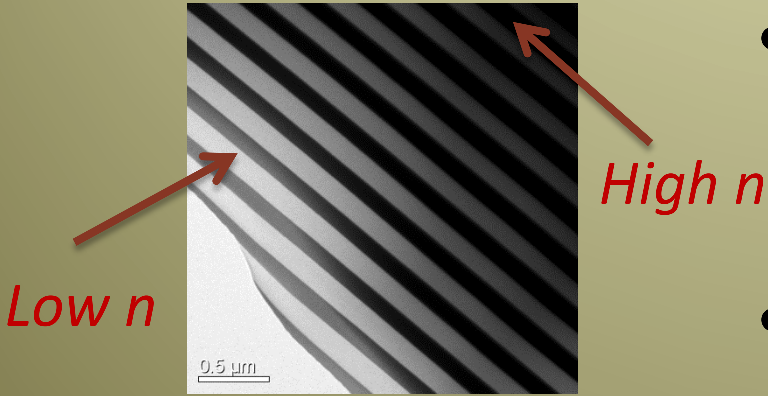
Interference of Light

Optical Coatings

- Often made of alternating layers of different materials
- Layer reflections interfere to cause coating reflection
  - Optimize layer thicknesses
  - Depends on indices of refraction
  - Can design for transmission



Coating Reflectivity



Alternating Layers

- Higher reflection
  - Increased number of layers
  - Bigger index (*n*) separation
- Scatter causes loss of light
- Absorption causes heating

Coating Thermal Noise I

Levin's Formula

- From Fluctuation-Dissipation Theorem
- Describes random motions of surface of coating relative to mirror center of mass

$$S_x(f) = \frac{4\,KB\,T\,d}{f\,Y\,w^2\,\pi^2}\,\phi$$

K_B: Boltzmann's constant

T: temperature in Kelvin

f: frequency

d: coating thickness

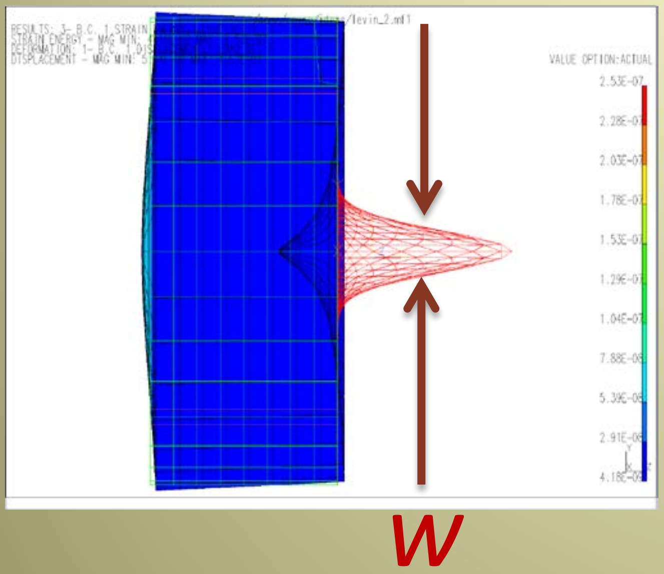
Y: Young's modulus

w: beam width

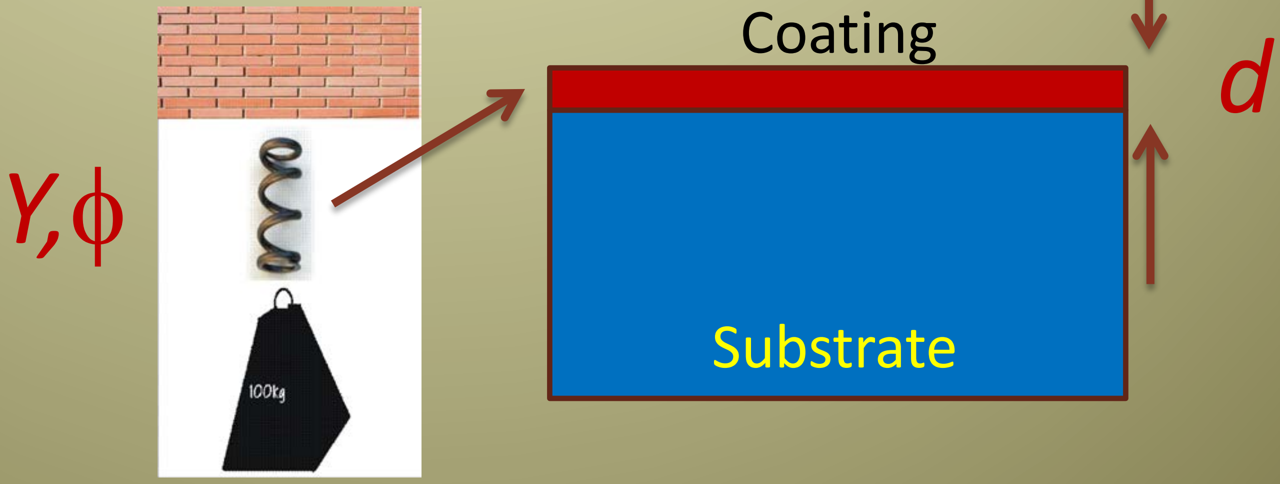
ϕ : mechanical loss

Coating Thermal Noise II

Side View of Optic



- *w*: how well noise is averaged
- *d*: how much coating
- *Y*: how stiff is the coating
- ϕ: how much heat energy can affect coating motion



Mechanical Loss of Coating Materials

High Index Materials

- Tantala Ta_2O_5 3 10^{-4}
- Titania-Tantala 1.5 10^{-4}
- Niobia Nb_2O_5 5 10^{-4}

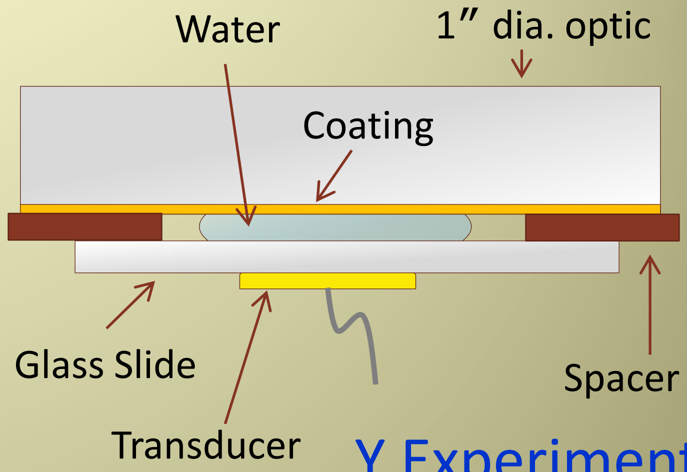
Low Index Materials

- Silica SiO_2 1 10^{-5}
- Alumina Al_2O_5 2 10^{-5}

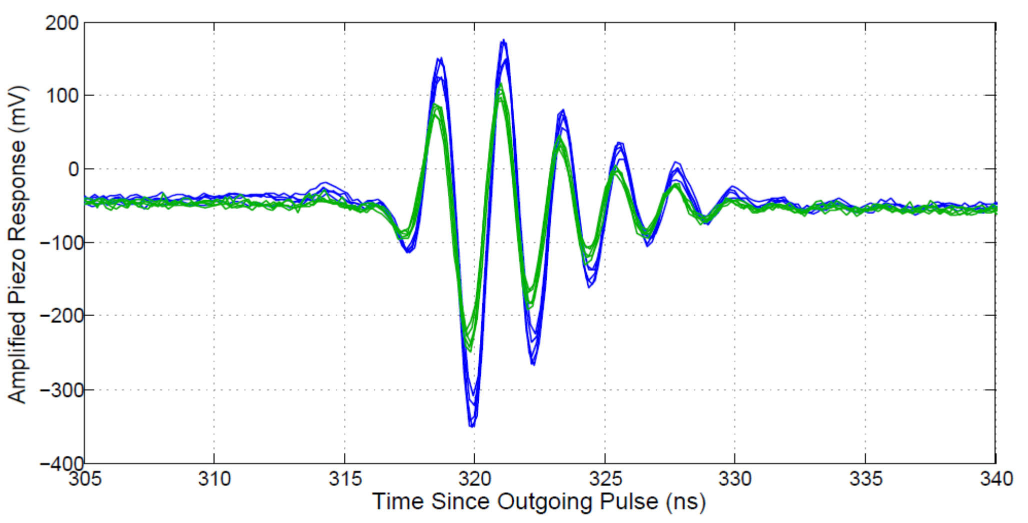
- High index materials have higher mechanical loss
  - Always? Generally? Still under study
  - Focus on finding new and better high index materials
- Many materials show different mechanical loss from different coating companies
  - Process is known to have some affect
  - Most coating companies keep process secret

Young’s Modulus Measurement

- Thermal noise is a force noise
- Stiffness converts force to position
- Young’s modulus of both coating and substrate important



Y Experiment



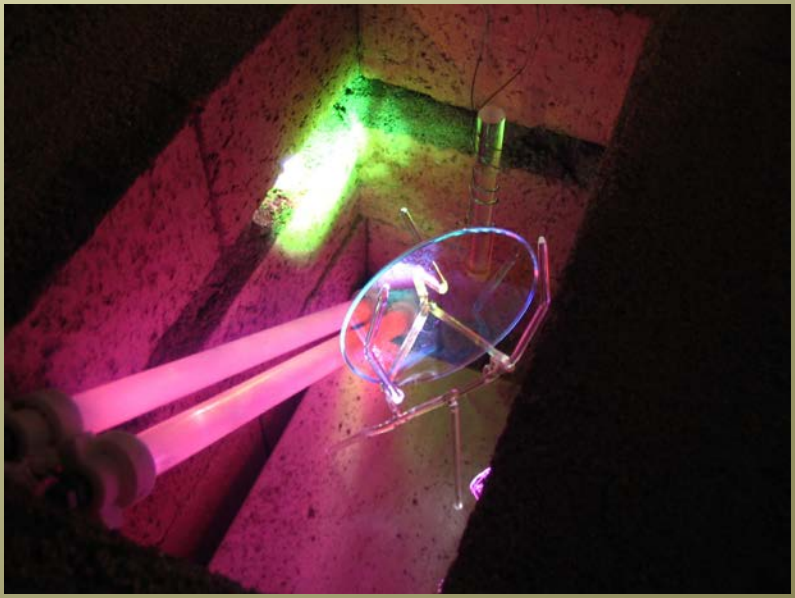
Pulse from Young’s Modulus Measurement

- Work at ERAU on Y
- Green trace from silica
- Blue trace from sapphire
- Also studying high index coating materials

Thermo-optic Noise

- Different form of coating thermal noise
- Thermal fluctuations cause change in index of refraction and layer thickness
- Does not depend on ϕ, but on dn/dT and dL/dT
- Generally less than Brownian thermal noise

  - ERAU center of thermo-optic noise research
  - Measuring dn/dT from changing reflectivity with temperature
  - Difficult data analysis from multiple layers



Experimental Setup at ERAU

Applications Limited by Coating Thermal Noise

- Gravitational Wave Detection
  - First concerned with coating thermal noise
  - Not limiting right now, probably about 3 years
  - Focus of ERAU (and American University) efforts
- Frequency stabilization
  - Precise timing measurements
  - Frequency combs
- Quantum optomechanics
  - Quantum behavior of macroscopic objects
- Cavity quantum electrodynamics
  - Single atom and photon interactions

Gravitational Wave Detection

- Measure prediction of Einstein’s theory of gravity
  - Moving masses produce waves in space and time
- Astronomical sized objects needed
  - Still very tiny effect, about 10^{-18} m at Earth
- Interferometer measures separation between two coated optics; need to boost signal
  - High laser power: hundreds of kilowatts
  - Long arms: 4 kilometers

LIGO Gravitational Wave Detectors

Inspiraling Neutron Stars

Gravitational Wave Optics

- 40 kilograms with 6 cm spot size
  - Increased *w* reduces coating thermal noise
- High optical power
  - Low scatter to keep light in arms
  - Low absorption to reduce temperature
  - Low optical loss allows for squeezed light

Large LIGO Optic

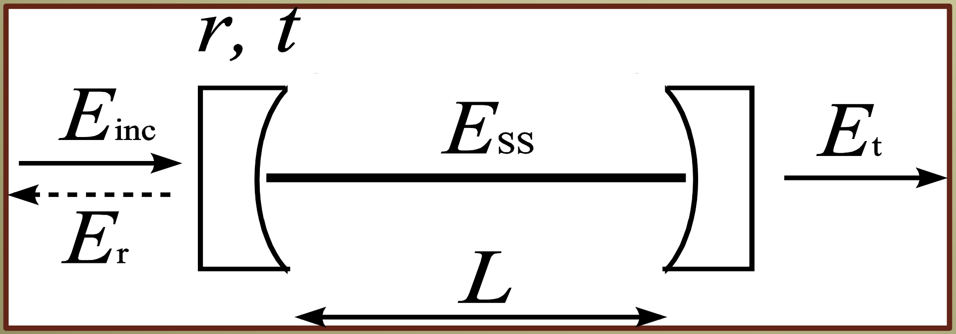
Coated LIGO Optic

Titania-Tantala/Silica Coatings

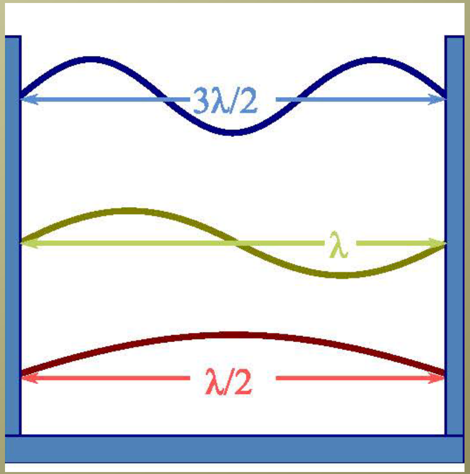
- Design to preserve reflectivity but reduce amount of titania-tantala
- Large index contrast, to keep coating thickness *d* low
- Reduced absorption, low scatter

Frequency Stabilization

- Optical cavities used as frequency reference
  - Cavities have coated mirrors on each end
- Light of certain frequency will resonate in cavity
- Length stability determines frequency stability
- Coating thermal noise will limit cavity length
  - Currently limited to proton radius over 1 second

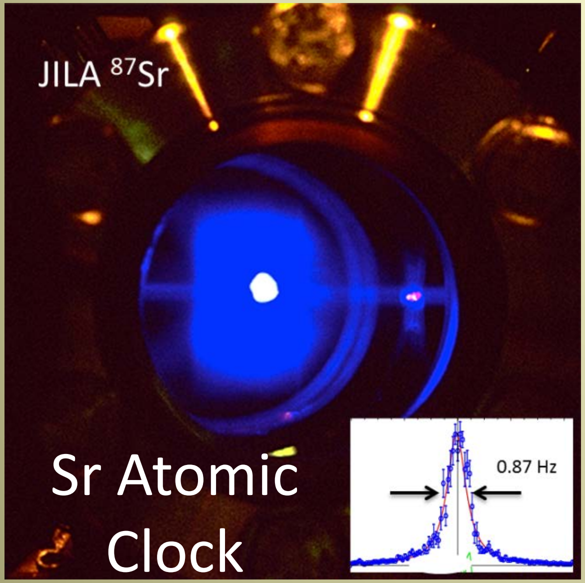


Optical Cavity



Cavity Resonance

Frequency Stabilization Applications



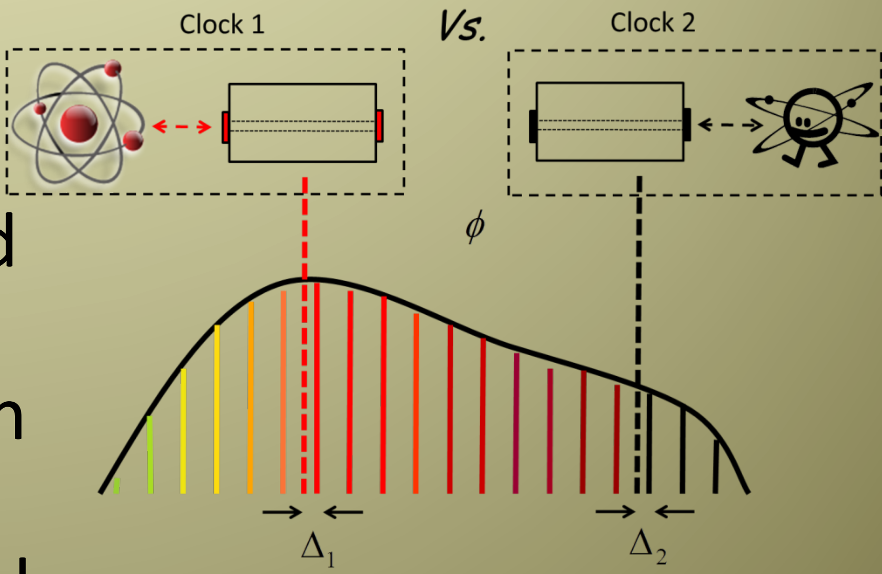
Atomic clocks

- Metrology of optical surfaces
- Improved spectroscopy
- Global positioning (GPS) technology
- Gravitational redshift measurement over 1 meter

Frequency combs

Link across frequencies

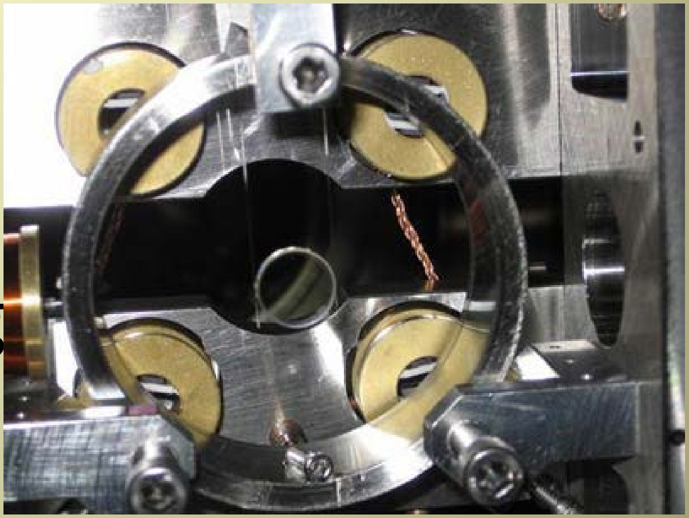
- Connects atomic clocks based on different species
- Optical frequency comparison to microwave standards
- Study changes in fundamental constants



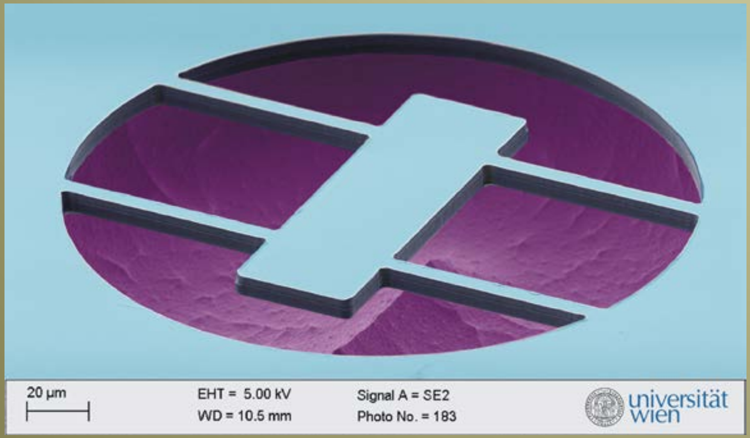
Frequency Comb

Cavity Optomechanics

- Measure motion of small, but macroscopic objects
  - Nano to milli grams
- Some samples made by etching
  - Only coatings, no substrates
  - Coating properties crucial
- Often cryogenic



Mini-mirror in Suspension

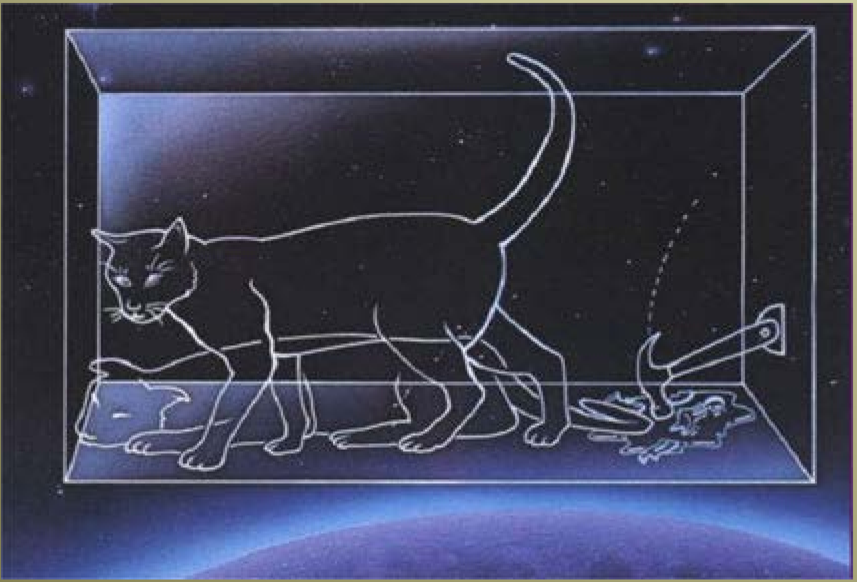


Micron Scale Oscillator

- Light acts as spring
  - Radiation pressure
- Exchange energy between mirrors and light
  - Doppler shift

Cavity Optomechanics Experiments

- Single electron spin detection
- Quantum information theory (Qubits)
- Quantum limits of force, mass, and position
- Quantum mechanical behavior of large objects
  - Coupling of large resonator to single atom
  - Schrödinger’s cat experiments

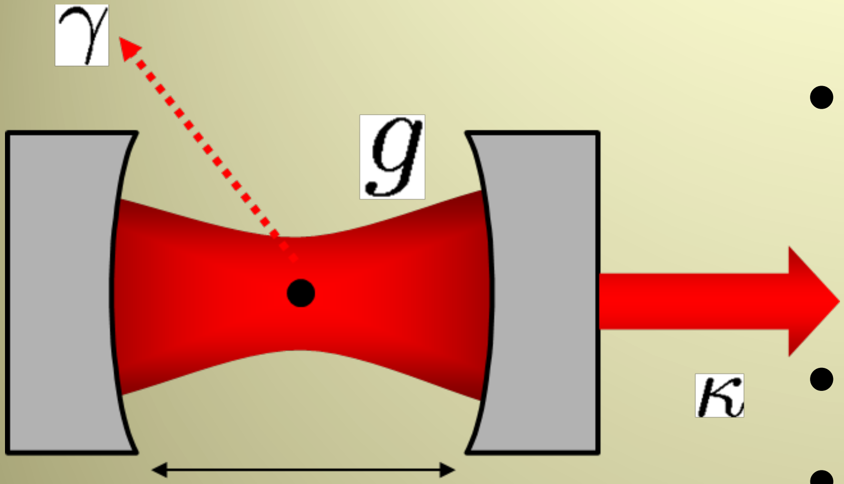


Schrödinger’s Cat Experiment

Schrödinger’s Cat

- Radioactive decay breaks poison bottle or not
- Macroscopic state depends of quantum event
- Just thought experiment until recently

Cavity QED

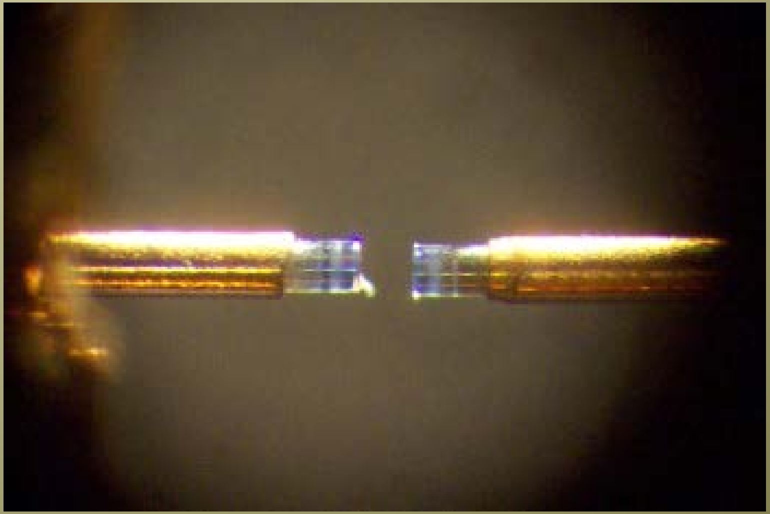


Cavity with Single Atom

- Single atom (ion) in cavity
  - Also quantum dot
  - Bose Einstein condensate
- Secondary beam traps atom
- Thermal noise can influence trapping

- Coating scatter very low
  - Chance of interaction with atom >> chance of scatter
- Can use optical fibers to define cavity
- Generate single photons

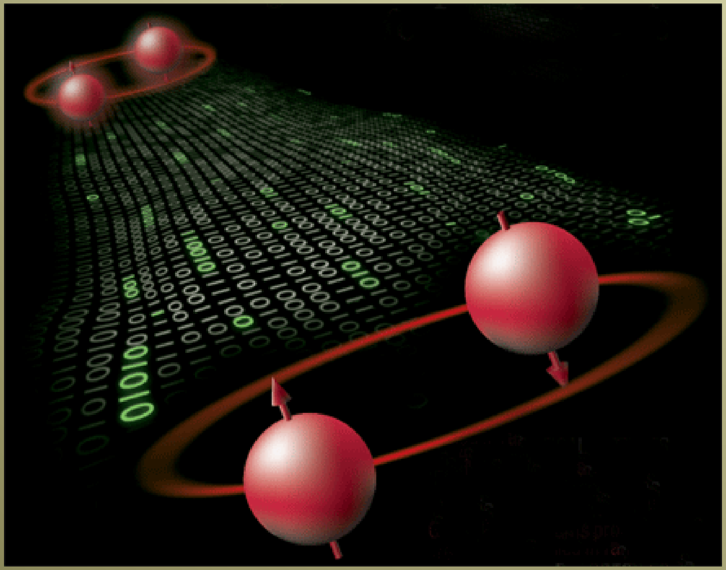
Fiber Optic Cavity



Cavity QED Applications

- Study fundamental quantum systems
  - Interaction of light and matter
- Single atom lasers

Single Atom Loaded Into Cavity



Quantum Computer

- Measure entanglement between different atoms
  - Secure quantum cryptography
- Quantum computation
- Quantum networks

Reducing Coating Thermal Noise

- Reducing temperature
  - Directly lowers T in thermal noise equation
  - Material properties (ϕ, Y, etc.) can also change
- Beam shaping
  - Effectively increase beam size
  - Can cause difficulty with interferometry
- Coating free mirrors
  - Eliminate need for coatings
  - Hard to get high reflectivity
- Khalili cavities
  - Get lower thickness coatings
  - Need extra mirrors

Cryogenics

- Reduction in *T* directly lowers thermal noise
- Need to study materials at low temperatures
  - Properties can improve, worsen, or stay same
  - New materials may become possible

Engineering challenges

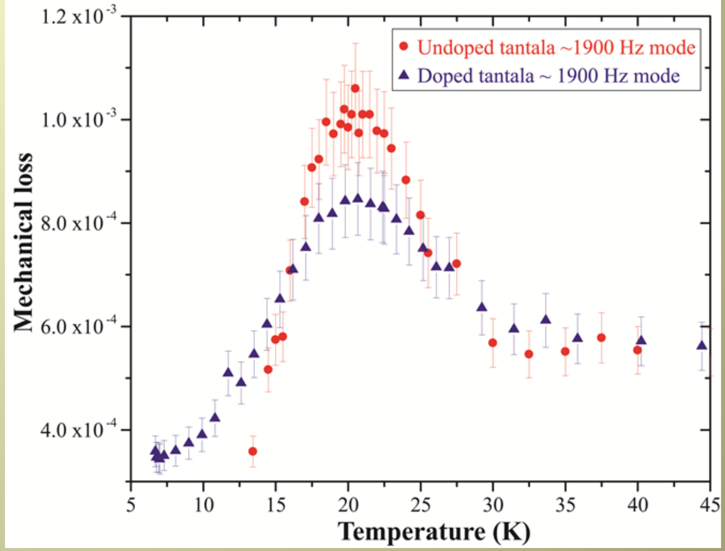
- High thermal conductivity materials to get heat out
- High light power can add heat to optics
- Refrigerators can cause vibration and other noise

Cooled Mirror

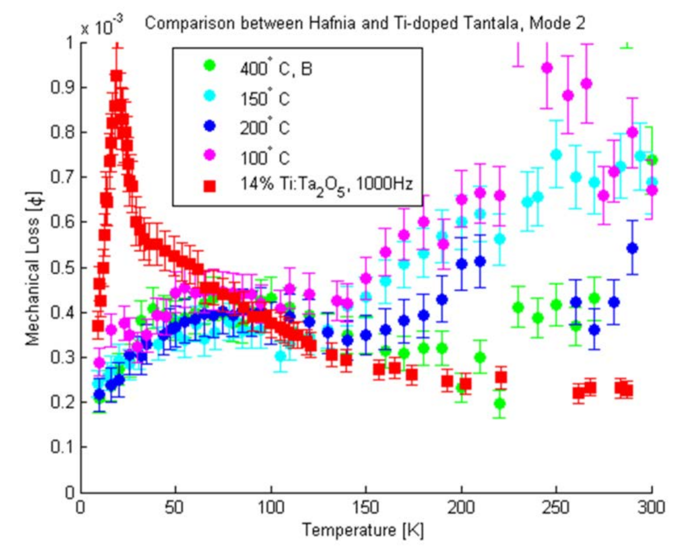
Cryogenics and Materials

- Material ϕ's change with T
- Often have loss peaks
  - Tantala, titania-tantala, silica
  - Help understand source of mechanical loss

Loss Peaks in Ta and Ti-Ta



- Very low T, ϕ's become low

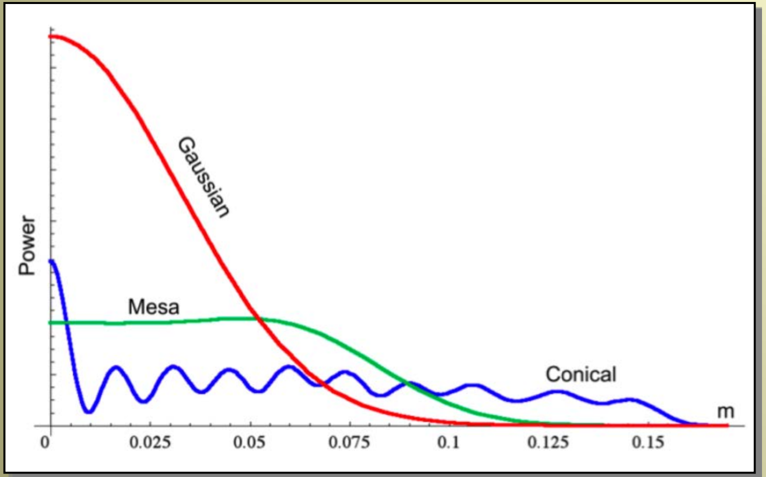


Hafnia Mechanical Loss

- Many loss peaks different with annealing/doping
- Hafnia (HfO_2) poor at room temperature but continually improves with low T

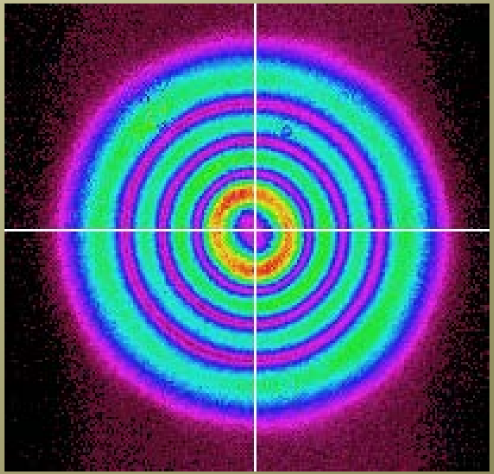
Beam Shaping

Different Shaped Beams



- Averaging across mirror gives lower thermal noise
- Effectively increasing *w* value
- Brings up optical problems
  - Optical loss at edge of mirror
  - Cavity stability at high power

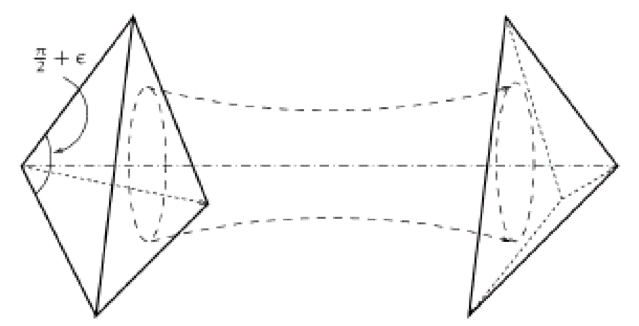
- Many experimental attempts
- Mesa beams
  - Requires special shaped mirror
- Laguerre Gauss beams
  - Use spherical mirrors
  - Plans for use in prototype



Laguerre Gauss 3,3 Mode

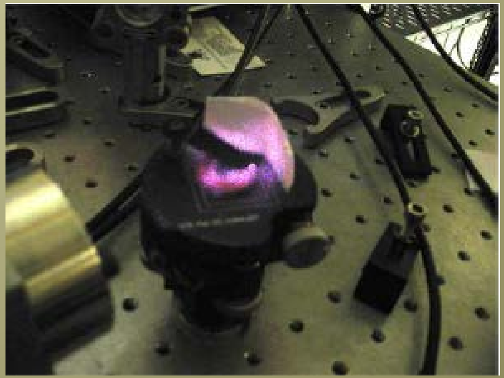
Coating Free Mirrors

Coating Free Mirrors



- Can use total internal reflection effect for mirror
- Need an anti-reflective coating on face
  - Much thinner than reflective
- Beam travels inside mirror
  - Scatter, absorption concerns

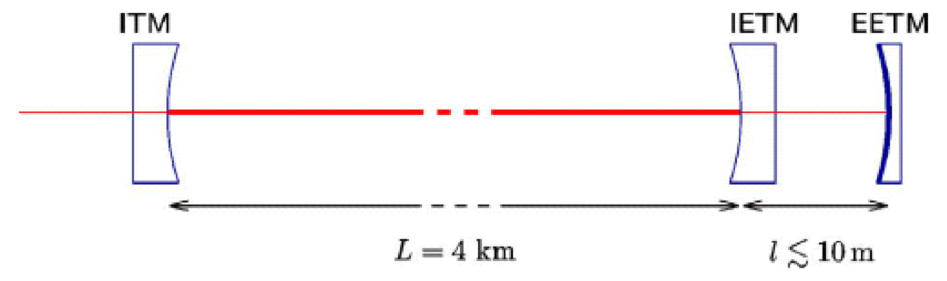
- Mostly theory and modeling work
- Concerns with level of reflectivity achievable
- Experiment using Brewster angle mirror



Brewster's Angle Reflector

Khalili Cavities

- Make one mirror of cavity itself a cavity
- Thick coating (EETM) sensed by less light
- Thin coating (IETM) sensed by more light



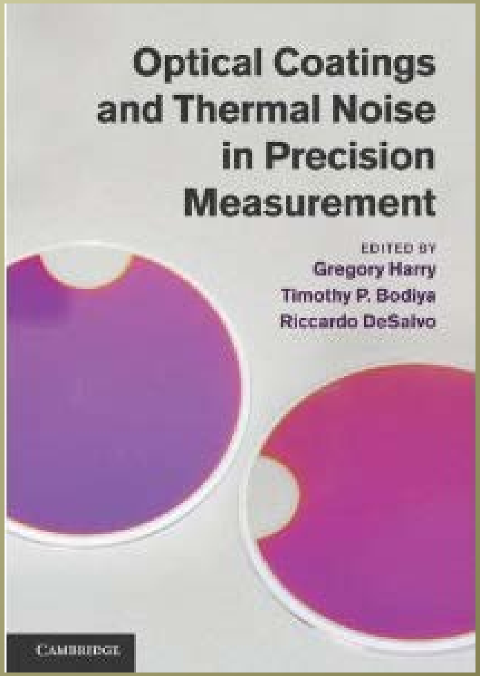
Khalili Cavity

- Planned for use in prototype interferometer
- Added complexity due to additional mirror
- Hope to study quantum noise and squeezed light

10 m Interferometer Prototype

Summary and Conclusion

- Coating properties limitation on many precision optical measurements
- Coating thermal noise limiting noise source
- Cutting edge physics and astronomy
  - Gravitational waves, atomic clocks, Schrödinger’s cat, quantum computing
- Many ways to improve thermal noise
  - Cryogenics one option
  - Much research needed
- Book from Cambridge University Press January 2012



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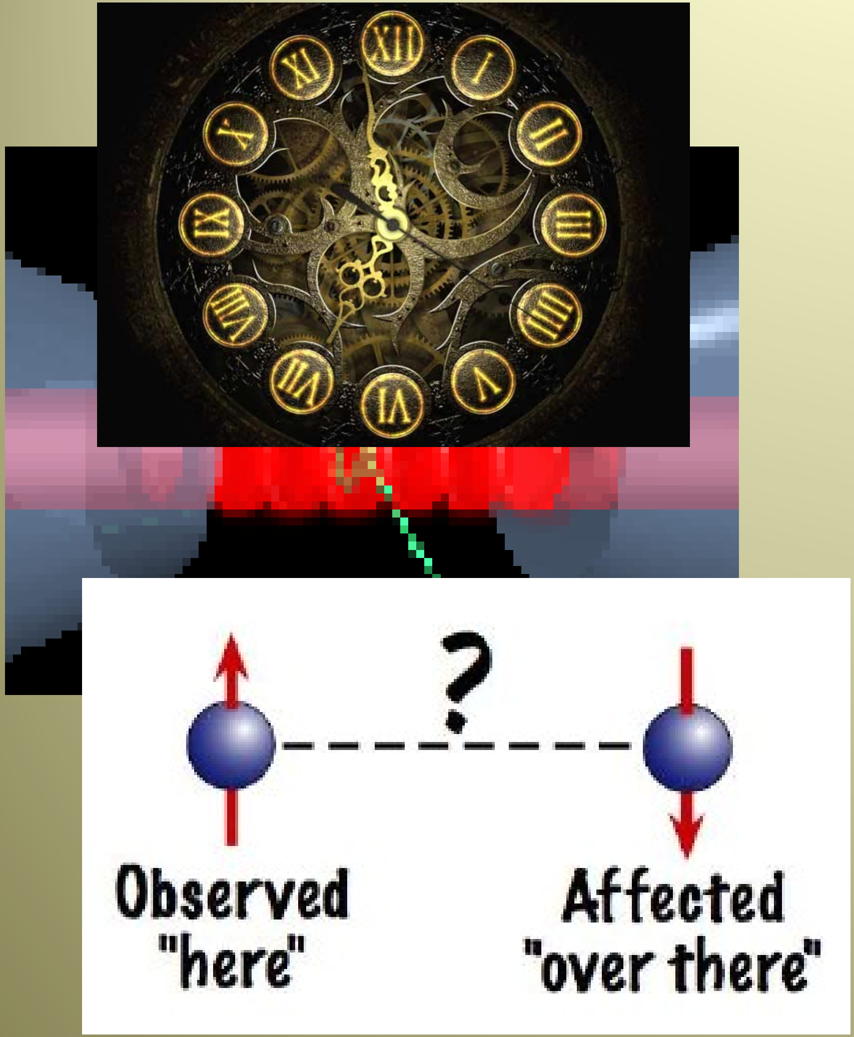
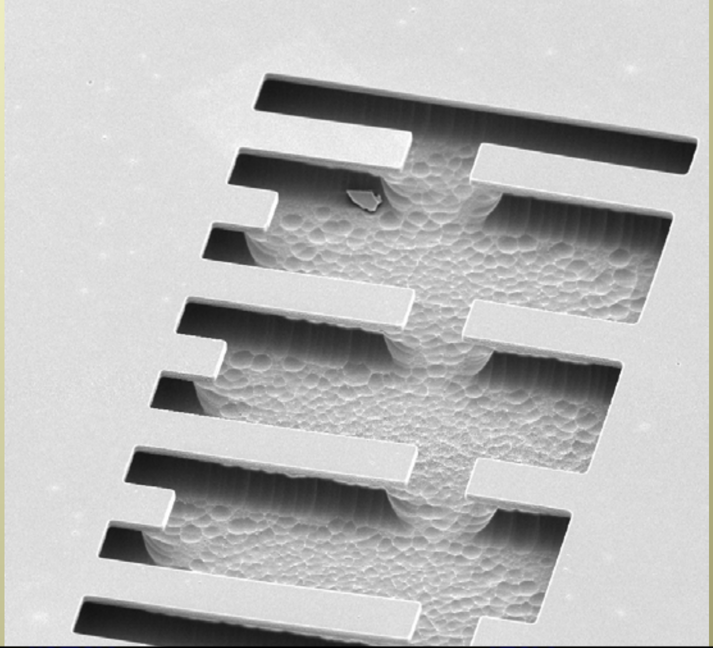
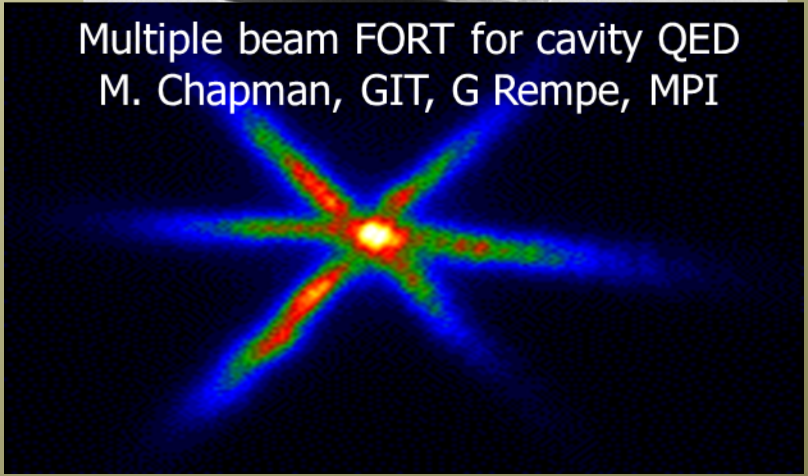


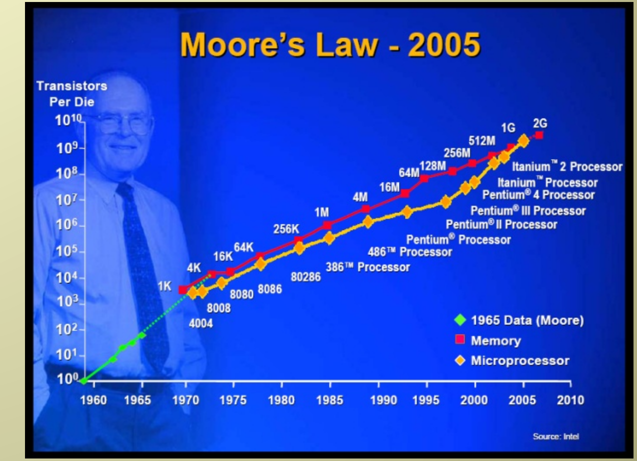




Multiple beam FORT for cavity QED
M. Chapman, GIT, G Rempe, MPI

Processes Limited by Thermal Noise

- Electronics – Johnson Noise
  - Possible end to Moore's Law
  - Can be used as source of signal



Moore's Law

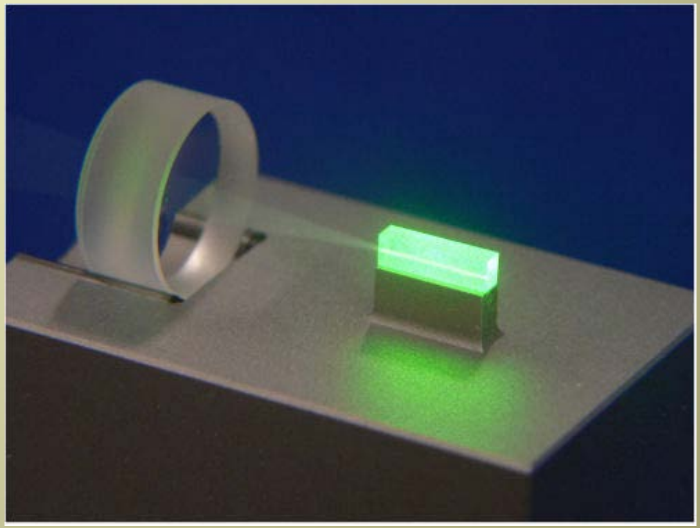
Hearing

- Human hearing – pressure noise
- Atomic force microscopes
- Precision measurement with interferometry

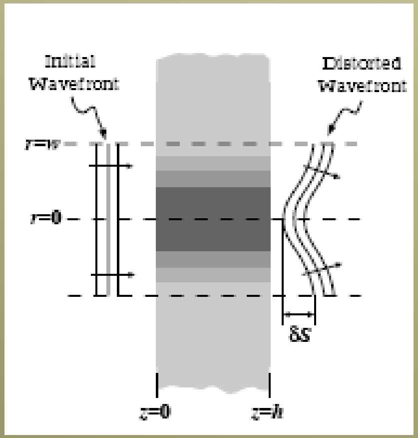
Coatings in Precision Measurement

- More light for more signal
  - Higher reflectivity
  - Low scatter
- Quantum squeezing
  - Lowers quantum noise
  - Limited by coating optical loss

Squeezed Light



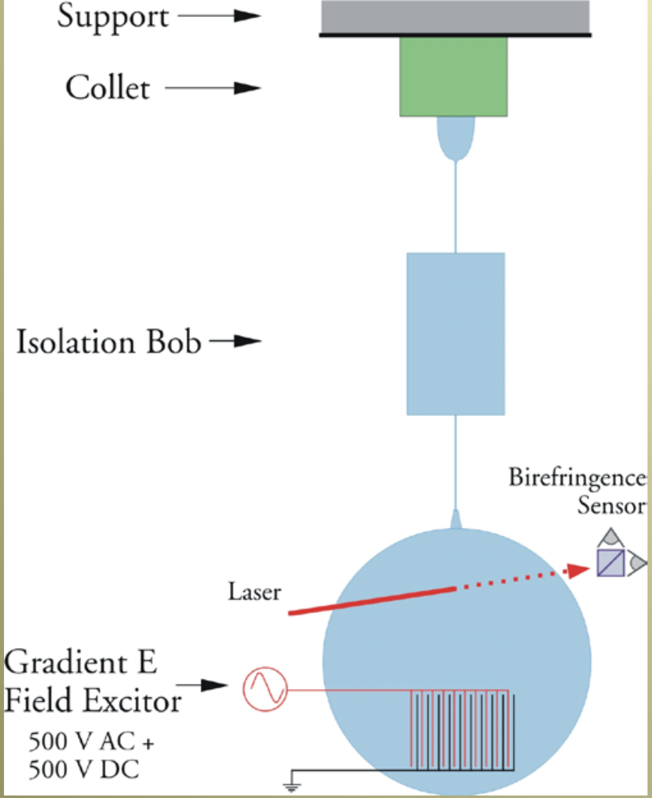
Thermal Deformation of Light in Heated Optic



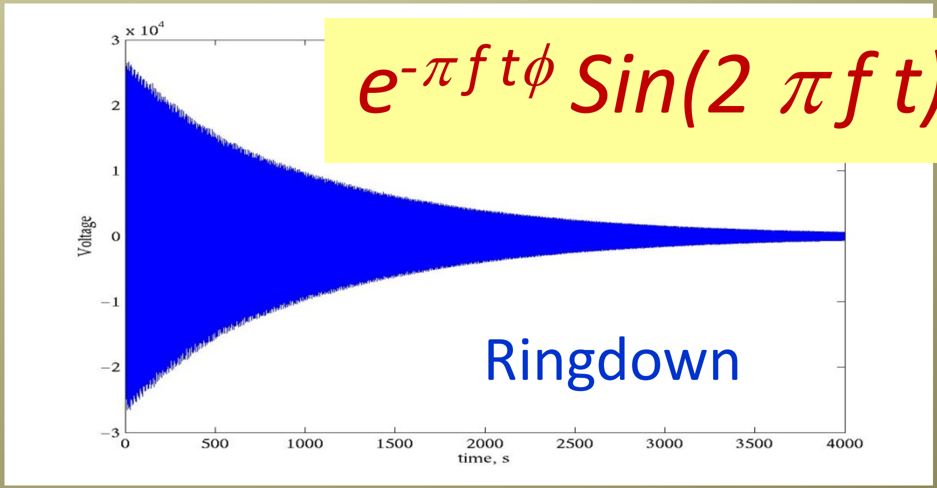
- Heating issues
  - Absorption turns light to heat
  - Heat can deform mirrors
  - Extreme heat causes damage
- Thermal noise

Measurements of Coating ϕ

Q Measurement



- Mechanical loss ϕ also causes ringdown of normal modes
  - Test samples rings like a bell
  - Energy slowly leaves ringing
- Can measure ϕ more easily than measuring thermal noise



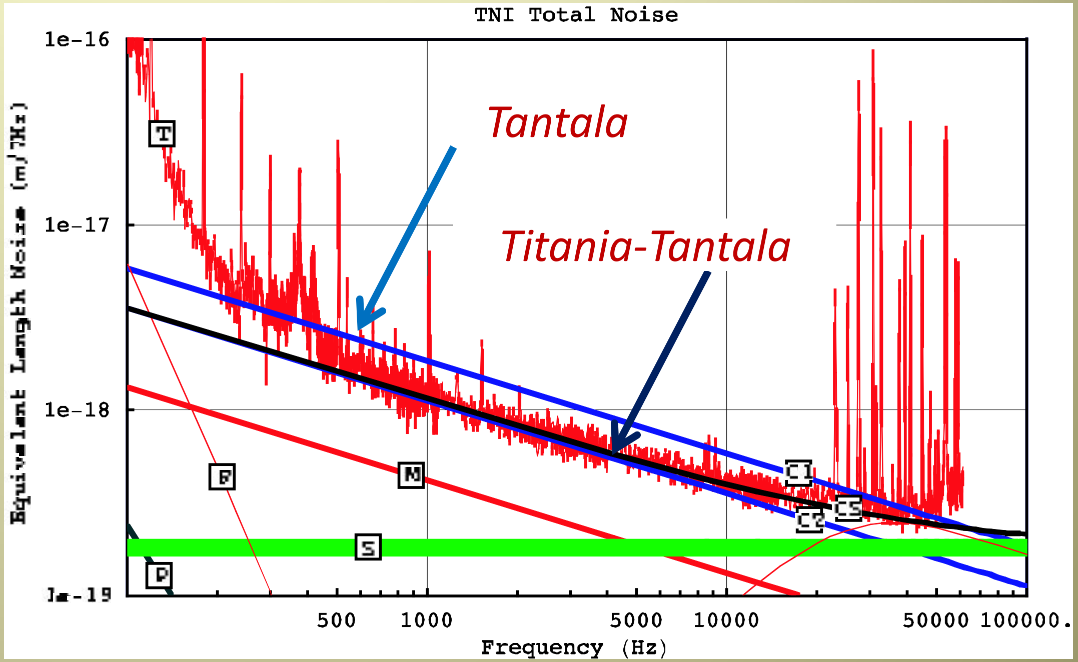
$$e^{-\pi f t \phi} \mathrm{Sin}(2 \pi f t)$$

Ringdown

Direct Thermal Noise Measurements

- Interferometer can directly measure coating thermal noise
- Very difficult
  - Years to perfect
  - Months to measure
- See *1/f* dependence

Coating Thermal Noise Data



- Clear improvement from tantala to titania-tantala
  - Reasonable agreement with Q measurements
- Seen improvement from using less tantala
- Can (and have) also study substrate thermal noise