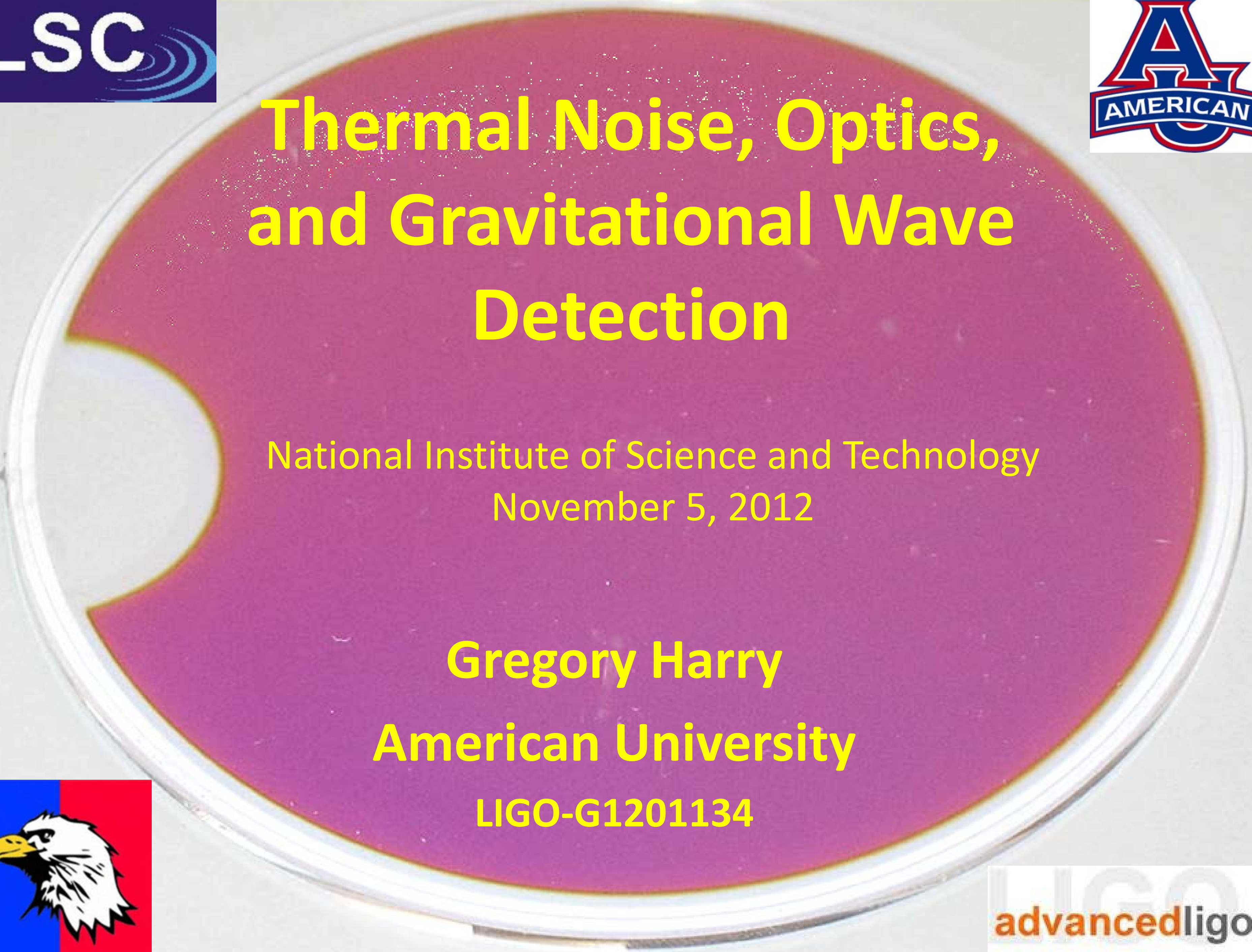


Thermal Noise, Optics, and Gravitational Wave Detection

National Institute of Science and Technology
November 5, 2012

Gregory Harry

American University

LIGO-G1201134

Outline

- Introduction to Thermal Noise
  - History and background
- Coating Thermal Noise
- Applications Limited by Coating Thermal Noise
- Gravitational Wave Detection and Advanced LIGO
- Optics in the Advanced LIGO Detectors
  - Issues arising during design, construction, and installation
- Optics Projects of Potential Mutual Interest

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

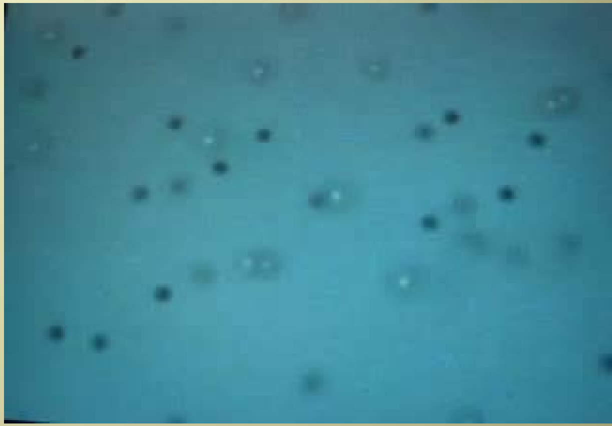
Cooling

- 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.)

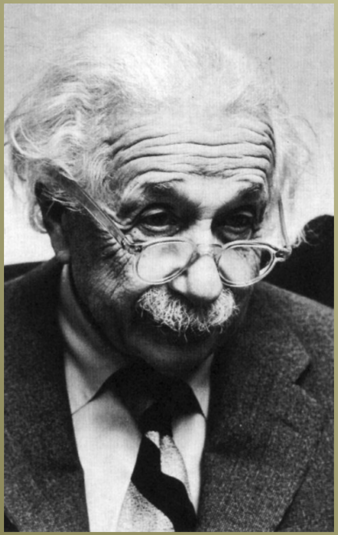
Brief History of Thermal Noise: I

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)

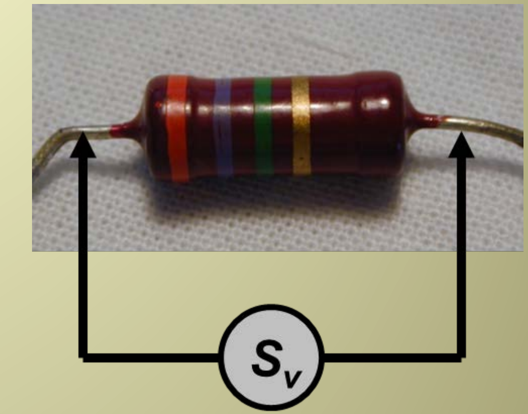
- Mathematics of Brownian motion
- Linked motion to fluid viscosity
- Most cited of Einstein’s papers

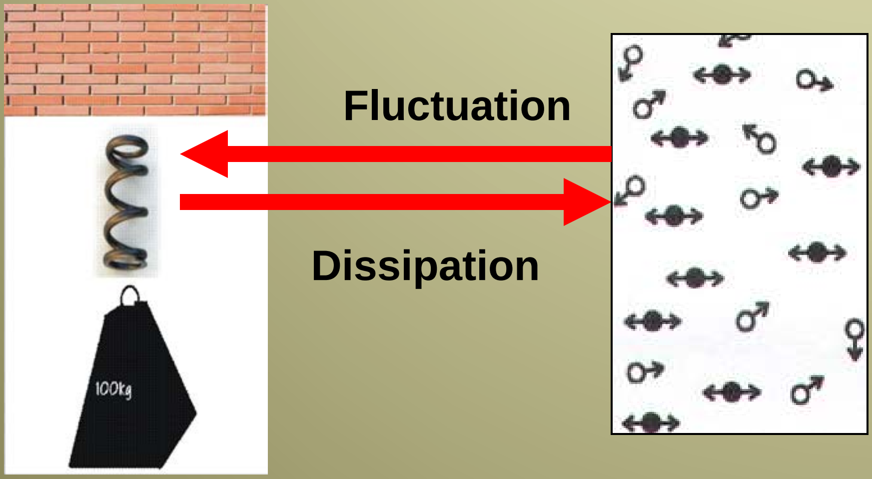
Brief History of Thermal Noise: II

Johnson and Nyquist (1926)

- Voltage noise around resistors
- Seemingly separate to Brown’s motion

Johnson Noise





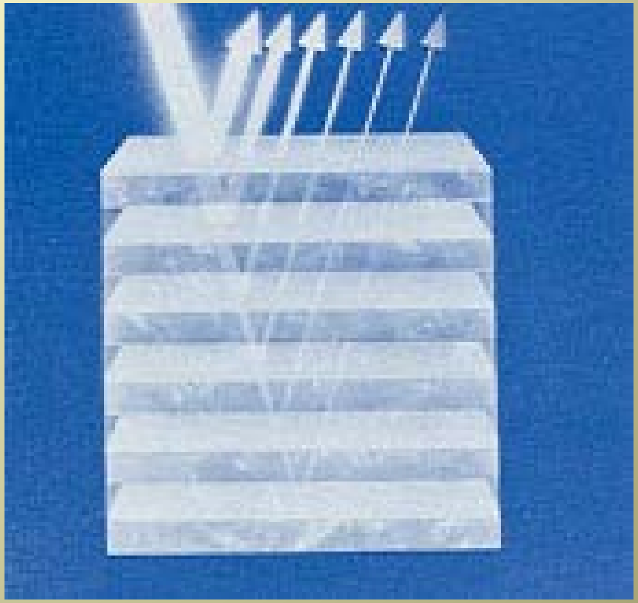
Fluctuation-Dissipation Theorem

Callen, Welton, and Greene (1950s)

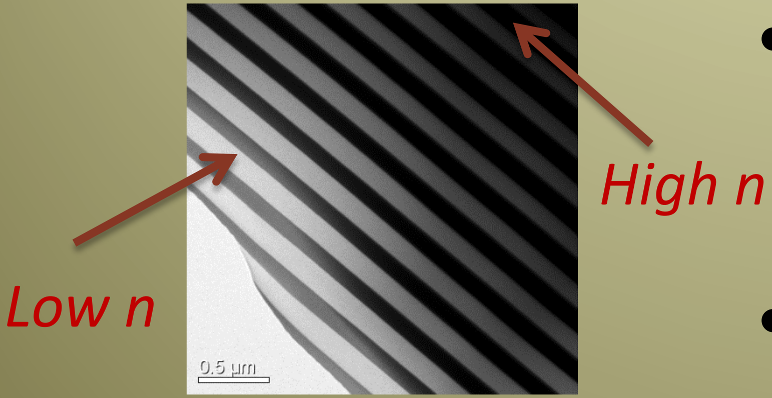
- Tie everything together
- Relates random motion to energy loss
- Fluctuation-Dissipation Theorem

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

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

K_B: Boltzmann's constant

T: temperature in Kelvin

f: frequency

d: coating thickness

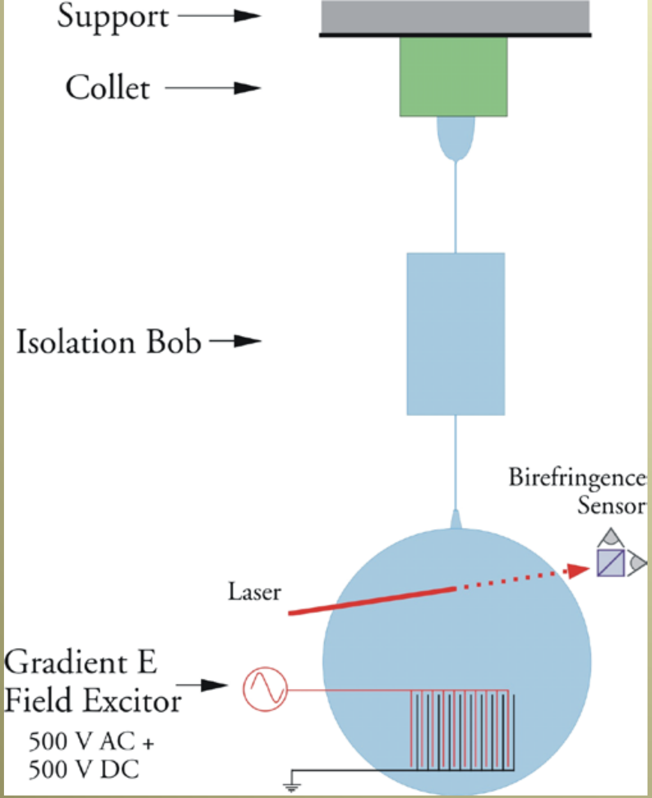
Y: Young's modulus

w: beam width

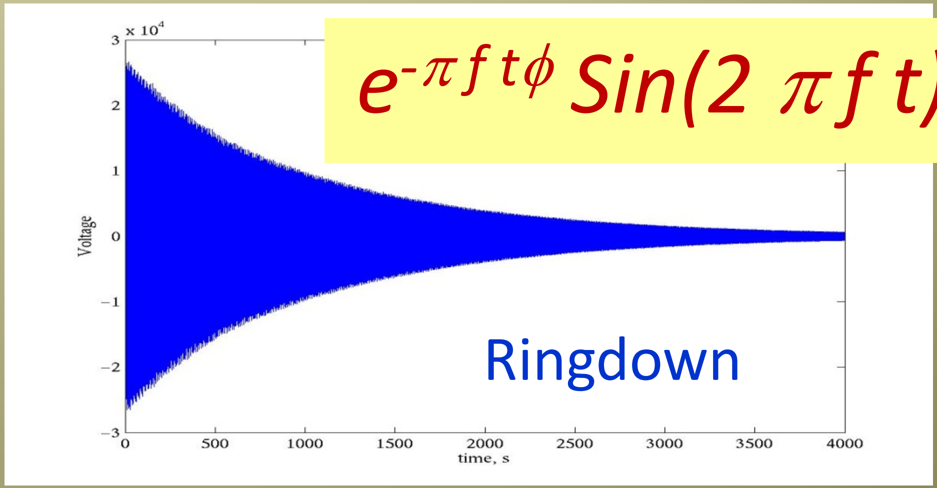
ϕ : mechanical loss

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
  - Measure modal Q's
- Can measure ϕ more easily than measuring thermal noise

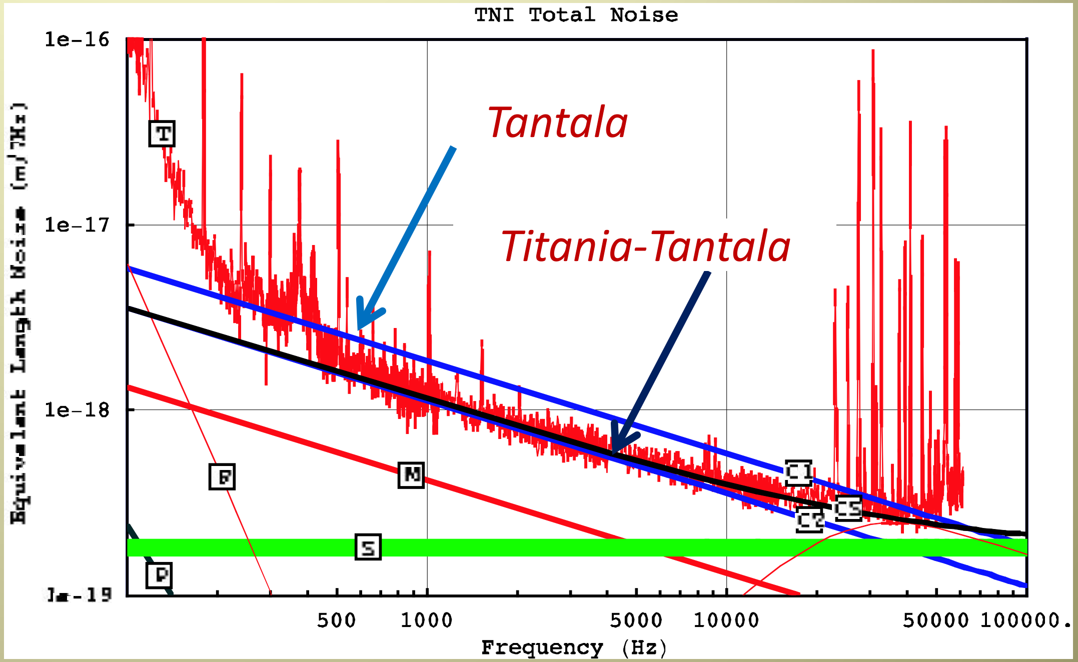


$e^{-\pi f t \phi} Sin(2 \pi f t)$

Direct Thermal Noise Measurements

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

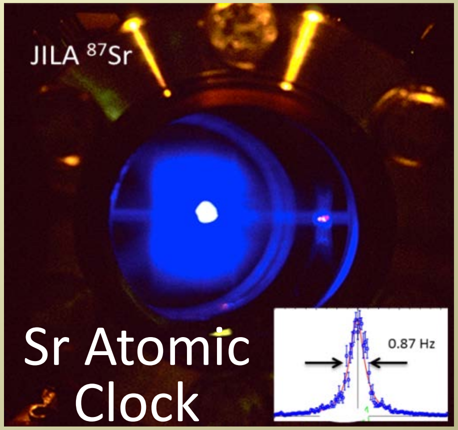
Coating Thermal Noise Data



- 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

Applications Limited by Coating Thermal Noise

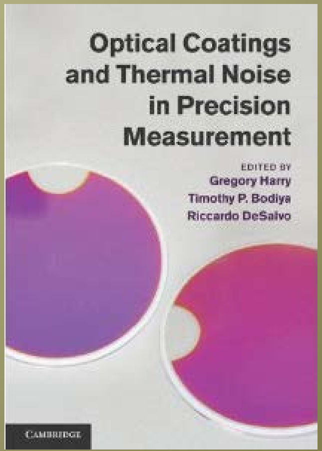
- Frequency stabilization
  - Precise timing measurements
  - Frequency combs
  - Work done at NIST-Boulder



Sr Atomic Clock

Atom in Cavity

- Quantum optomechanics
  - Quantum behavior of macroscopic objects
- Cavity quantum electrodynamics
  - Single atom-photon interactions
- Gravitational Wave Detection
  - First research on coating thermal noise
  - Focus of American University efforts
- Book on coatings and applications



Optical Coatings
and Thermal Noise
in Precision
Measurement

EDITED BY
Gregory Harry
Timothy P. Bodiya
Riccardo DeSalvo

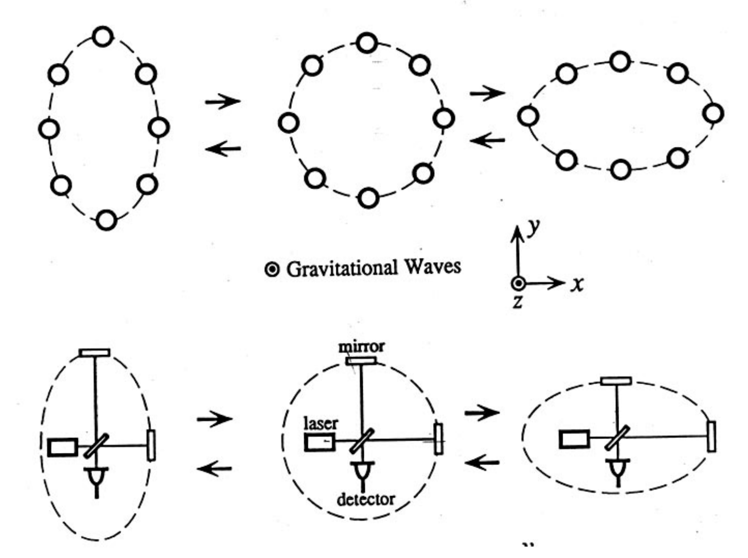
CAMBRIDGE

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 coated optics; need to boost signal
  - High laser power: hundreds of kilowatts
  - Long arms: 4 kilometers

LIGO Gravitational Wave Detectors

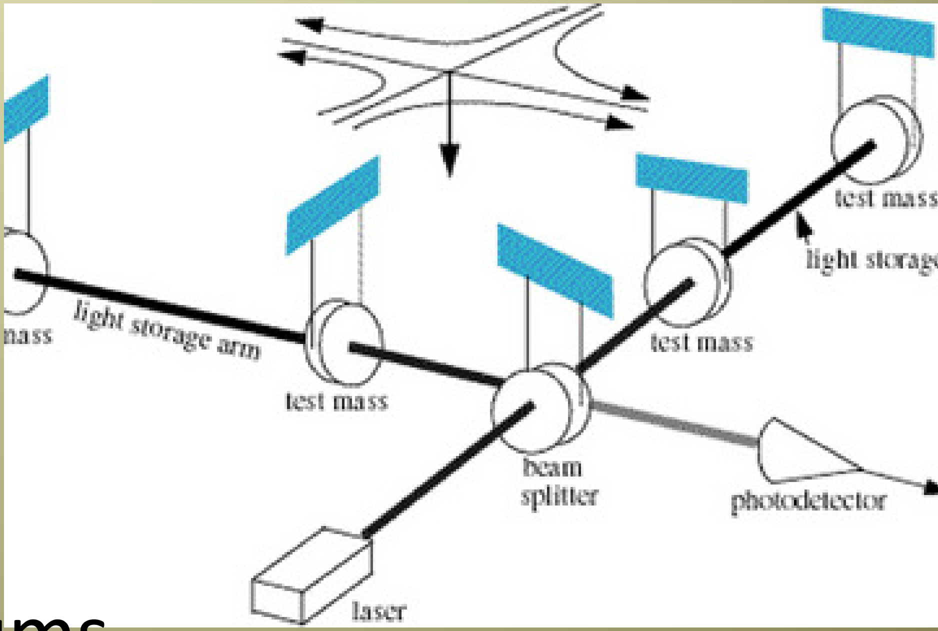
Effect of Gravitational Waves



LIGO Detectors

- Initial LIGO had two 4-km long and one 2-km long interferometers
  - Livingston Louisiana and Hanford Washington
- Advanced LIGO has three 4-km interferometers under construction
- One each in Livingston, Hanford, one in India
- Michelson configuration with Fabry-Perot arms
  - Also signal and power boosting mirrors
- Mirrors hang as pendulums
- Full 8-km optical path in vacuum

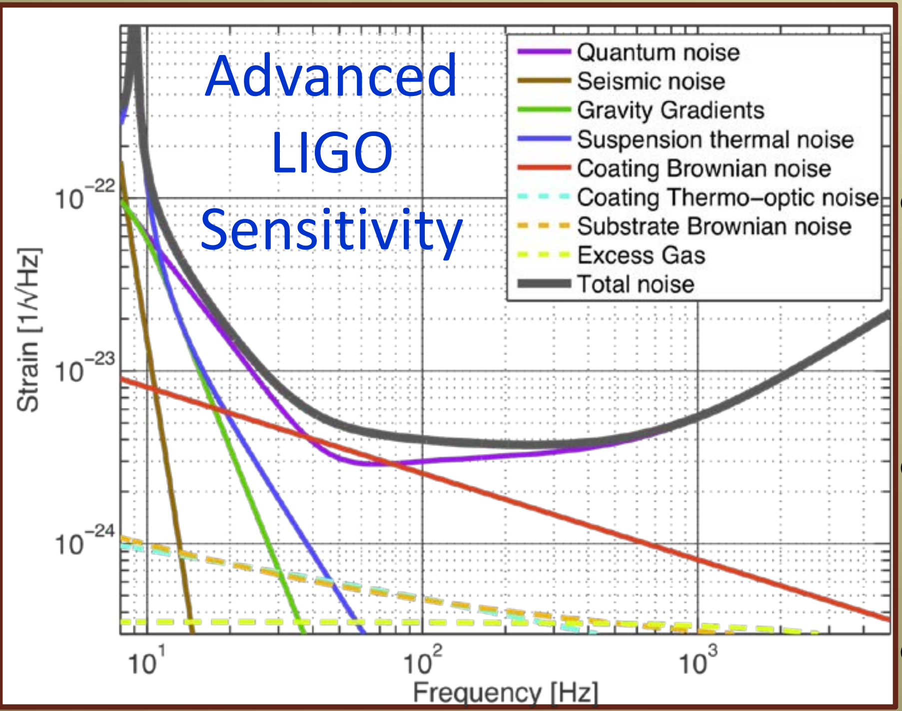
Simplified LIGO Interferometer



Advanced LIGO

- October 2010, installation began on Advanced LIGO (aLIGO)
- Most hardware procured
- Installation of mirrors and other hardware in progress

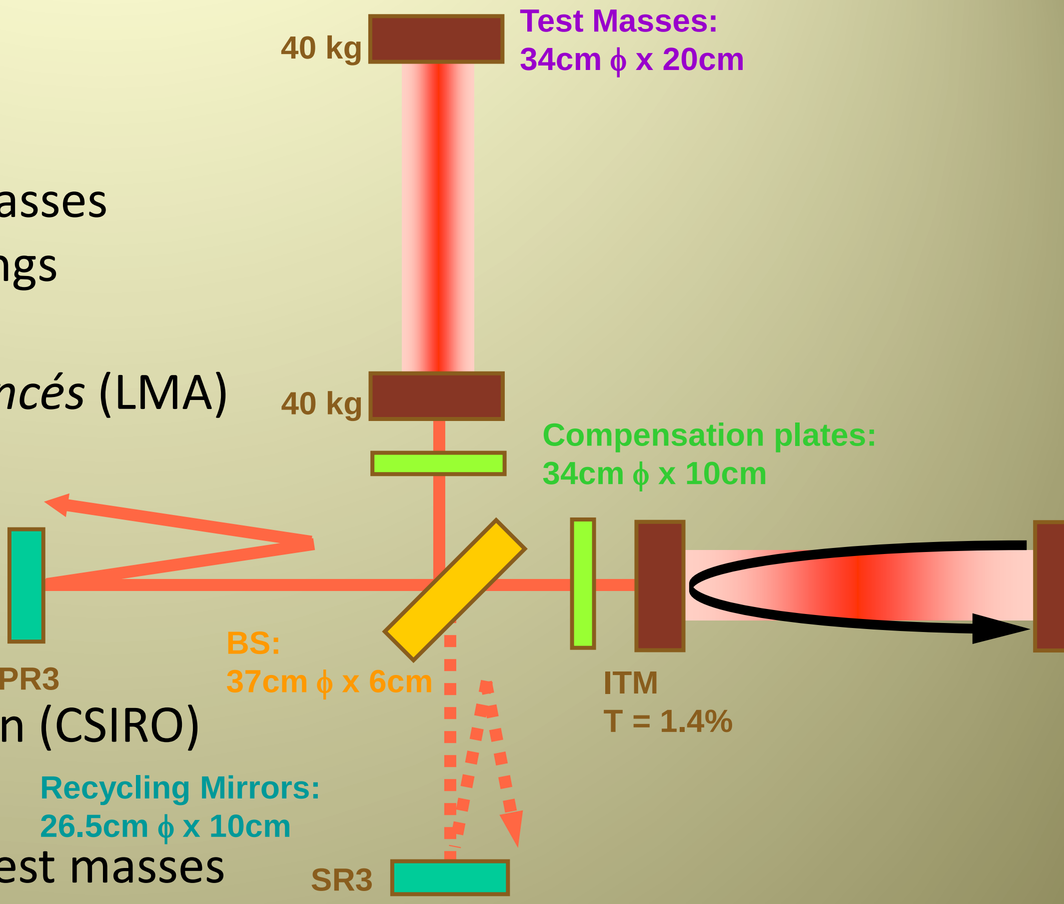
Astronomical Reach



- Sensitivity designed to be 10X initial LIGO
  - Initial LIGO saw no signals
- Limited in sensitive band by coating thermal noise
- Early data in 2015

Advanced LIGO Optics Types

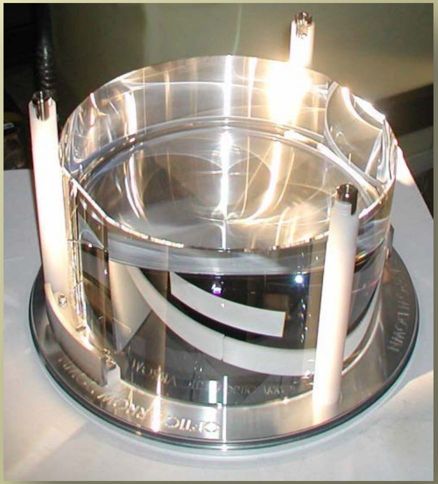
- Test masses
  - Define Fabry-Perot cavities
  - End test mass and input test masses
  - Highest optical power on coatings
  - Most stringent requirements
  - *Laboratoire des Matériaux Avancés* (LMA)
- Beamsplitters
  - Divide the beam into two arms
  - Equal stress on both sides
  - Commonwealth Scientific and Industrial Research Organization (CSIRO)
- Compensation plates
  - Secondary optic behind input test masses
  - Used to adjust thermal lensing
  - CSIRO
- Recycling mirrors
  - Reflect both optical power and signals back into interferometer
  - CSIRO

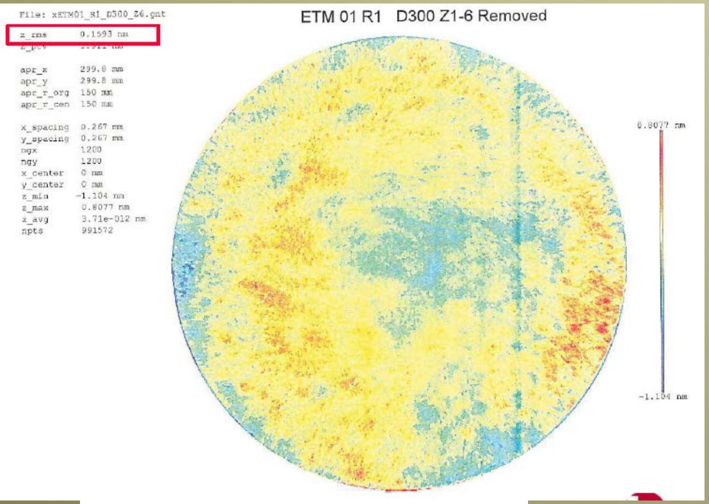


Advanced LIGO Test Masses

- 40 kilograms with 6 cm spot size
  - Large spot reduces coating thermal noise
  - Fused silica glass for low thermal noise
- Two step polish
  - Superpolish to 1 Å microroughness , within 100 nm of figure requirement
  - Ion beam figuring to correct figure
  - Polishing done at Coastline and Zygo Extreme Precision Optics

LIGO Test Mass





```
File: xETM01_R1_D300_Z6.gnt
z_rms       0.1593 nm
z_pcv       1.911 nm

apr_x       299.8 mm
apr_y       299.8 mm
apr_r_org   150 mm
apr_r_cen   150 mm

x_spacing   0.267 mm
y_spacing   0.267 mm
ngx         1200
ngy         1200
x_center    0 mm
y_center    0 mm
z_min       -1.104 nm
z_max       0.8077 nm
z_avg       3.71e-012 nm
npts        991572
```

Surface Figure

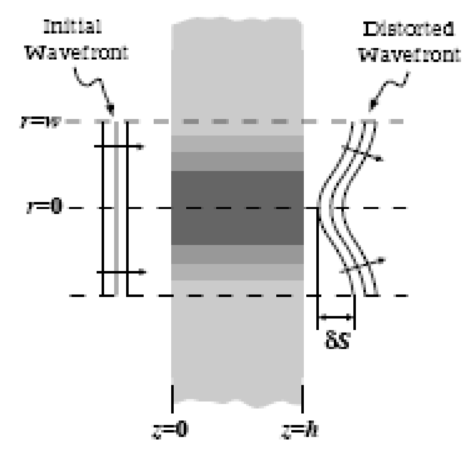
Metrology

Property	Requirement	Measurement
Microroughness	0.16 nm rms	0.11 nm rms
Radius of Curvature	2245-5+15 m	2249.8 m
Surface Figure Error	0.3 nm rms	0.12 nm rms
Astigmatism	3 nm rms	0.04 nm rms

Advanced LIGO Optics Coatings

Property	**Requirement**	**Measurement**
Scatter	10 ppm	6.5 ppm
Absorption	0.5 ppm	0.5 ppm
Uniformity of reflectivity	0.2%	0.2%
End Mirror Transmission	5 ± 1 ppm	4.8 ppm
Input Mirror Transmission	1.4 ± 0.1 %	1.38%
Transmission Matching	1%	TBD

Thermal Lensing



Coated LIGO Optic

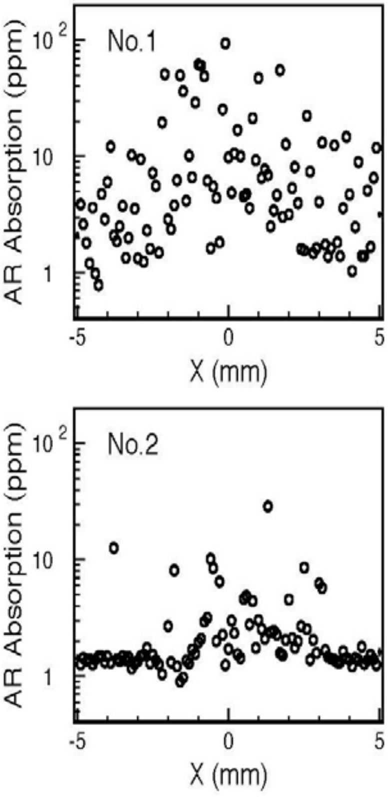
Coatings

- Ion beam deposition coating
- Titania doped tantala/silica
  - Lower thermal noise
  - Large index contrast, low coating thickness
  - Reduced absorption, low scatter
- Design to preserve reflectivity but reduce amount of titania-tantala

Advanced LIGO Optics Issues

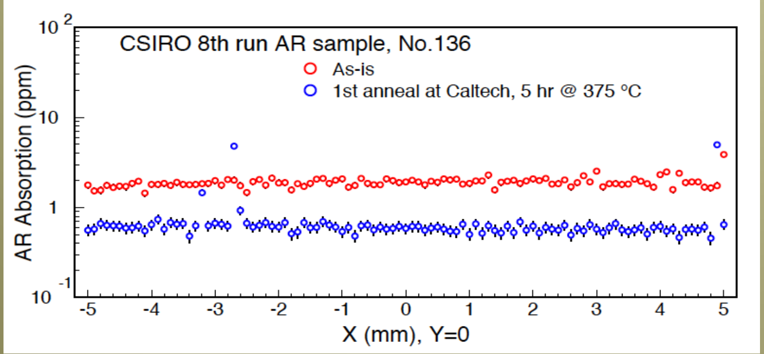
- Absorption of AR coatings
  - Inexplicably large in some samples, overall high
  - Annealing bringing down close to specifications
- Figure change with annealing
  - Significant distortion in optic shape
  - Only some optics, mostly Corning glass
- Polishing effects on thermal noise
  - Ion beam etching used with superpolish
  - Both techniques demonstrated to not adversely effect thermal noise; details unknown

AR Coating Absorption



- Possibly related to thin tantala layer
  - Only seen on beamsplitters and compensation plates; have thin layers
- Consistent with tantala, substrate and/or interlayer absorption
- Improves with annealing
  - Can take > 100 hours at > 450 C
- Humidity while annealing may play role

Absorption with Annealing



Models of Absorption vs Depth

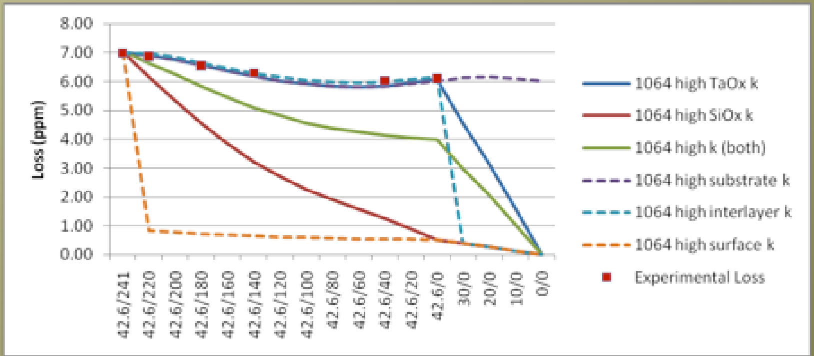
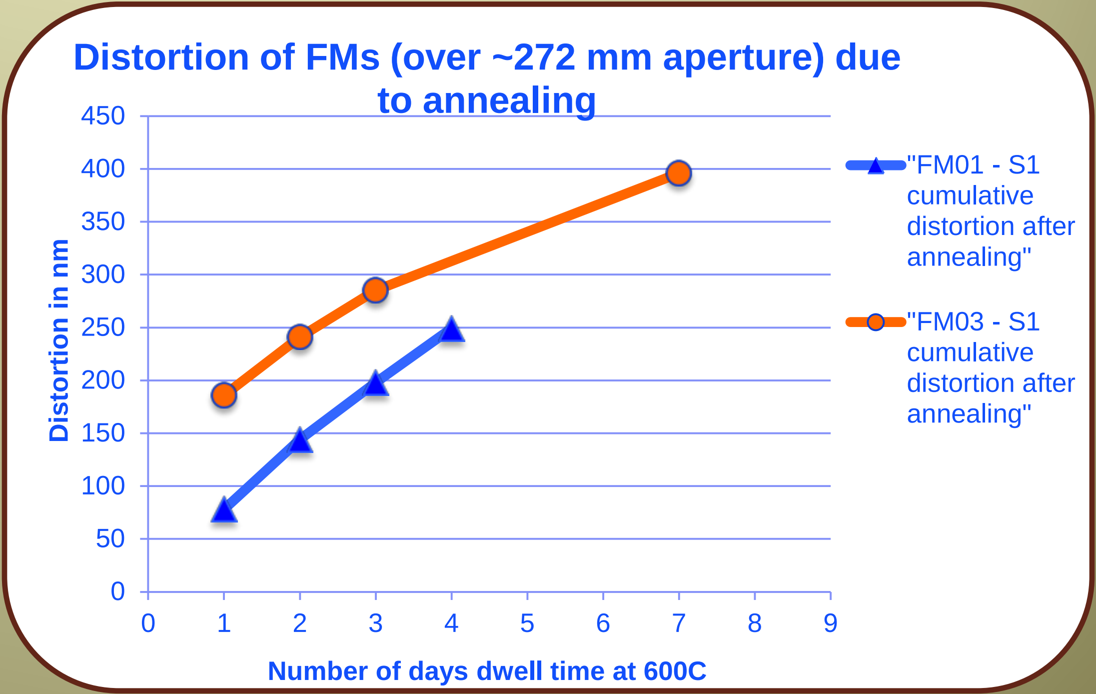


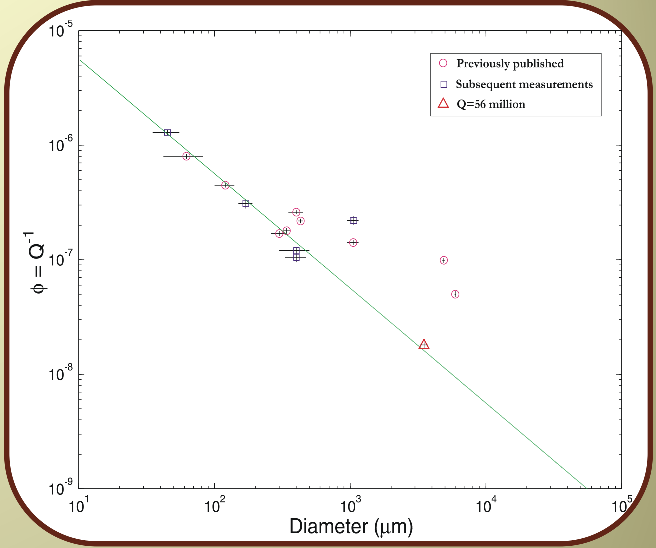
Figure Change with Annealing

- Change in surface figure with annealing observed in some Advanced LIGO optics
- Primarily in Corning 7980 fused silica
- Corning optics replaced with Heraeus glass
- Recently seen in Heraeus as well
  - About 10% of Corning change
- No understanding of cause or cure



8 nm stability required

Polishing and Thermal Noise

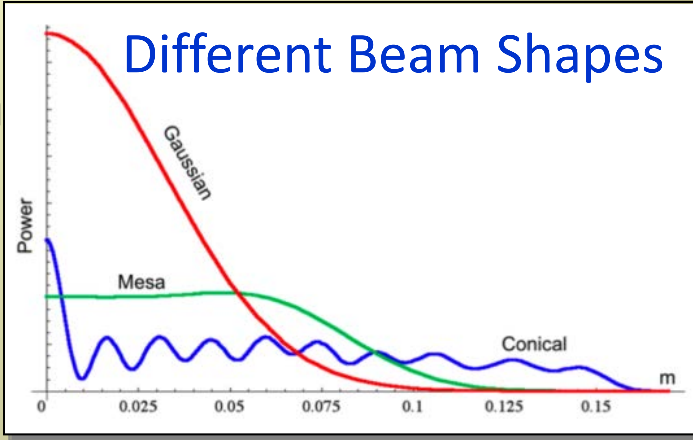


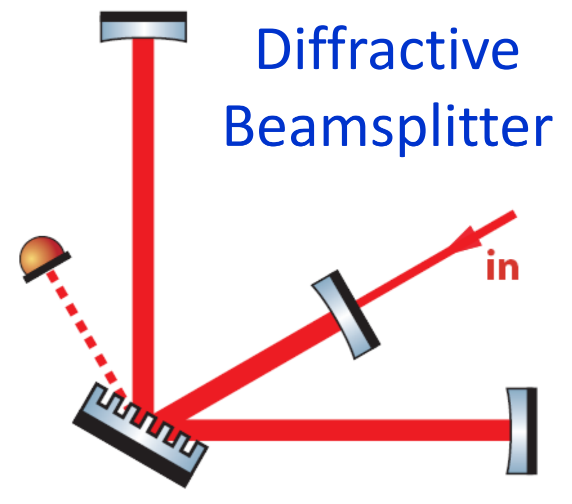
Silica Mechanical Loss vs Surface to Volume Ratio

- Mechanical loss of glass surfaces worse than bulk
- Flame polished silica surfaces well characterized
- No large thermal noise effects from super- or ion beam polish
  - Details unstudied
  - Might be able to improve with annealing, chemical treatment, or other processes
  - Trade offs between roughness and mechanical loss?
- Magneto-rheological polishing another option
  - Experience has microroughness high

Improved Coatings for Next Generation Detectors

- Reducing temperature
  - Lowers T in thermal noise equation
  - Properties (ϕ, *Y*, etc.) can change
- Beam shaping
  - Effectively increase beam size
  - Strict figure requirements

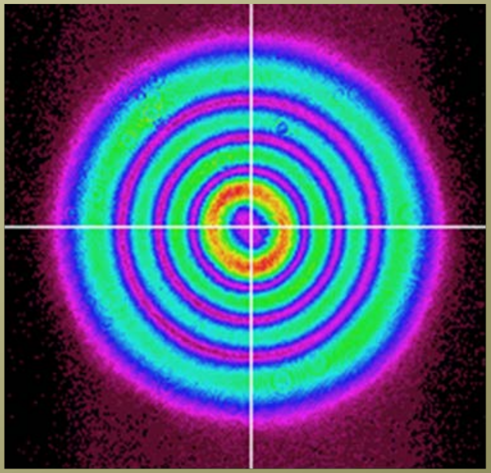

Different Beam Shapes


Diffractive Beamsplitter

- All reflective optics
  - Diffractive coatings
  - Improved thermal lensing
- Coating free mirrors
  - Eliminate need for coatings
  - Hard to get high reflectivity

Next Generation Polishing Issues

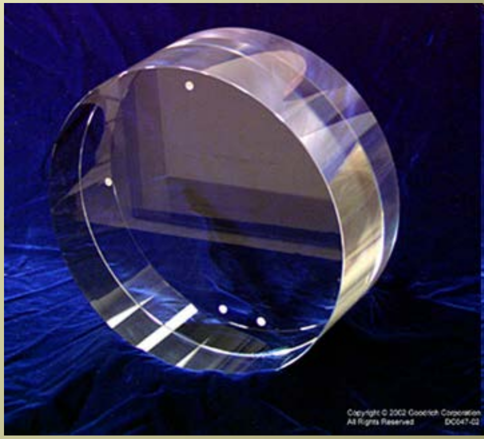
- Mesa beam or other unusual beam shapes allow for larger spot sizes
  - Reduce thermal noise, better averaging
  - Difficult to polish, may require new techniques
- Gauss-Laguerre modes allow spherical polish but require extreme figure
- Coating-free mirrors may have strict roughness and figure needs
  - Also require AR coatings so absorption is important



Laguerre Gauss 3,3 Mode

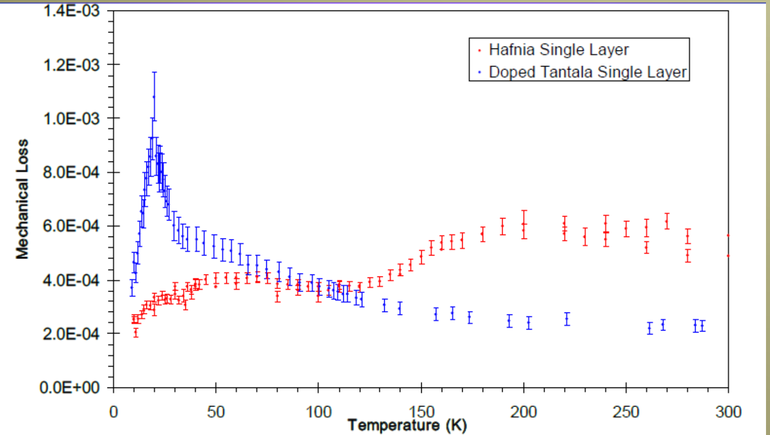
Next Generation Optics Materials

- Cryogenic silicon or sapphire mirrors
  - Thermal noise lower at low temperatures
  - What figure/microroughness is possible?
  - What homogeneity can silicon have at 1550 nm?
  - How does polish effect thermal noise?
  - What coatings are possible?



40 kg Sapphire Optic

Tantala and Hafnia vs Temperature



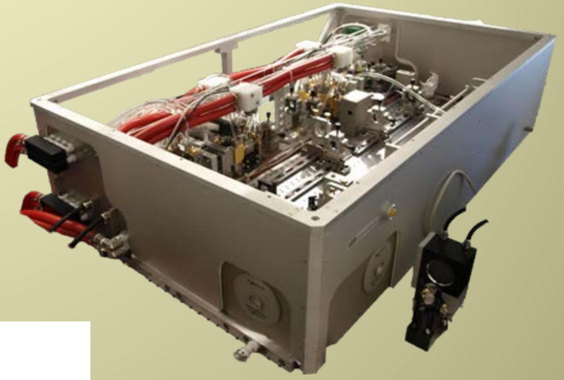
- New coating materials
  - Silica /tantala increase mechanical loss at low temperature
  - Hafnia improves mechanical loss
  - Crystalline coatings promising: AlGaAs, AlGaP

Conclusions

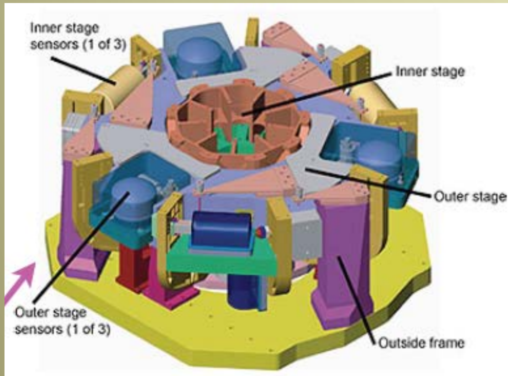
- Coating thermal noise limitation in many precision optical measurements
  - Gravitational wave detectors prime example
- Advanced gravitational wave detectors coming soon
  - Improved technology will provide greater sensitivity
- aLIGO mirrors are larger with bigger spot sizes, finer polish, lower absorption, and lower thermal noise
- aLIGO optics issues during fabrication include high absorption and figure change with annealing
- Next generation detectors need optics research
- Many areas of mutual interest with NIST

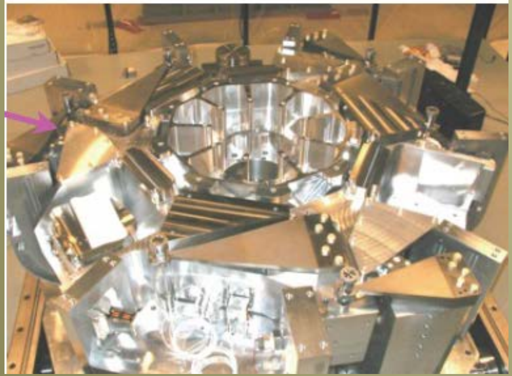
Advanced LIGO Technology

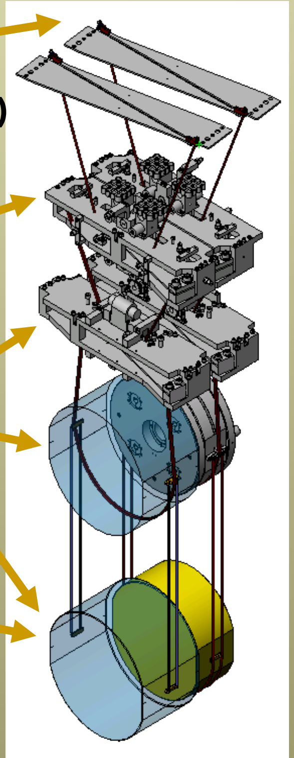
180 W Nd:YAG Laser



Multistage Active Seismic Isolation







Optics Table Interface (Seismic Isolation System)

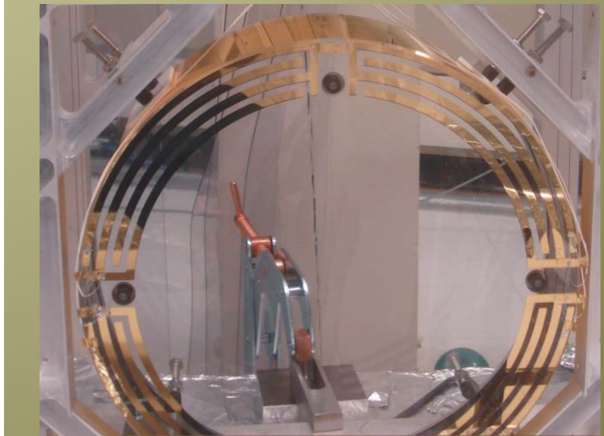
Damping Controls

Hierarchical Global Controls

Electrostatic Actuation

Quadruple Pendulum Suspension

Feedback and Control



Questions on Figure and Annealing

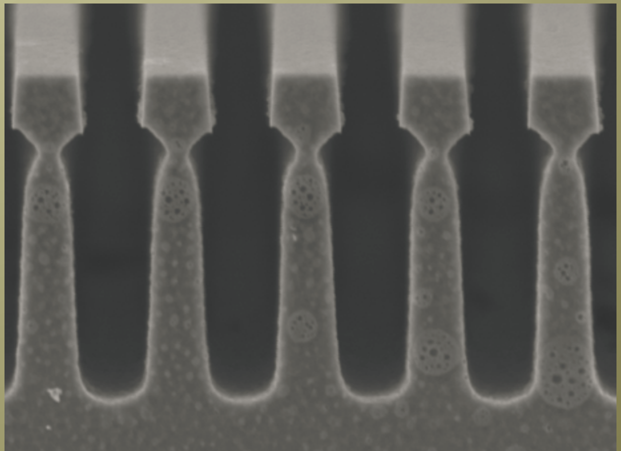
- Does type of glass matter?
  - Primarily seen in Corning 7980 fused silica
  - Also in one Heraeus glass optic
- Is type or quality of polish important
  - Heraeus optic that changed had spotty surface with high microroughness
- Are there correlations between figure change and molecular level issues in glass
  - Impurities
  - Bond angle changes
  - Can these be studied with X-ray or other techniques
- Preliminary interest in this issue from Corning

Diffractive Optics

Diffraction Grating Coating

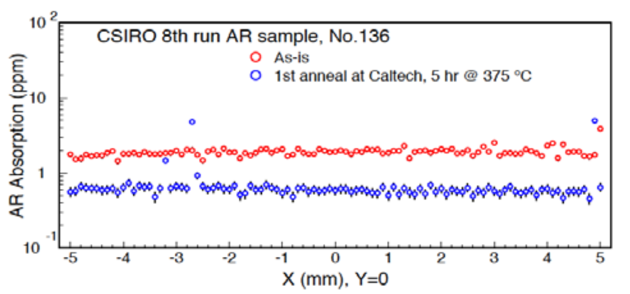
- Primary value of diffractive optics improved thermal lensing
  - No transmission in substrates
- Can be made of opaque material
  - Silicon at 1064 nm
- Thermal noise needs more research
  - Surface quality may be important
- Mirror size needs development
- Noise from lateral displacement needs solution
- Exact topology to be determined

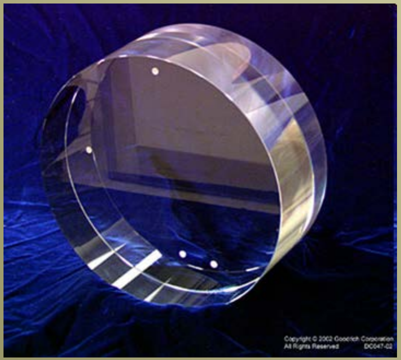
Silicon Waveguide Grating



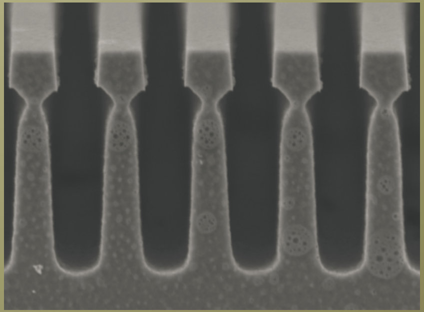
Projects of Mutual Interested between LIGO and NIST

- Causes and cures of absorption in AR coatings
- Causes and cures of figure change in silica with annealing





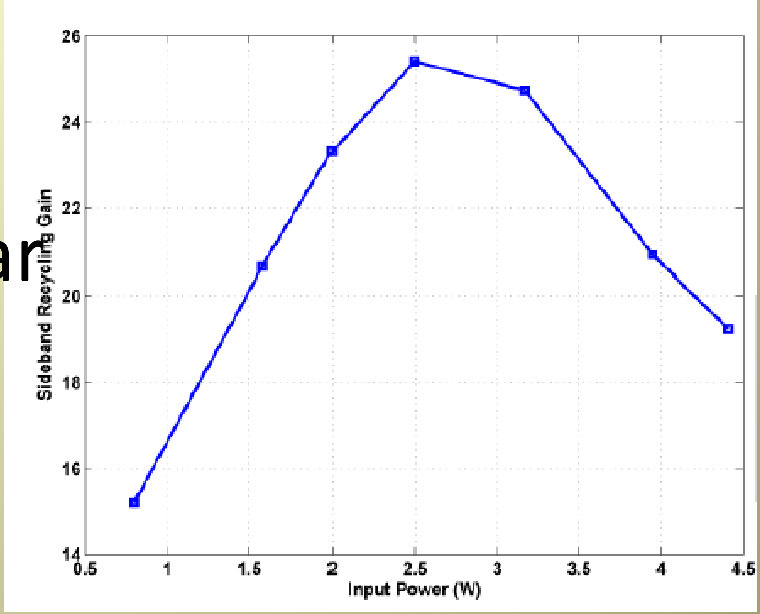
- Thermal noise, microroughness, and figure from polishing techniques
- Polish and thermal noise in sapphire and silicon substrates



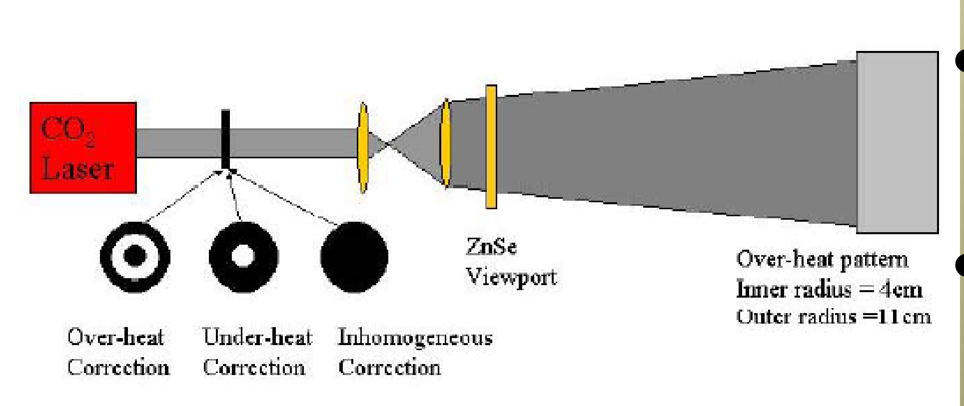
- Microroughness, figure, and thermal noise in crystalline coatings and diffractive optics

Thermal Lensing In aLIGO Optics

- Initial LIGO optics polished assuming thermal lens forms
- Point design assume particular absorption values
- Needed to go to feedback system with CO_2 laser



Cavity Gain in Initial LIGO



Thermal Compensation System

- Advanced LIGO designed with compensation
- Minimize CO_2 laser power to reduce noise

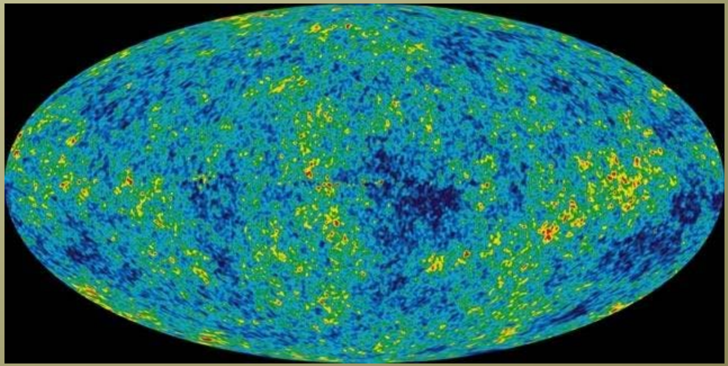
Astronomical Sources of Gravitational Waves

Inspiral Sources:
Neutron Stars

Periodic Sources:
Rotating Neutron Stars

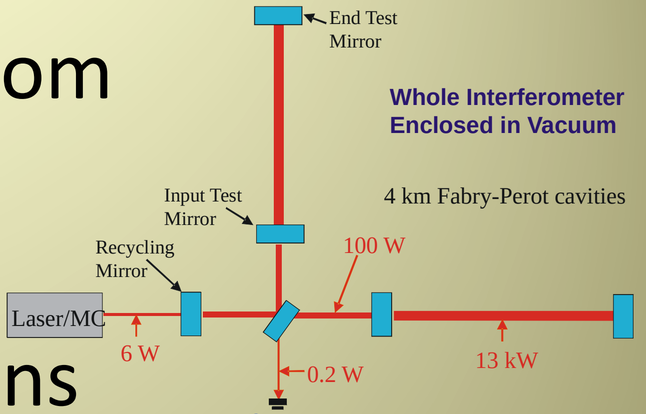
Burst Sources:
Supernova

Stochastic Sources:
Gravitational Wave Background

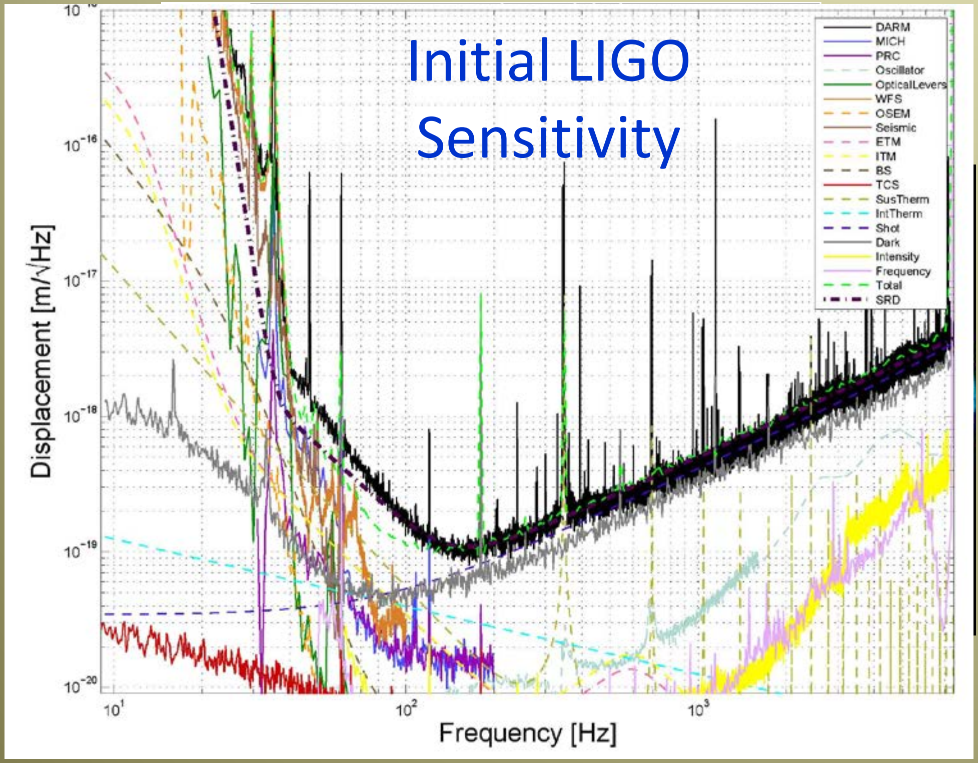


Results from Initial LIGO

- Initial LIGO at design sensitivity from November 2005 to October 2007
- No gravitational waves detected
- Interesting /notable non-detections



Initial LIGO Detector


Initial LIGO Sensitivity

- Crab Pulsar
  - Energy loss due to gravitational waves less than 6%
  - Ellipticity limit $< 3\ 10^{-4}$
- GRB070201
  - Either not in Andromeda or not neutron star inspiral
- Stochastic background below theoretical limits

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

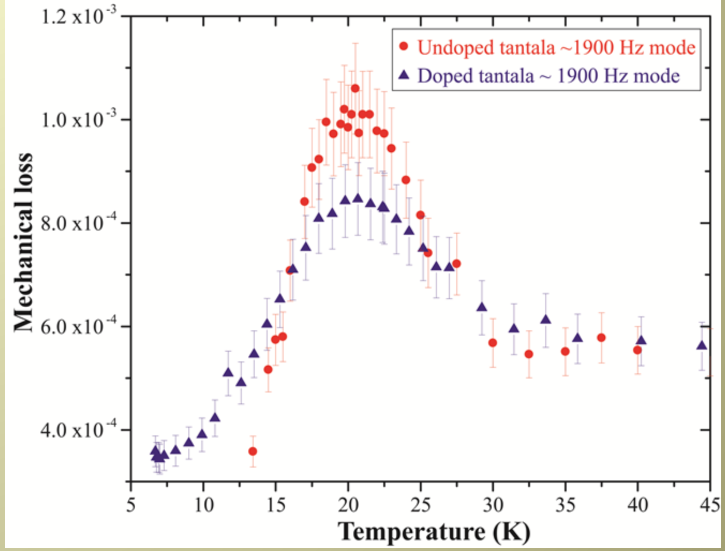
- High thermal conductivity materials to get heat out
- High light power can add heat to optics
- Refrigerators can cause vibration and other noise

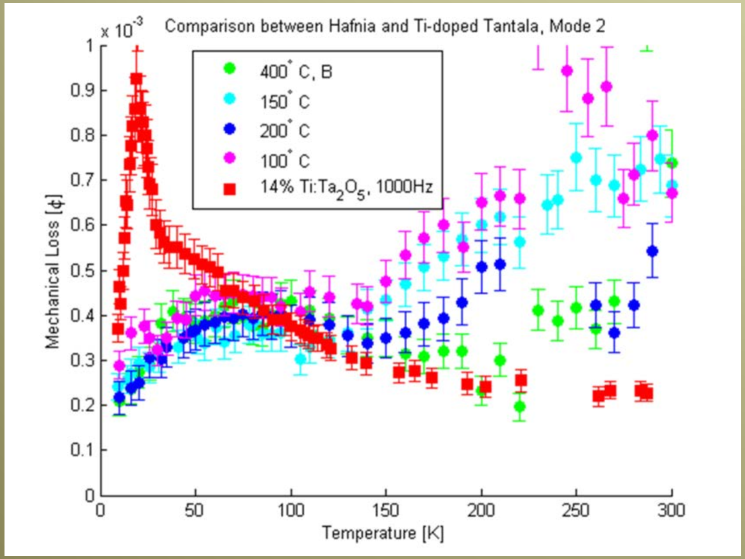
Cooled Mirror

Cryogenics and Materials

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

Loss Peaks in Ta and Ti-Ta



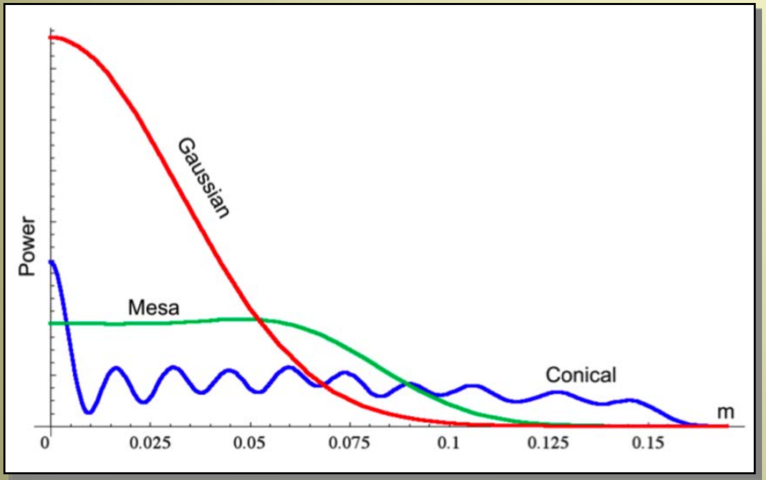


Hafnia Mechanical Loss

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

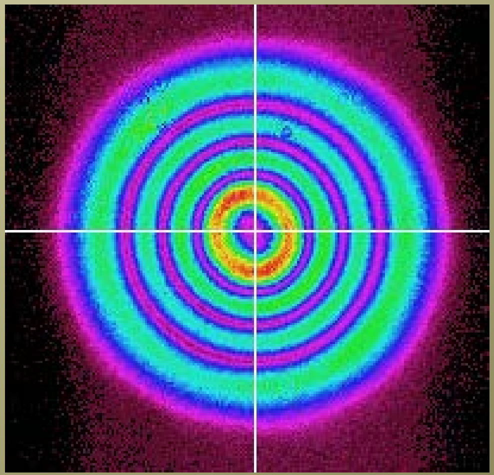
Beam Shaping

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

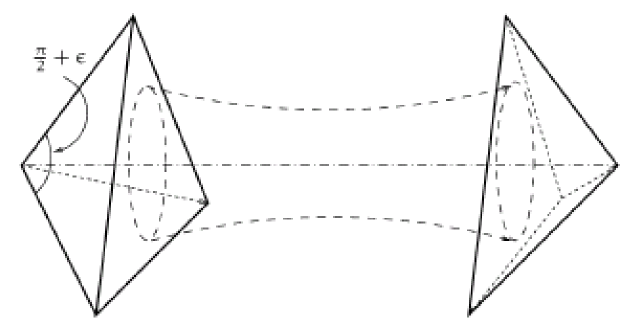
- Many experimental attempts
- Mesa beams
  - Requires special shaped mirror
- Laguerre Gauss beams
  - Use spherical mirrors
  - Plans for use in prototype



Laguerre Gauss 3,3 Mode

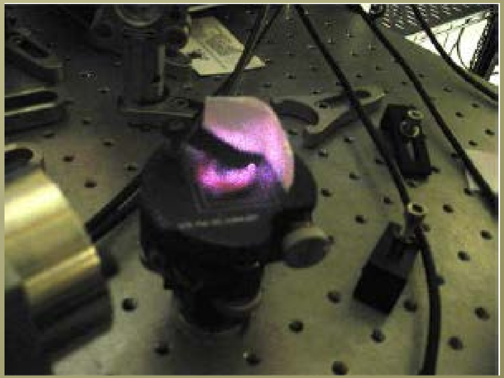
Coating Free Mirrors

Coating Free Mirrors



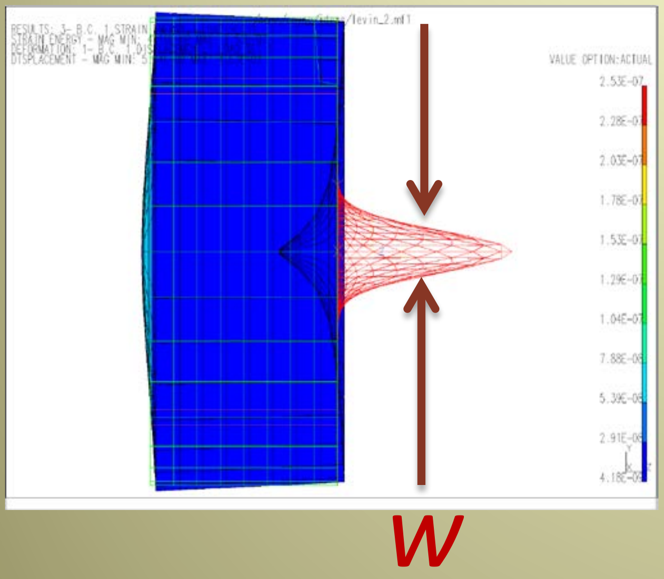
- Can use total internal reflection effect for mirror
- Need an anti-reflective coating on face
  - Much thinner than reflective
- Beam travels inside mirror
  - Scatter, absorption concerns

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

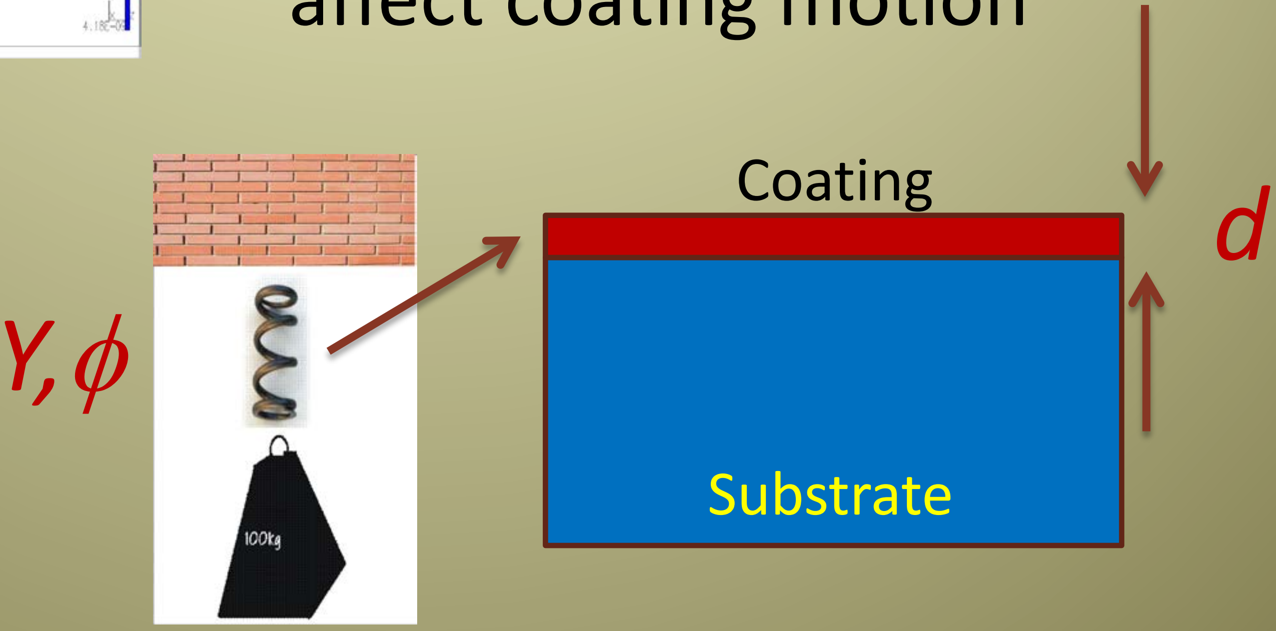

Brewster's Angle Reflector

Coating Thermal Noise II

Side View of Optic

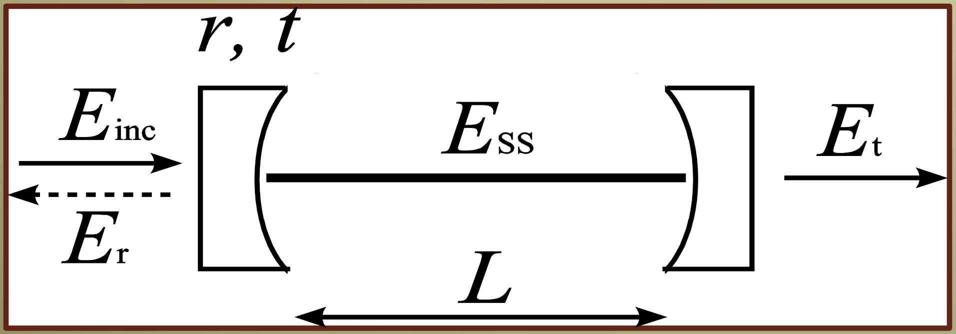


- *w*: how well noise is averaged
- *d*: how much coating
- *Y*: how stiff is the coating
- *ϕ*: how much heat energy can affect coating motion

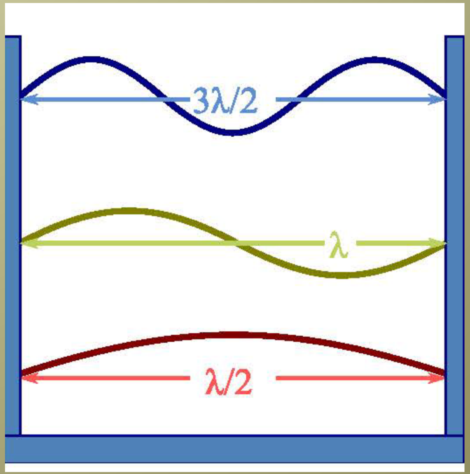


Frequency Stabilization

- 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



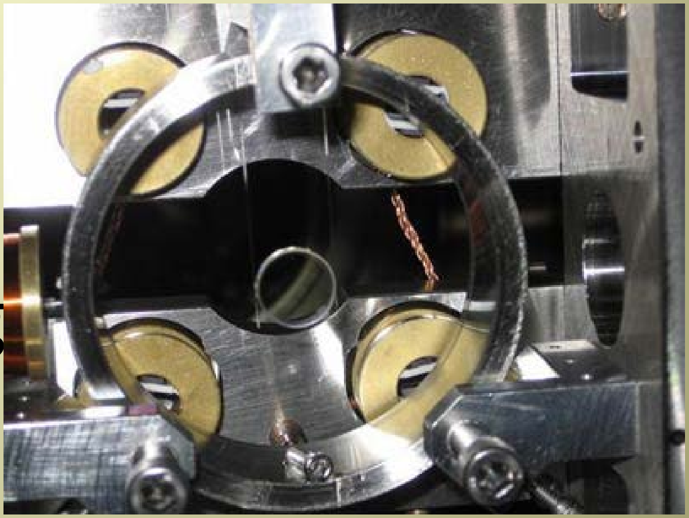
Optical Cavity



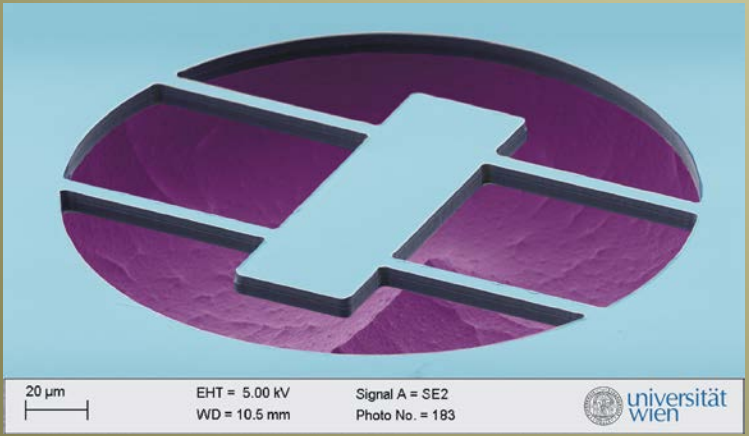
Cavity Resonance

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



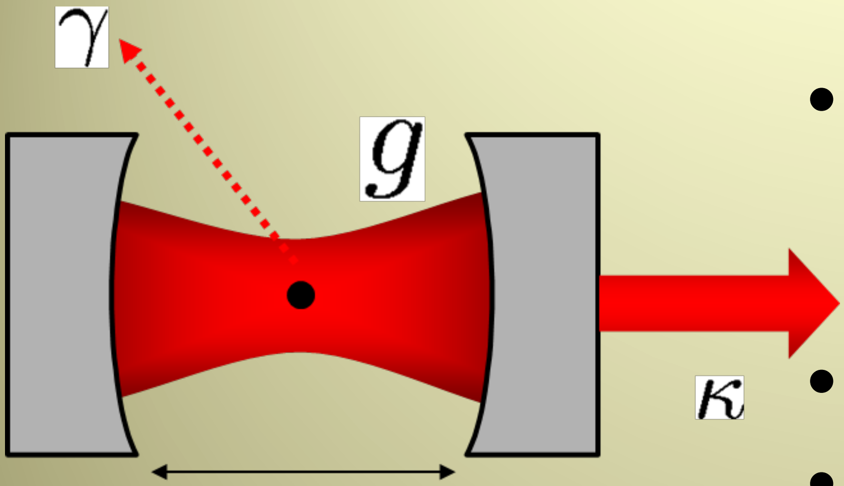
Mini-mirror in Suspension



Micron Scale Oscillator

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

Cavity QED

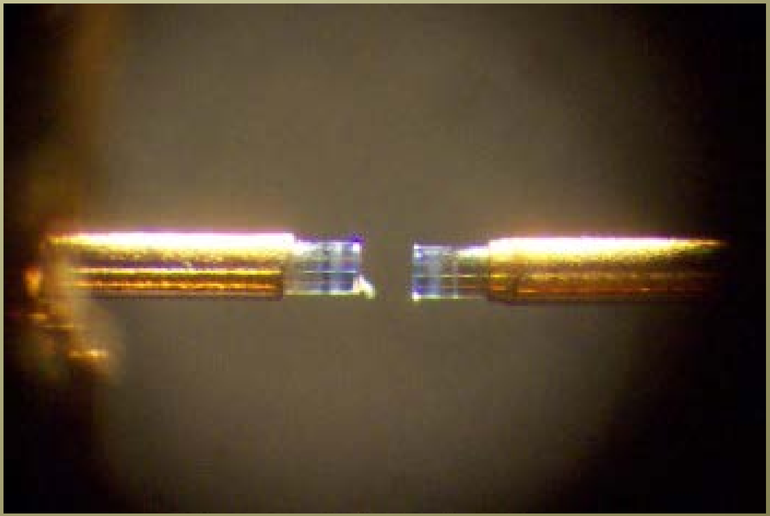


Cavity with Single Atom

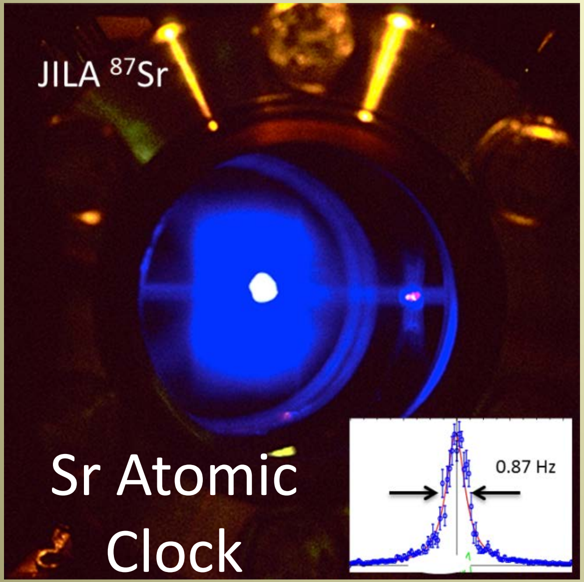
- Single atom (ion) in cavity
  - Also quantum dot
  - Bose Einstein condensate
- Secondary beam traps atom
- Thermal noise can influence trapping

- 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



Frequency Stabilization Applications



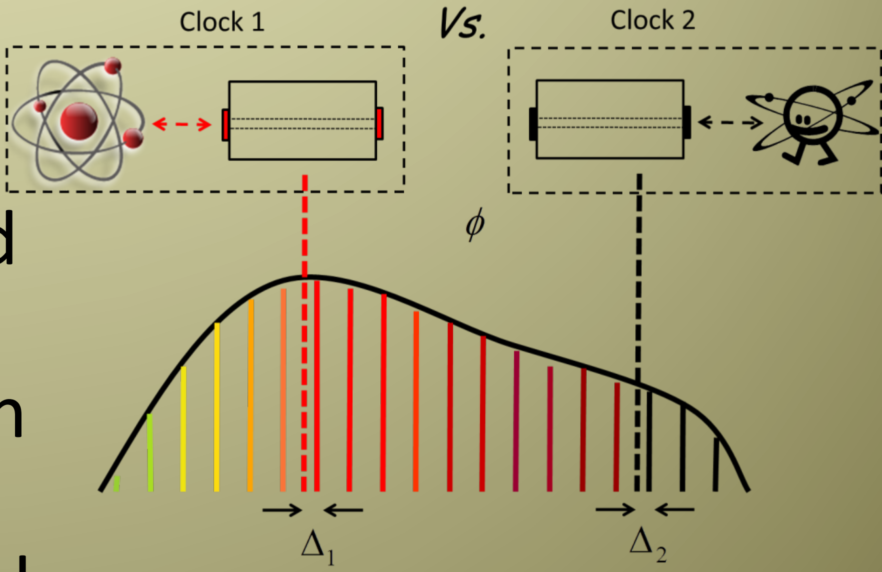
Atomic clocks

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

Frequency combs

Link across frequencies

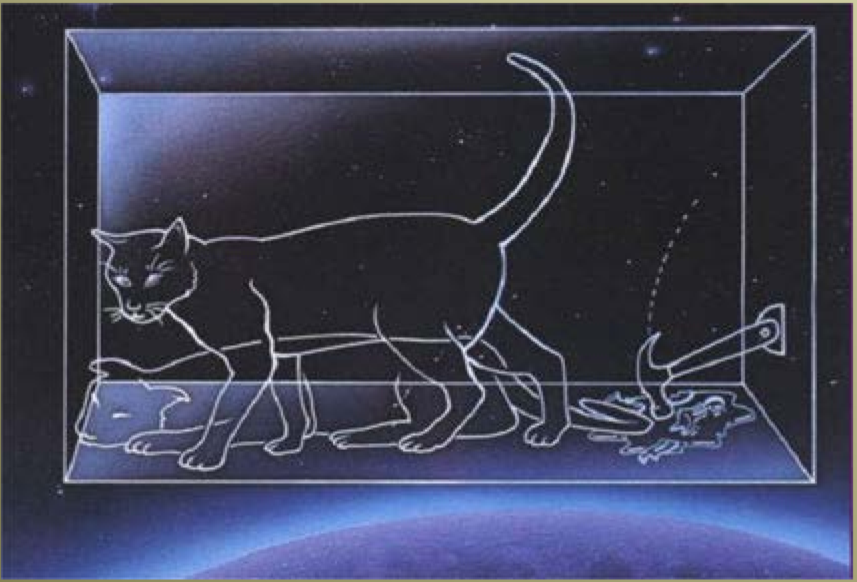
- Connects atomic clocks based on different species
- Optical frequency comparison to microwave standards
- Study changes in fundamental constants



Frequency Comb

Cavity Optomechanics 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

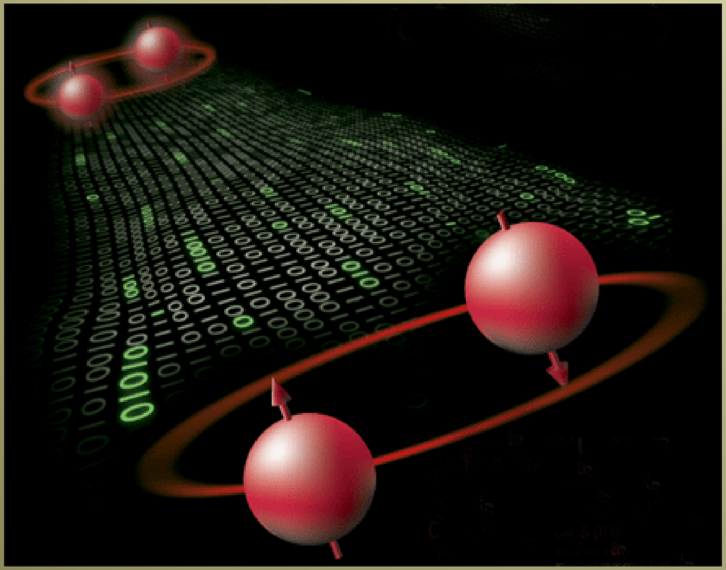
Schrödinger’s Cat

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

Cavity QED Applications

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

Single Atom Loaded Into Cavity

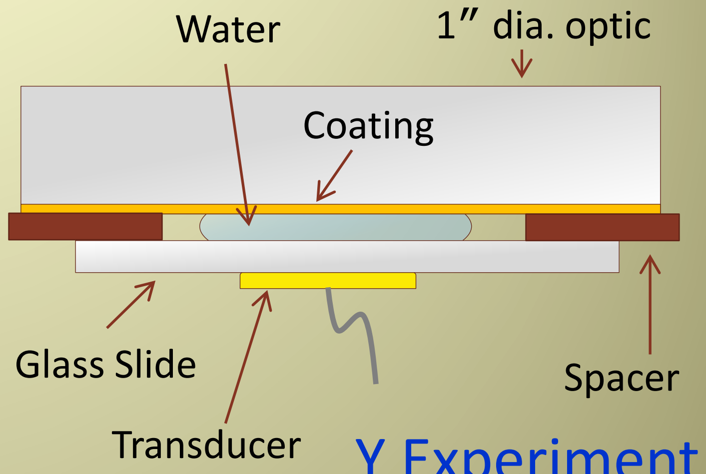


Quantum Computer

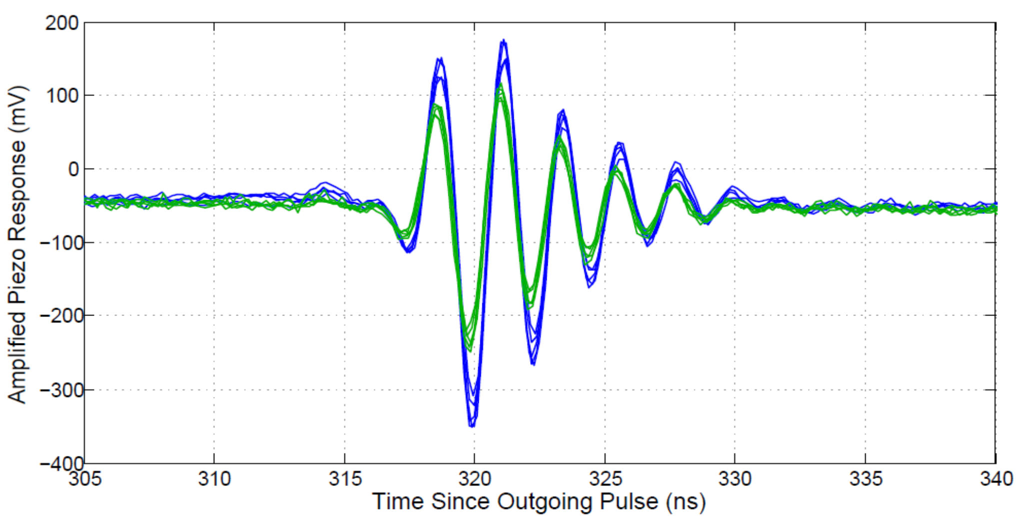
- Measure entanglement between different atoms
  - Secure quantum cryptography
- Quantum computation
- Quantum networks

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



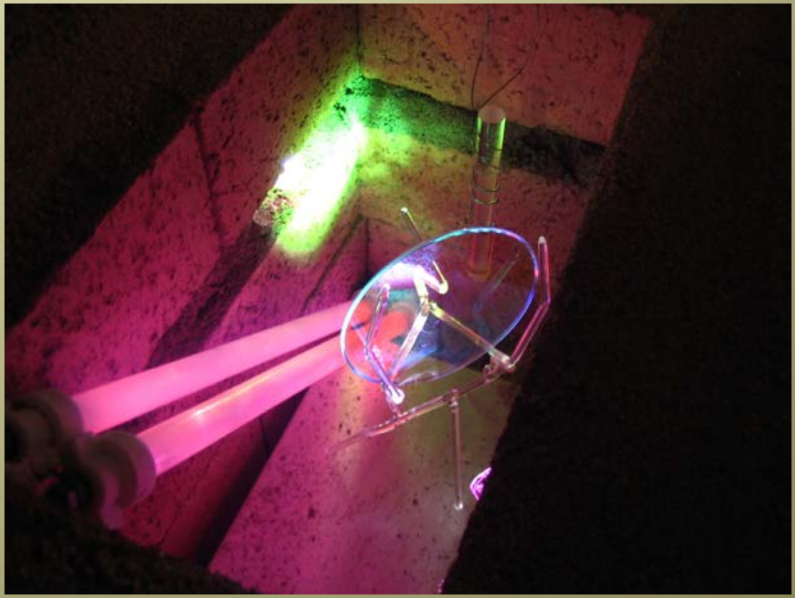
Pulse from Young’s Modulus Measurement

- 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

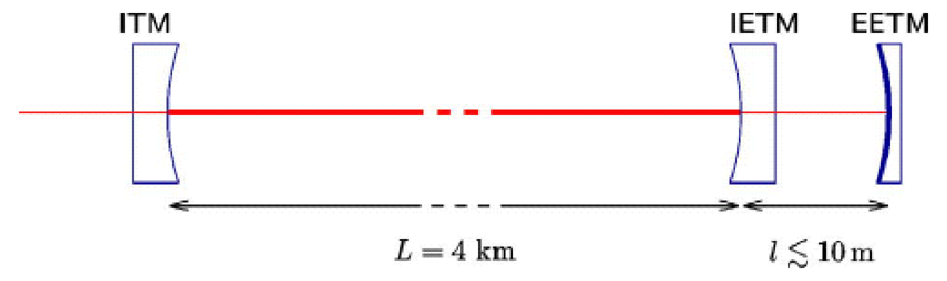
  - ERAU center of thermo-optic noise research
  - Measuring dn/dT from changing reflectivity with temperature
  - Difficult data analysis from multiple layers



Experimental Setup at ERAU

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

Initial and Advanced LIGO Sensitivity