Einstein's Dual Legacy: Thermal Noise and Gravitational Waves

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Outline

Show how understanding two of Einstein's great ideas will allow for the birth of gravitational astronomy…

- **Two of Einstein's Great Ideas**
  - **Brownian Motion**
  - **Gravitational Waves**
- **Gravitational Wave Detection**
  - **Detection Methods**
  - **Astronomical Sources**
- **Sensitivity and Detectability**
  - **Thermal Noise Limitations**
  - **Future Ideas and Detectors**

Einstein and Thermal Noise

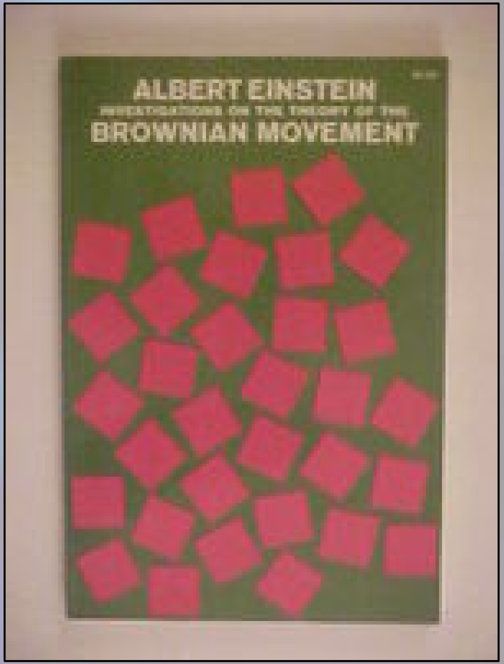
Einstein's first challenge to LIGO:

"I did not believe that it was possible to study Brownian motion with such a precision." -*Letter from Albert Einstein to Jean Perrin (1909)*

- **Einstein's Brownian motion paper**

  "On the motion of small particles suspended in liquids at rest required by the molecular-kinetic theory of heat", *Annalen der Physik* **17** (1905) 549.

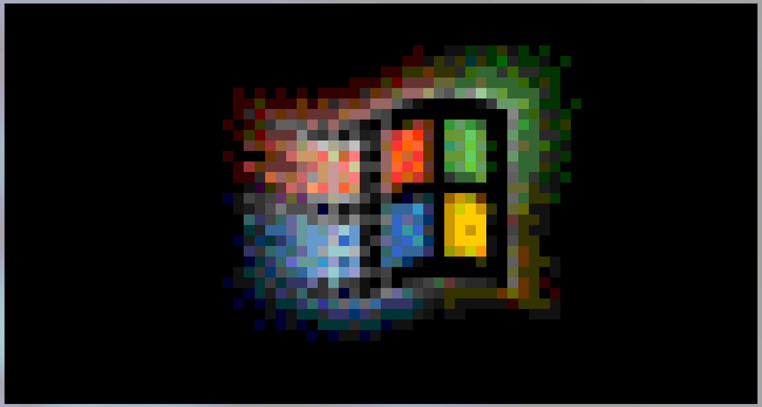
  - **Most cited of all Einstein's papers**
- **Linked fluctuations to fluid viscosity**
- **Confirmed statistical physics models**
  - **Atoms as basic units of matter**
  - **Kinetic theory of heat**
- **Also contributed to the theory of lasers (Einstein's A and B coefficients)**



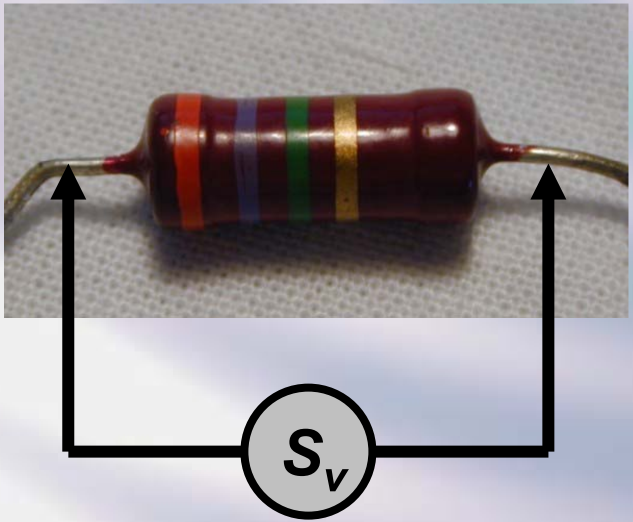
Thermal Noise

<u>**Fluctuations from heat bath**</u>

- **Mechanical ⇒ Brownian motion**
- **Electrical ⇒ Johnson noise**
- **Optical ⇒ Thermorefraction**
- **Others**



Brownian Motion in Fluid



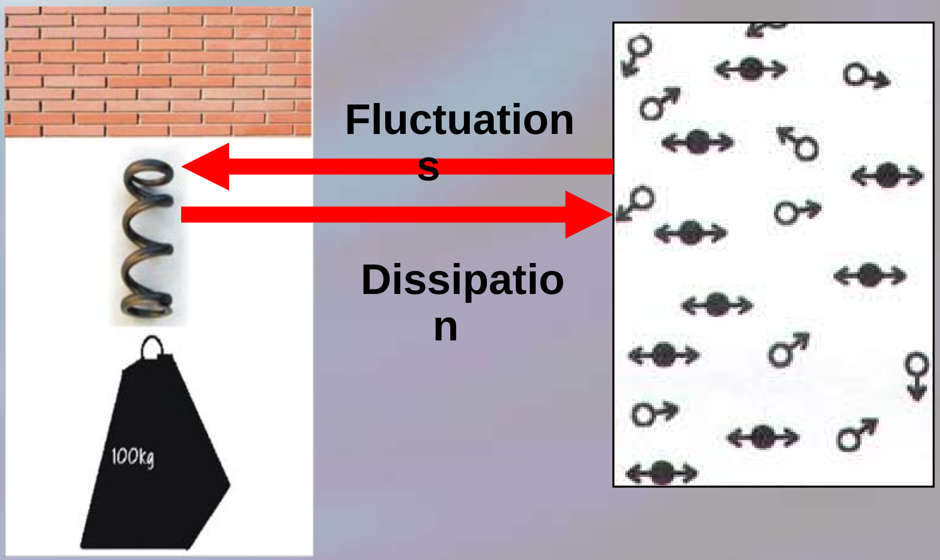
Related to energy loss in system

- **Viscosity for particle in fluid**
- **Resistance in Johnson noise**
- **Internal friction for mechanical systems**

Callen and Welton's Fluctuation-Dissipation Theorem

Fluctuation-Dissipation Theorem

- **Nyquist (1920s) proposed general relationship between energy loss and thermal noise**
- **Callen and Welton (1950s) proved Fluctuation-Dissipation Theorem**
- **Path for energy loss also a path for thermal excitation**
- **Thermal equilibrium required**
- **Thermal bath can be same system**

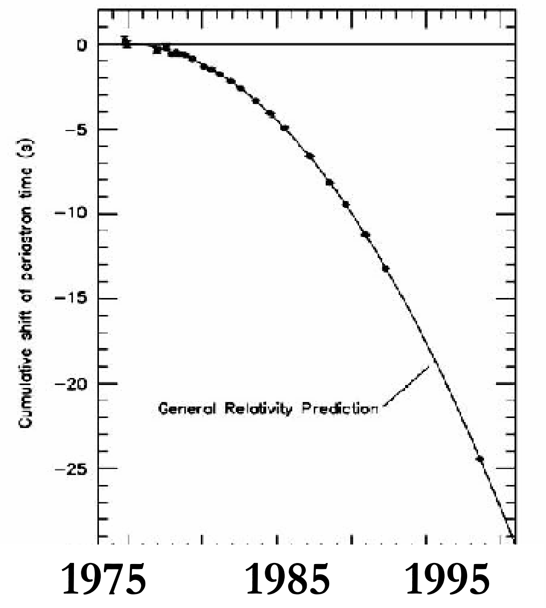


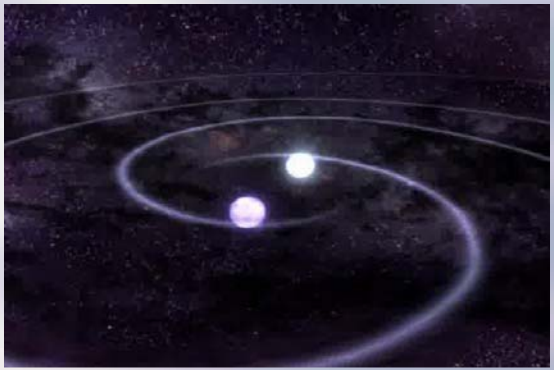
Gravitational Waves

Einstein's second challenge to LIGO:

"Do Gravitational Waves Exist?"-*Title of paper submitted to (and rejected by) Physical Review by Einstein and Rosen (1936)*

- **Einstein's General Theory of Relativity** ➡ $G_{\mu\nu} = 8\pi\, T_{\mu\nu}$
  - **Analogous to Maxwell's equations**
  - **Has wave solution**
- **Oscillations in space-time**
- **Propagate at *c***
- **Two polarizations: X and +**





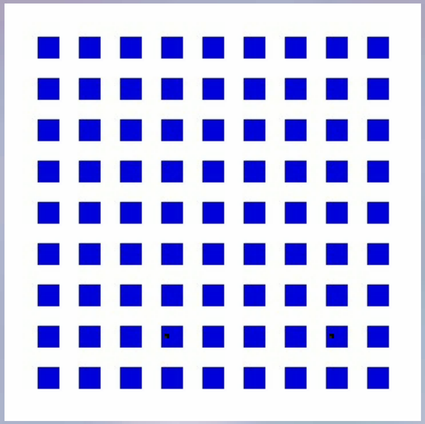
Indirect Detection (1990s)

- **Binary Pulsar System 1913+16**
- **Nobel Prize 199**

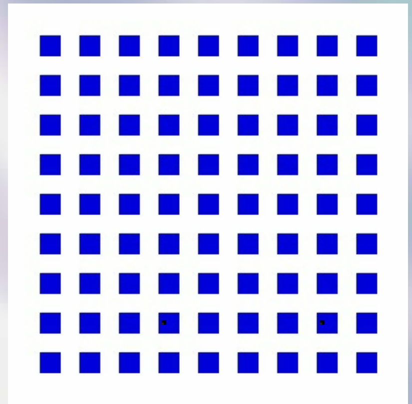
  Joseph Taylor and Russel Hulse

Gravitational Waves

Comparison with Electromagnetic Waves



Electromagnetic Wave



Gravitational Wave

- Quadrupolar
  - Influences design of detectors
  - Dipole (E&M) forbidden by momentum conservation
- Much Weaker

  $L \sim G/c^5 \, L^2_{internal}$

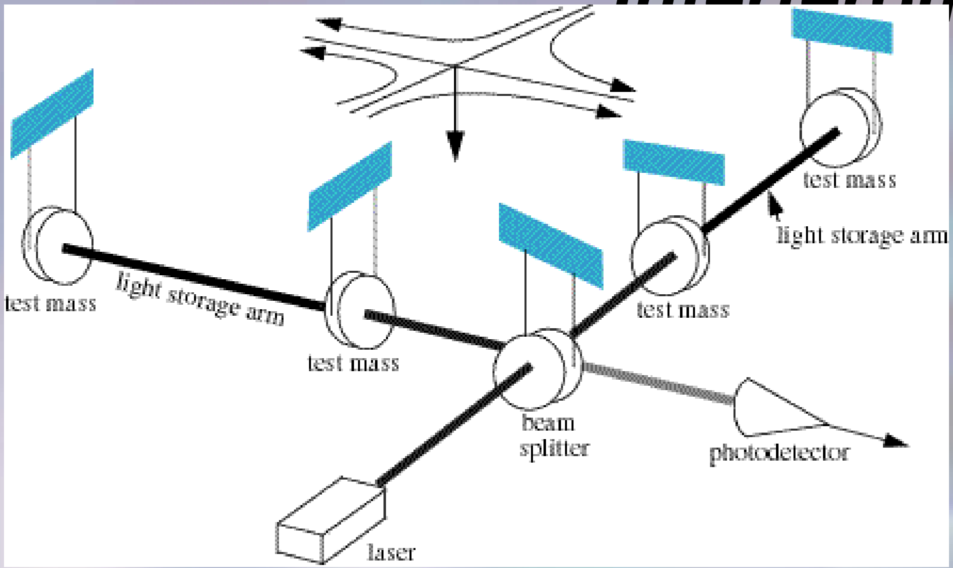
  $G/c^5 \approx 2.5 \; 10^{-35} \; 1/W$

- Strain rather than force

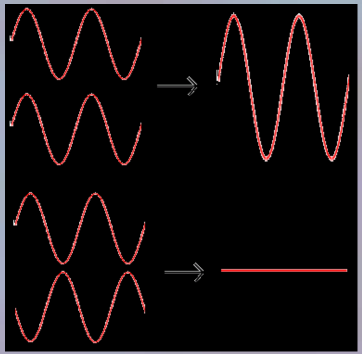
  $h = \Delta L / L \approx 10^{-21}$

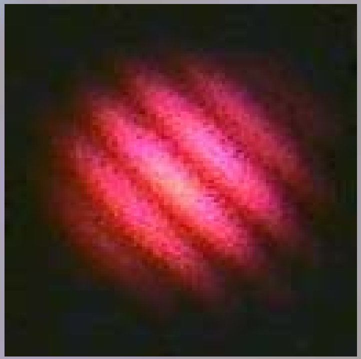
Detection of Gravitational Waves

Interferometers



- Light goes down two perpendicular arms
  - Similar to Michelson-Morley
- Mirrors are free to move
  - Gravity or other forces
- Returning light recombines
  - Constructively: equal arm length
  - Destructively: different arm lengths
- Gravitational wave
  - Stretch one arm, shrink other





Interference of Light

Laser Interferometer Gravitational-wave Observatory (LIGO)

LIGO Livingston

LIGO Hanford

LIGO Vacuum Chambers

- Two sites in the US
  - Livingston, LA
  - Hanford, WA
- Arms 4 km long (2 km for 2nd Hanford)
- Sensitive to strains around $h=10^{-21}$
- $\Delta L = h\,L \approx 10^{-18}$ m: subnuclear
- Entire beam path in vacuum

Generations of LIGO

Initial, Enhanced, and Advanced

Initial LIGO

- **Reached design sensitivity**
  - **Neutron star inspiral: 15 Mpc**
- **Steel wire suspensions**
- **Standard coatings on silica**

Enhanced LIGO

- **Improvements to Initial LIGO**
  - **Neutron star inspiral: 30 Mpc**
- **Steel wire suspensions**
- **Standard coatings on silica**
- **Begin taking data 2009**

Advanced LIGO

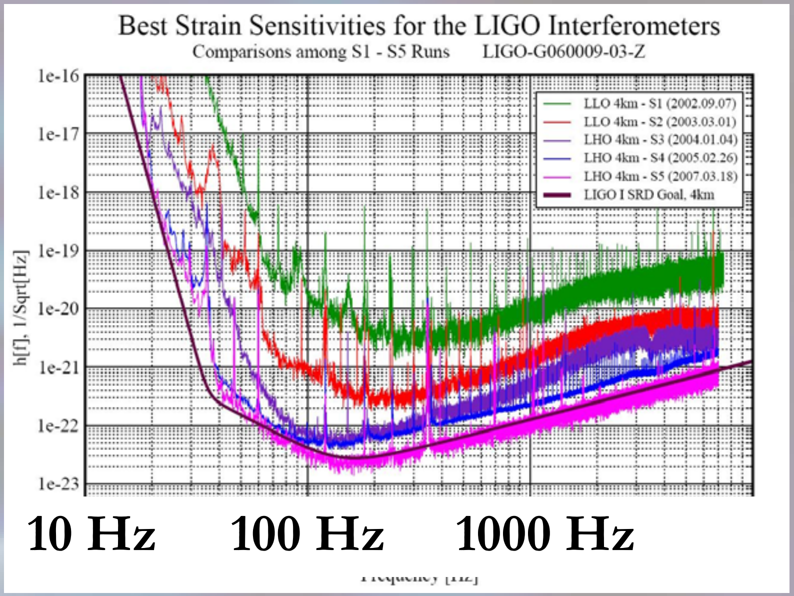
- **Major upgrade**
  - **Neutron star inspiral: 170 Mpc**
- **Silica ribbon suspensions**
- **Improved coatings on silica**
- **Funding 4/08: Online 2013**

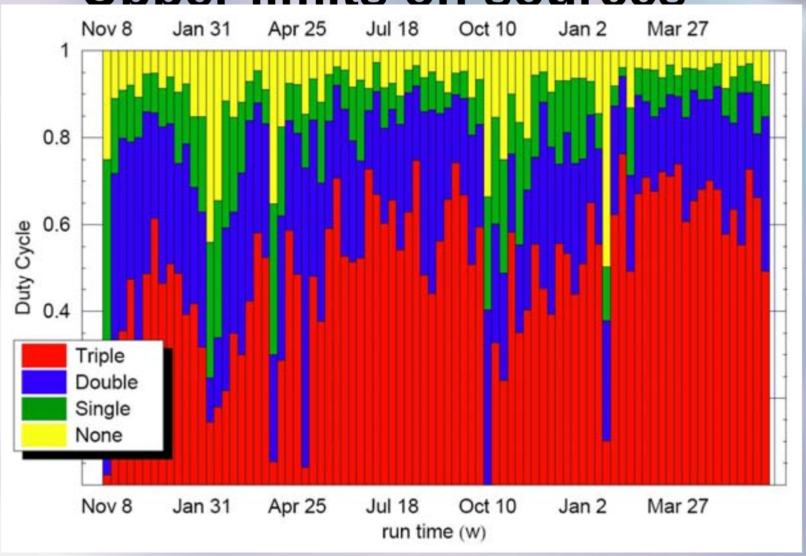
Initial LIGO Sensitivity

Initial LIGO Noise

- Sensitivity improves over time
- Data taken at most sensitivities
  - Technical checks
  - Upper limits on sources
-

LIGO Sensitivity in Time





S5 Coincidence

Science Data Run (S5)

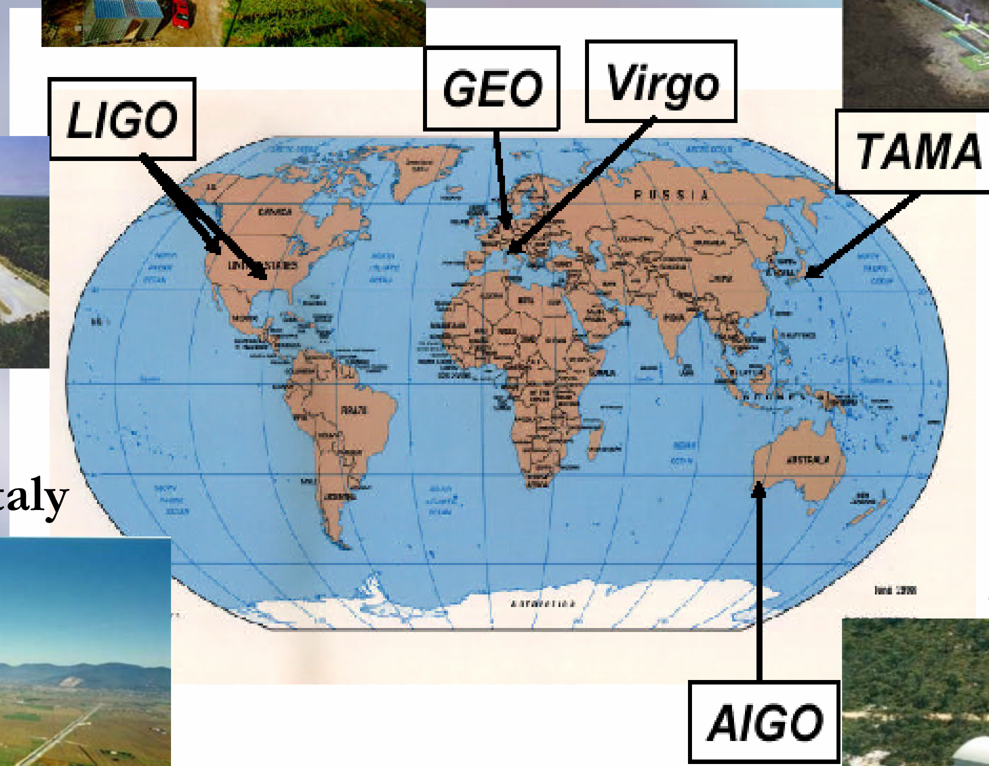
- Full year of coincidence between three interferometers
- Two years of calendar time
- Finished November 2007

World Network of Detectors

LIGO

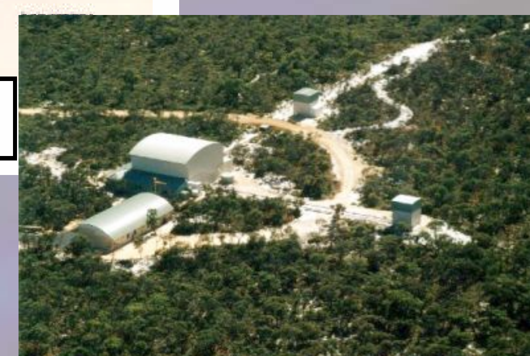
GEO 600 in Germany

Proposed LCGT in Japan

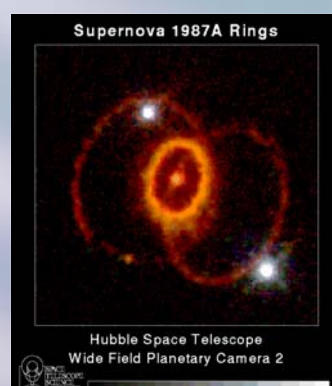
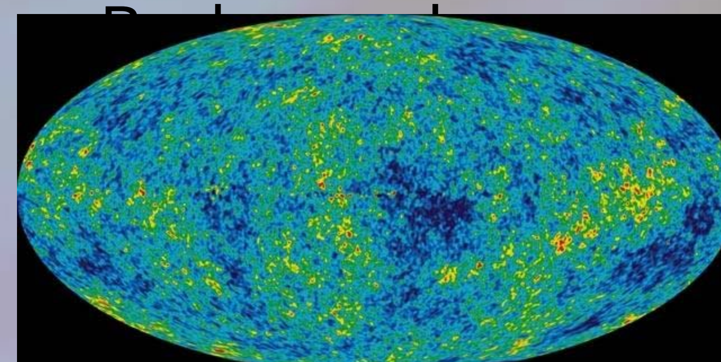


Virgo 3 km in Italy

Gingin site in Australia



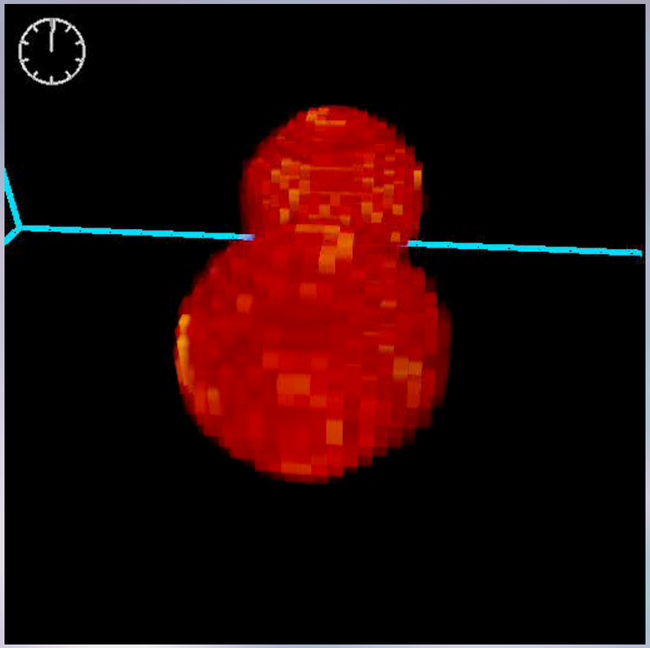
Astronomical Sources

	Short Duration	*Long Duration*
Modeled	Compact Body Inspirals 	Periodic Sources 
Unmodeled	Bursts 	Stochastic 

Astrophysical Results

Inspirals

Numerical Model of Inspiral



High density objects in mutual orbit

- Black holes
- Neutron stars
- White dwarfs

Gamma Ray Bursts

- GRB070201
  - Galaxy M31 (750 kPc away)
  - *NO* inspiral or short transients
  - *NOT* binary neutron star inspiral
  - *arXiv:0711.1163, ApJ*
- Over 200 GRBs during S5
  - Analysis underway
  - ~10% short GRBs ⇒ likely to be inspirals
  - Long GRBs could be supernova

LSC

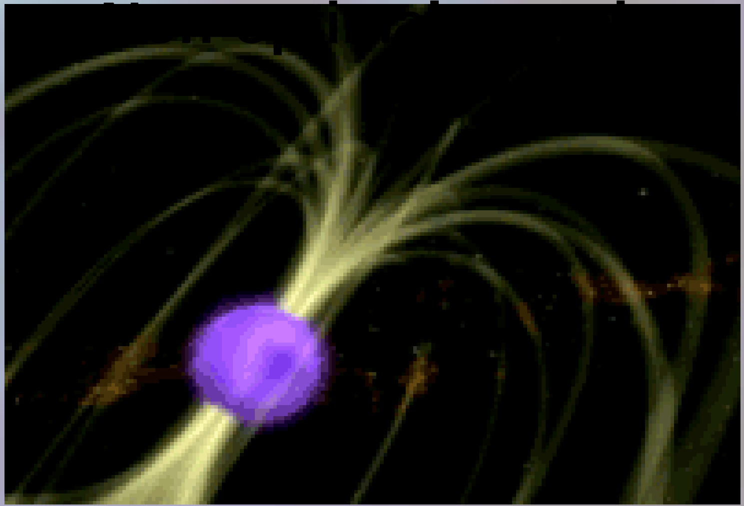
Astrophysical Results

Bursts

<u>Gamma Ray Repeaters</u>

- Hyperflare in SGR 1806-20
  - Magnetar ~ 6 - 15 kPc away
  - *NO* signals found at normal mode frequencies
  - Not during S5
  - Only Hanford 4 km detector
  - *Phys Rev D 76 (2007) 062003.*
- Hyperflare in SGR 1900+14
  - During S5
  - Analysis underway

- Catastrophic events
  - 10s of solar masses
  - Supernova etc
- Sources not modeled
  - No theoretical model



Artists Conception of Hyperflare

Astrophysical Results

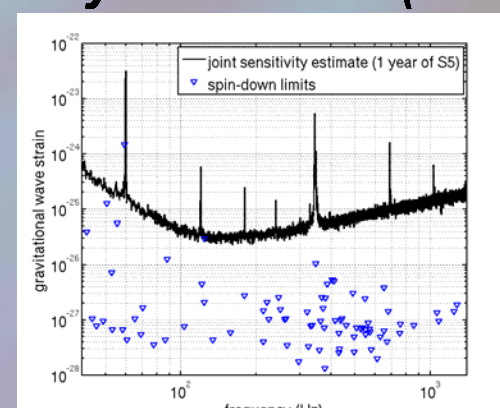
Periodic

- **Rapidly rotating compact body**
  - **Pulsar**
  - **Low mass X-ray binary**
- **Needs asymmetry**
  - **Sphere not**

Artists Conception of Accretion

Crab Pulsar

- **Position, frequency & spin down rate known**
- ***NO* signal seen**
  - **Spin down *NOT* from gravitational waves**
- **Limits on 78 other pulsars**
  - ***Phys Rev D 76 (2007) 042001.***

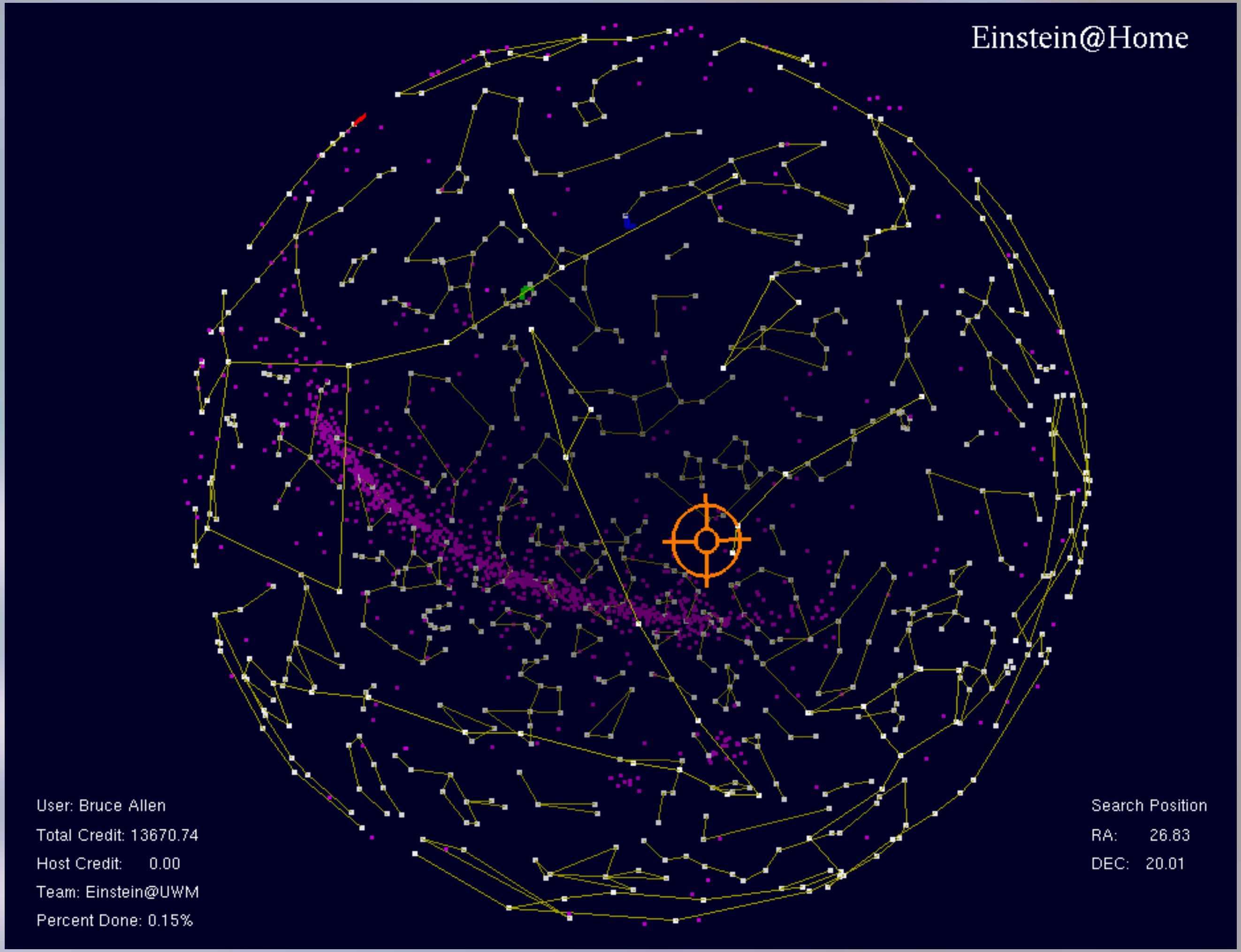


Sensitivity to Pulsars

Einstein @ Home

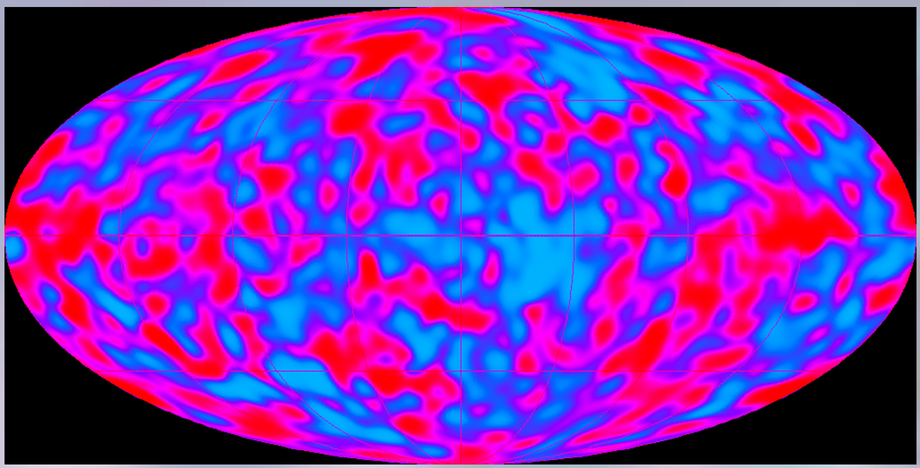
http://einstein.phys.uwm.edu/

- Based on SETI@Home
- Searching for unknown pulsars
- Operating systems:
  - Windows
  - Mac
  - OSX
  - Linux
- More computing power
- Low cost



Astrophysical Results

Stochastic



Big Bang

- Similar to cosmic microwave background
- Probe closer to beginning
- Tests of inflation, quantum gravity, etc.

Cosmological Background

- ***NO*** **correlated signal seen**
- **Similar to theoretical limit**
  - $\Omega_{GW} < 9\ 10^{-6}$ *(preliminary)*
  - Assumes frequency independent spectrum

Nearby Sources

- Unresolved background of burst type sources
- Distant supernova, mergers, accretions, etc.

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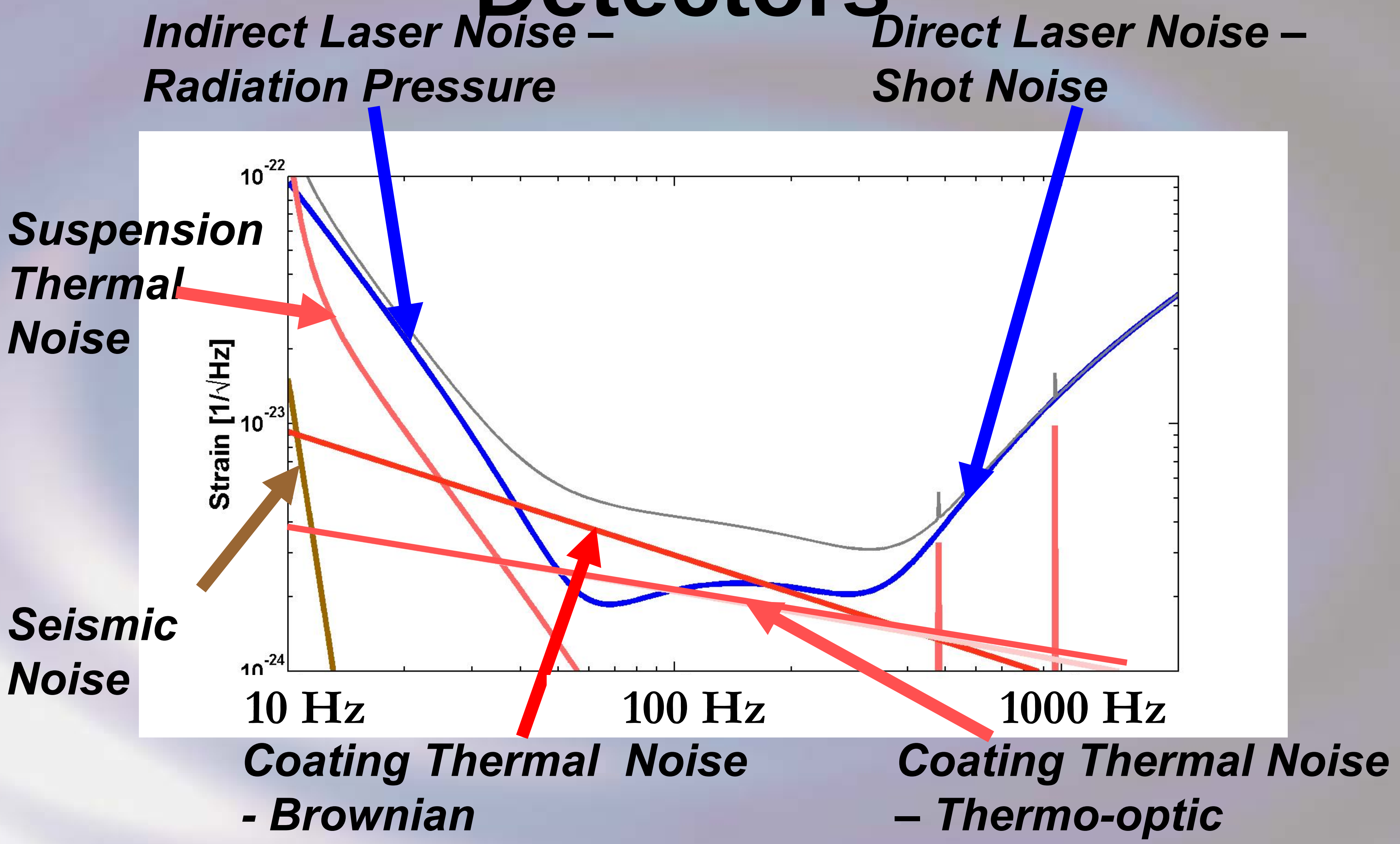
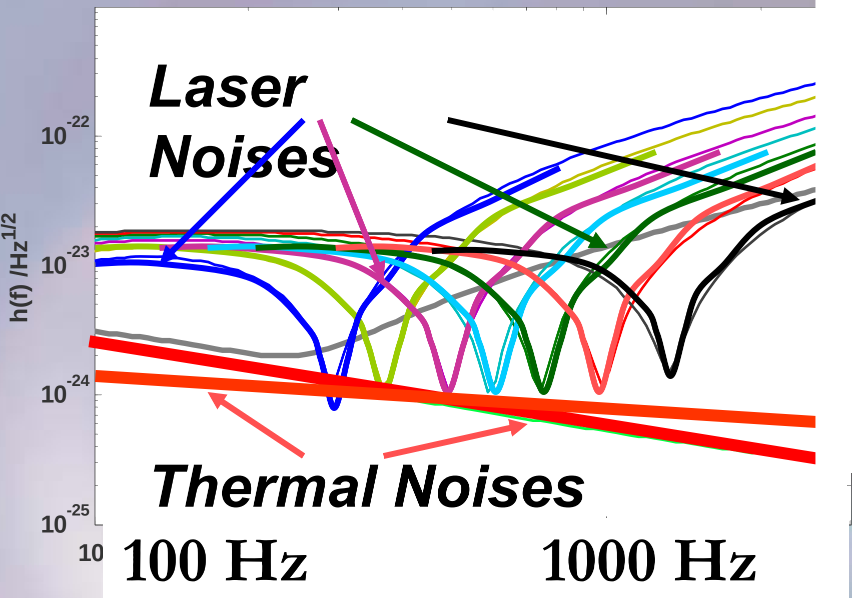
Noise in Inteferometric Detectors

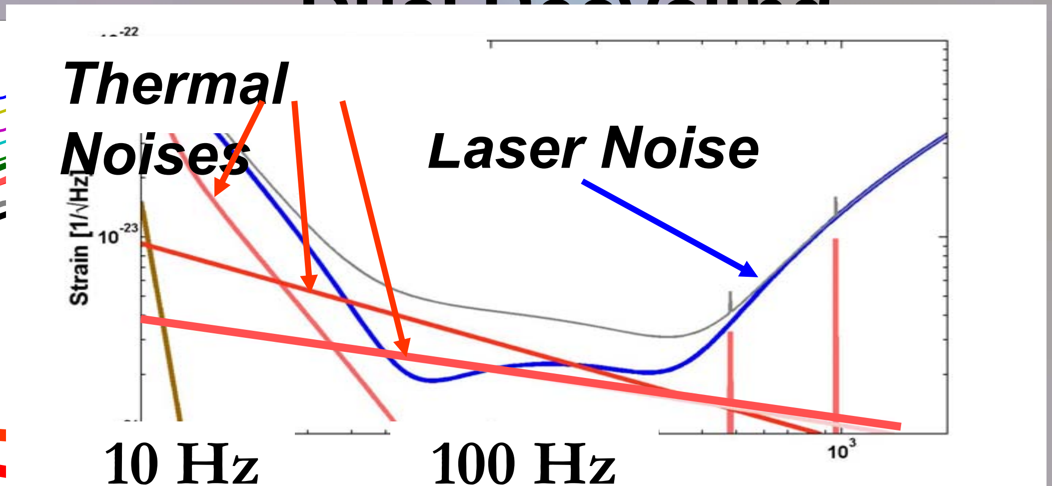


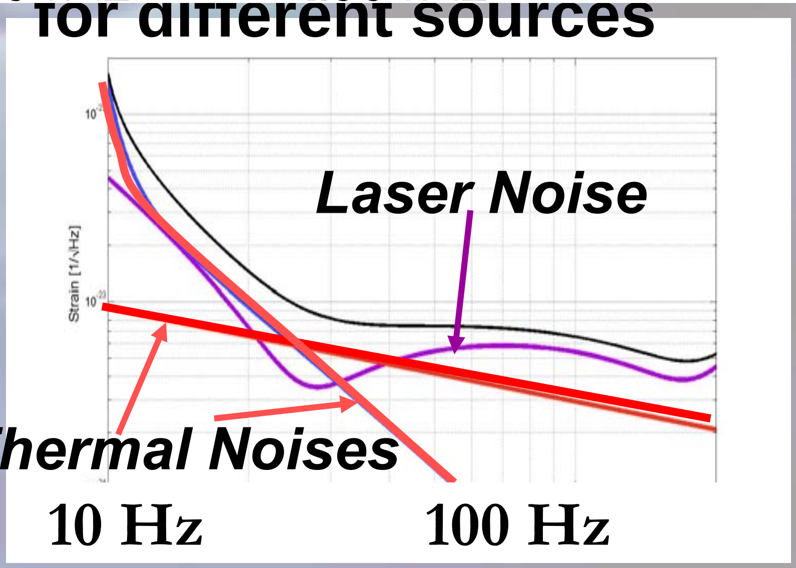
Shaping Laser Noise

Dual Recycling

High Frequency Narrowband





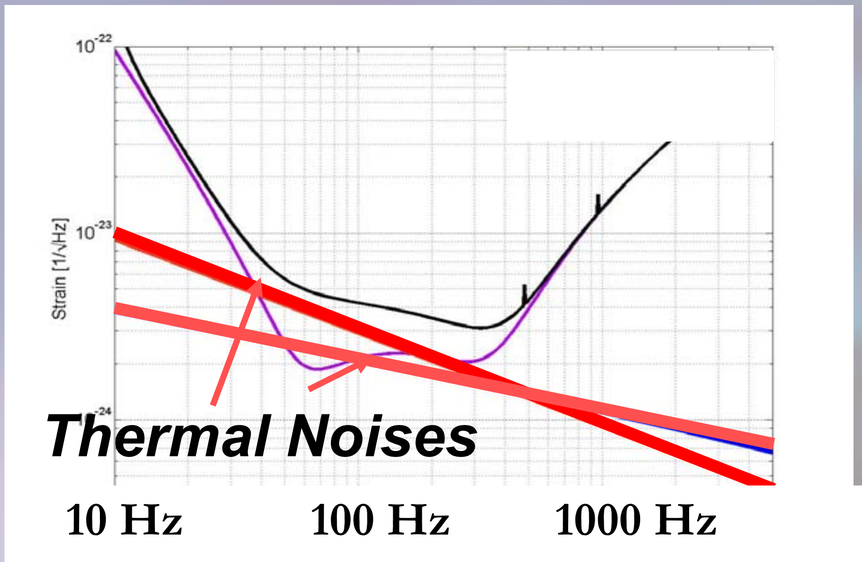


Low Frequency Optimized

- High frequency narrowband
  - Known pulsars
- Low frequency
  - Stochastic background
- Mid frequency broadband
  - Inspirals and bursts

Thermal Noise and Sensitivity

Wideband: Inspirals and Bursts



Wideband Advanced LIGO Sensitivity

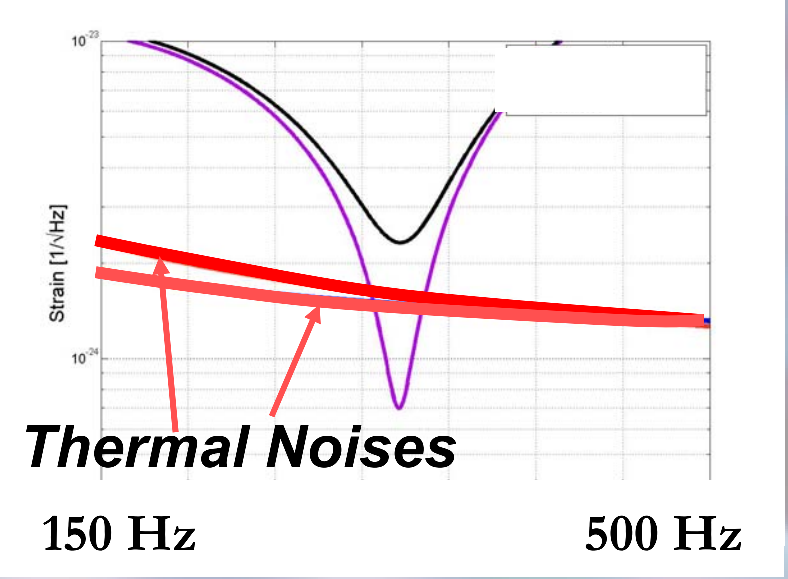
- **Coating thermal noises limit sensitivity**
- **Improved coatings in Advanced LIGO**
  - **Titania doped Tantala/Silica**
  - **Increased laser spot size**
  - **Optimize design to reduce thermal noise**
  - **Sensitivity greatly improved**

- **Inspiral range increased**
  - **Neutron star binaries**
  - **Black hole binaries**
- **Burst sensitivity also improved**
  - **Depends on noise**

Generation	Neutron Star	10 M_o BH
Enhanced LIGO	30 Mpc	180 Mpc
Advanced LIGO	170 Mpc	980 Mpc
Next Generation	300 Mpc	1600 Mpc

Thermal Noise and Sensitivity

High Frequency Narrowband: Pulsars



Narrowband Advanced LIGO Sensitivity

Low Mass X-ray Binaries

- Narrowband Advanced LIGO
- Coating thermal noise-limited
  - Brownian
  - Thermo-optic
- Gravitational waves depend on ellipticity (ε)

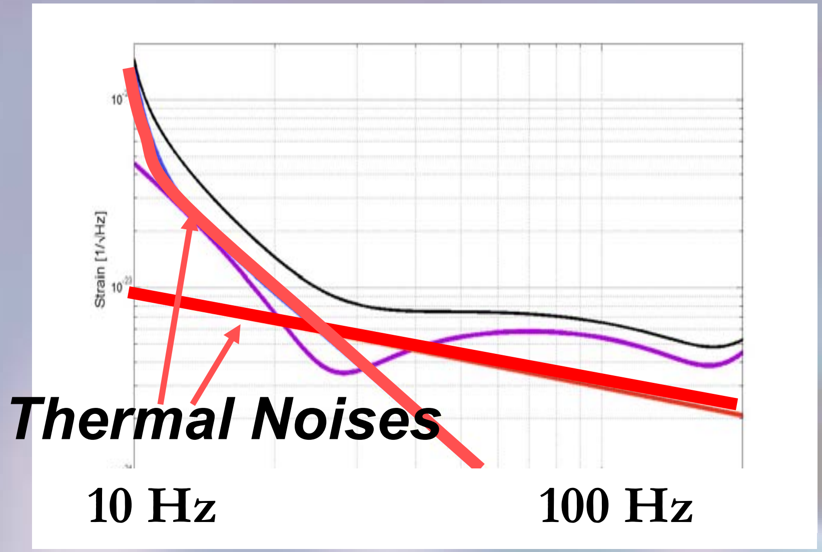
High Frequency Pulsars

- Crab Pulsars and others
- Coating thermal noise-limited
- Laser, suspension thermal, & seismic noises play roles

Generation	Crab ε (59.9 Hz)	Sco X-1 ε (620 Hz)
Enhanced LIGO	$7\ 10^{-6}$	$1\ 10^{-7}$
Advanced LIGO	$7\ 10^{-7}$	$1\ 10^{-8}$
Next Generation	$2\ 10^{-7}$	$7\ 10^{-9}$

Thermal Noise and Sensitivity

Low Frequency : Stochastic



Low Frequency Advanced LIGO Sensitivity

Stochastic Sensitivity

- Only at low frequency
  - Frequency scale: *c / D ~ 100 Hz*
- Limited by thermal noise
  - Suspension at lowest frequencies
  - Coating at higher frequencies

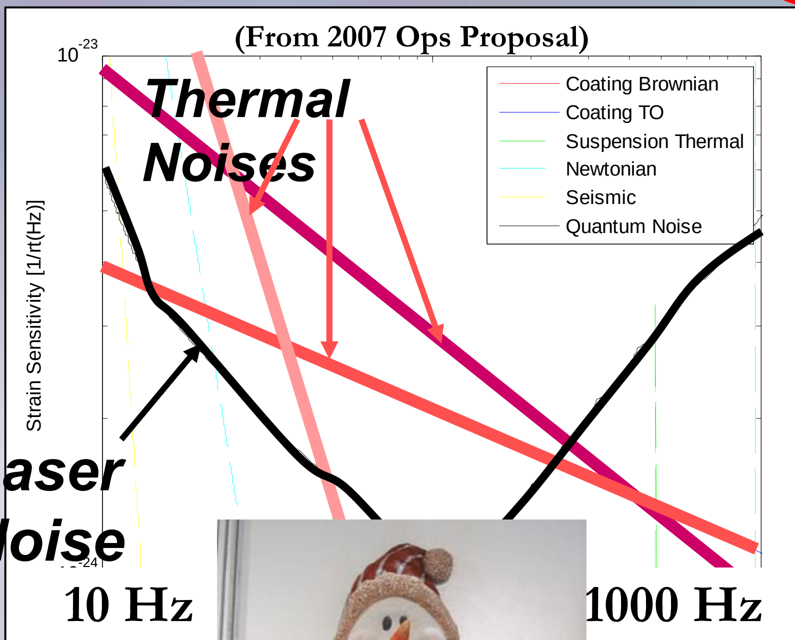
Stochastic Signal

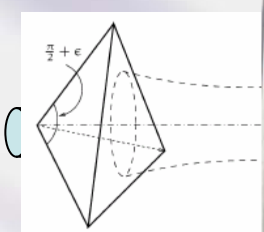
- Depends on model
  - Many ideas
  - Unknown in practice
- Frequency dependence
  - Also unknown

LIGO Generation	Suspension	Stochastic Background
Enhanced LIGO	Steel Wire	$6\ 10^{-7}$
Advanced LIGO	Silica Ribbon	$1\ 10^{-9}$
Next Generation	Sapphire Ribbon	$3\ 10^{-10}$

Next Generation Research

$$S_x(f) = k_B T d Y_{coat} \phi / (\pi^2 f w^2 Y_{sub}^2)$$





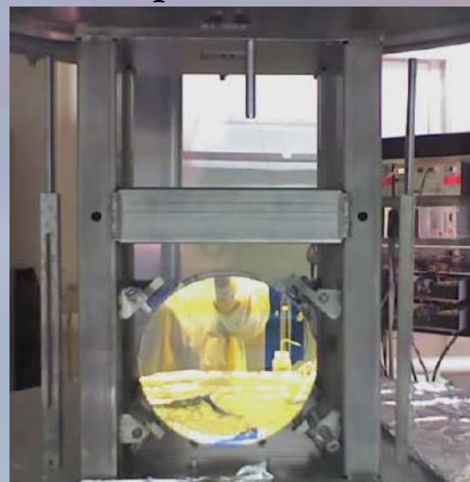
Corner Reflector
Cooled Mirrors

- New coating materials – ϕ, Y_{coat}
- Reduce coating thickness - d
  - Cavity reflectors
  - Corner reflectors
- Change geometry - w
  - Mesa beams and other shapes
- Reduce temperature - T
  - Cryogenics
  - Japanese 2nd generation
- New substrates – Y_{sub}
  - Sapphire
  - Silicon

Thermal Noise Research

LIGO / MIT

MIT Suspension Experiment

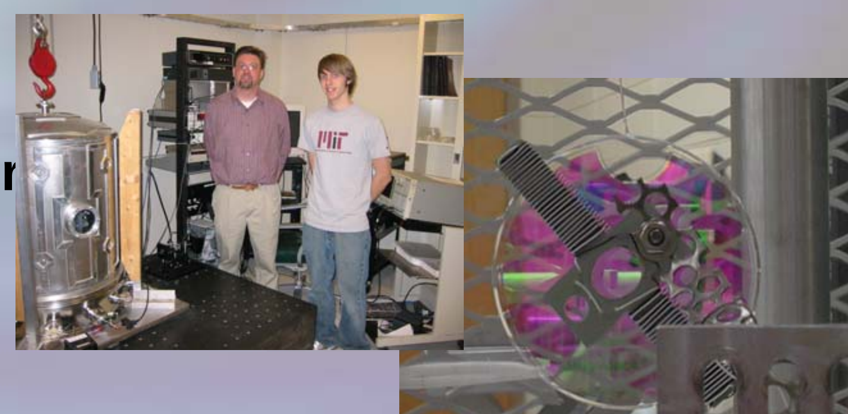


Suspension Thermal Noise

- Improving Enhanced LIGO
  - New materials / techniques
  - With work at Livingston & Hanford
- Researching Advanced LIGO
  - Diagnosing problems

Coating/Substrate Thermal Noise

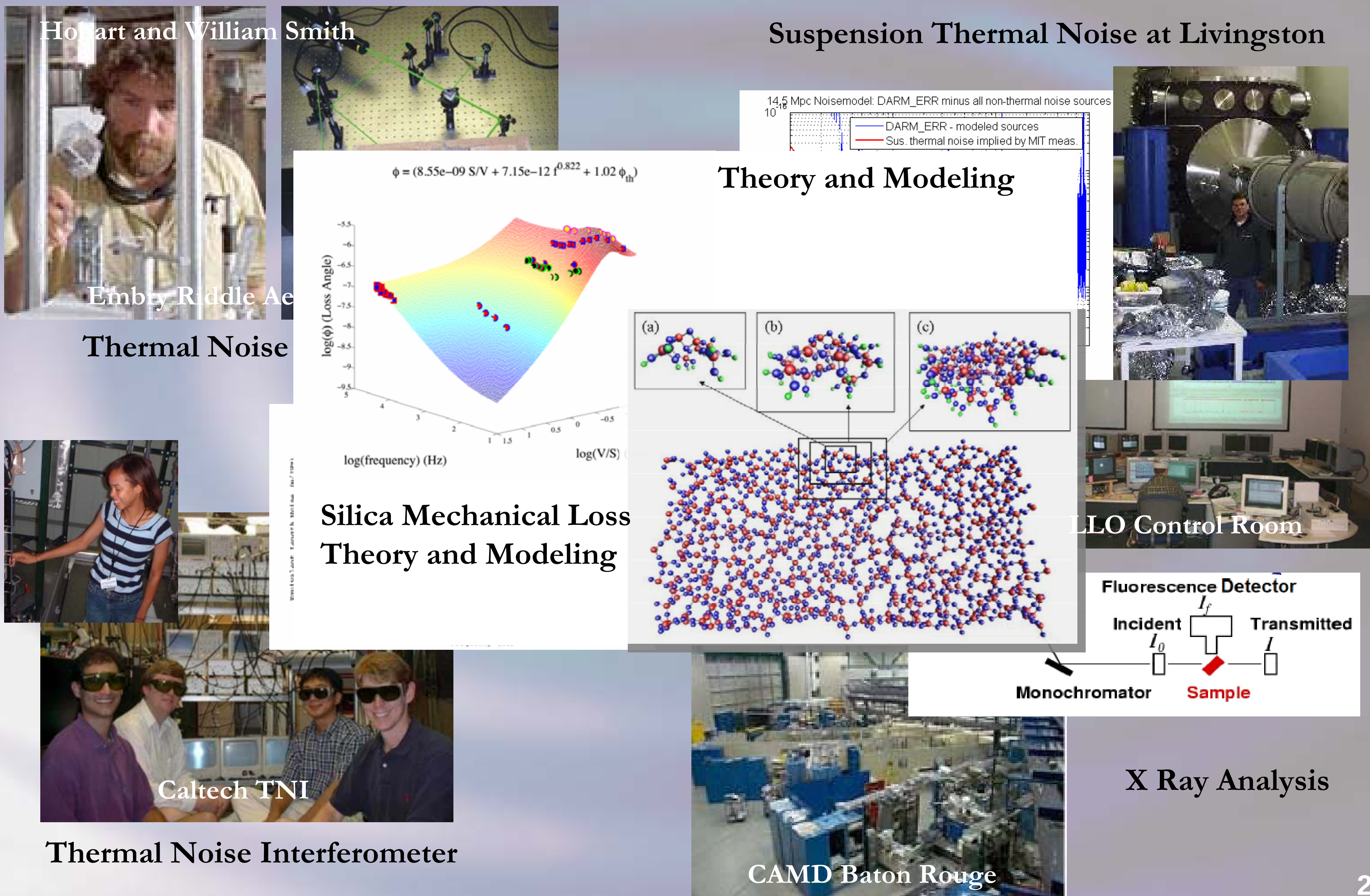
- Mechanical loss in coatings
  - Titania doping in Tantala
  - Hafnia, Lutetium, Niobium, other
- Mechanical loss in substrates
  - Silica: Theory and Experiment
  - Sapphire: Crystal effects



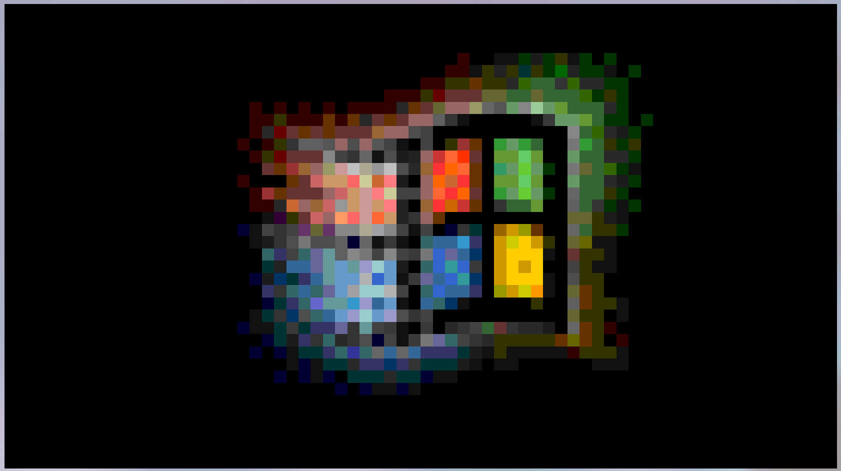
MIT Coating Thermal Noise Experiment

Thermal Noise Research

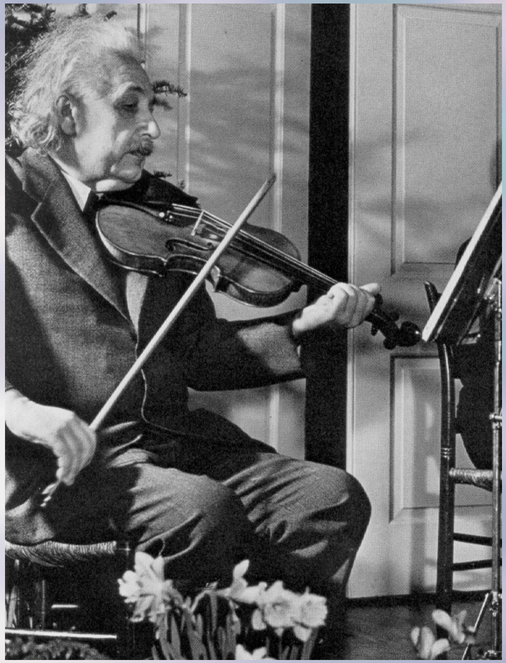
LIGO Collaboration



Conclusion



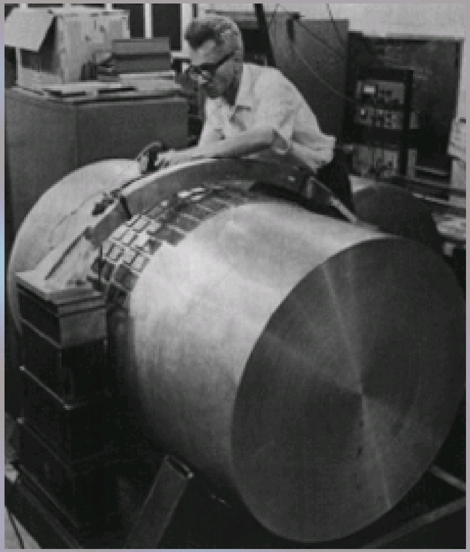
- Reduced thermal noise and gravitational waves make gravitational astronomy a reality
- Lots of interesting physics along the way



Detection of Gravitational Waves

Resonant Masses

- Weber (1960s) suggested gravitational waves could be detected
- Resonant aluminum bars detectors
  - Limited frequency bandwidth
  - Thermal noise limiting noise source
  - Sensitive to events in our galaxy



Joe Weber and Bar

AURIGA Cryogenic Bar

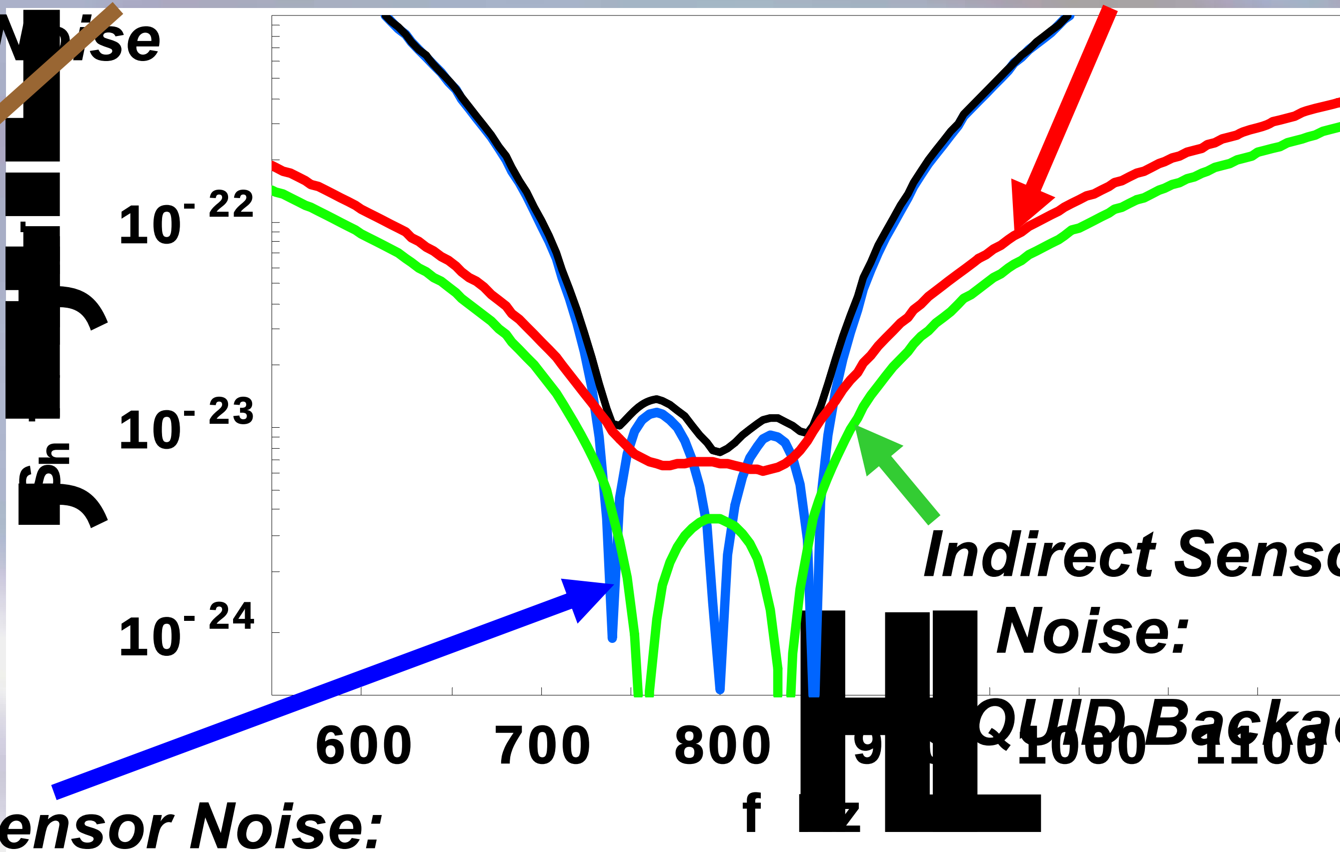
- Cryogenic bars (1980s)
  - Low T $\Rightarrow$ low thermal noise
- Spherical antennas (1990s)
  - Higher sensitivity
  - High frequency bandwidth
  - Improved materials $\Rightarrow$ low thermal noise

miniGRAIL Sphere

Noise Sources in Resonant Mass Antennas

Seismic Noise

Thermal Noise



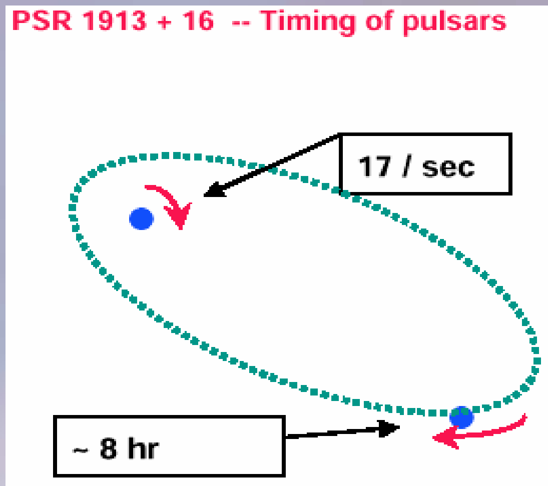
Indirect Sensor Noise:

SQUID Backaction

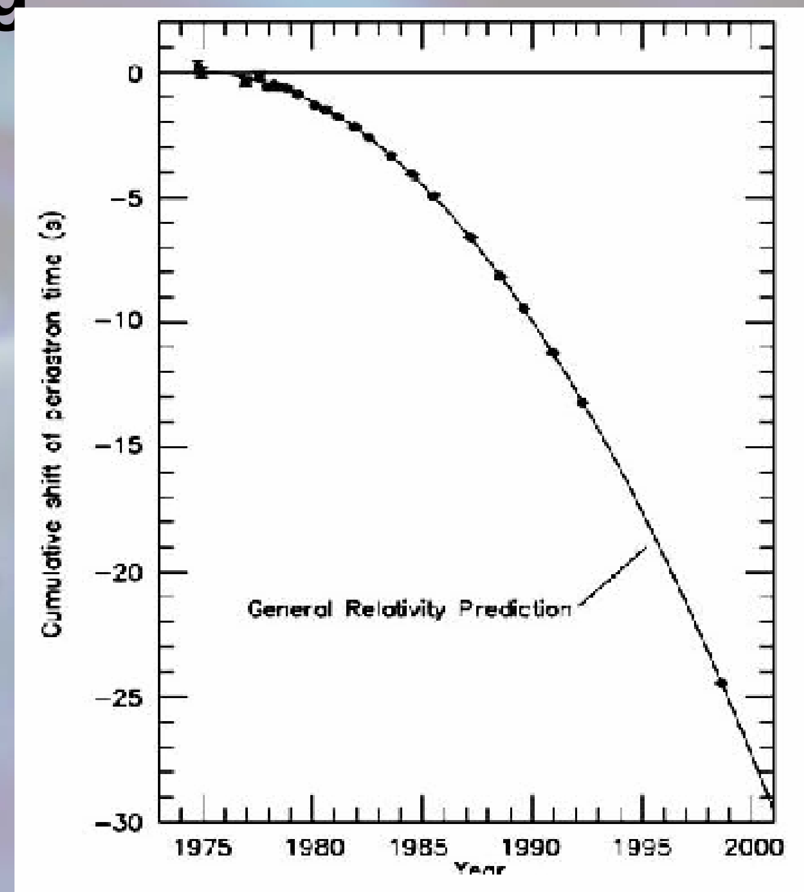
Direct Sensor Noise:

SQUID Johnson Noise

Indirect Detection



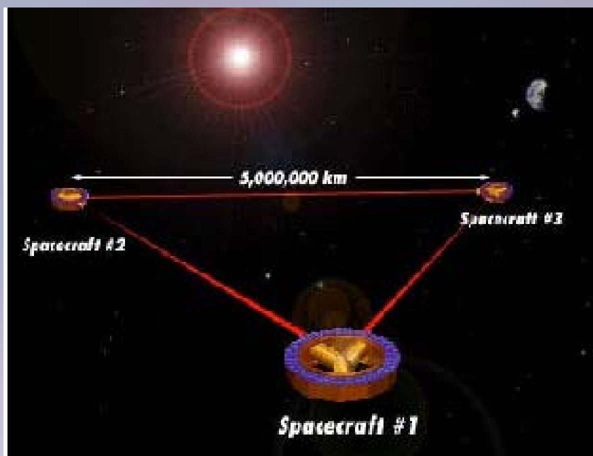
- Binary Pulsar 1913+16
- Slowly inspiralling, orbit decaying



- Energy loss
  - Gravitational wave emission
  - Large orbit, slow motions
- Followed for 30+ years
- Nobel Prize 1993
  - Russel Hulse
  - Joesph Tayor

Proposed Space-based Detectors

LISA in Orbit



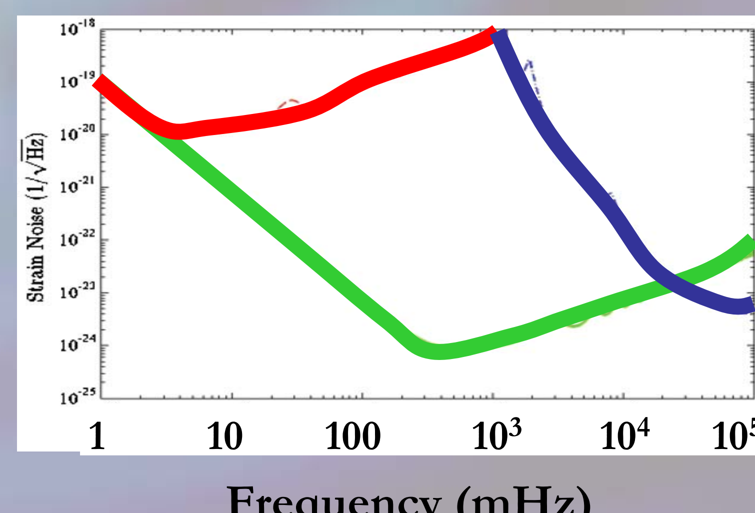
Laser Interferometer Space-based Antenna (LISA)

- Three spacecraft in solar orbit
- Much longer arm length ($5\ 10^9$ m)
- Lower frequency $\Rightarrow$ different sources
- Scheduled Launch 2015
- Changing budget priorities $\Rightarrow$ delays

Big Bang Observer (BBO)

- Shorter arms than LISA ($5\ 10^7$ m)
- Frequency band between LISA and LIGO
- More ambitious – advanced technologies

Frequency Bands for LISA, BBO, and LIGO



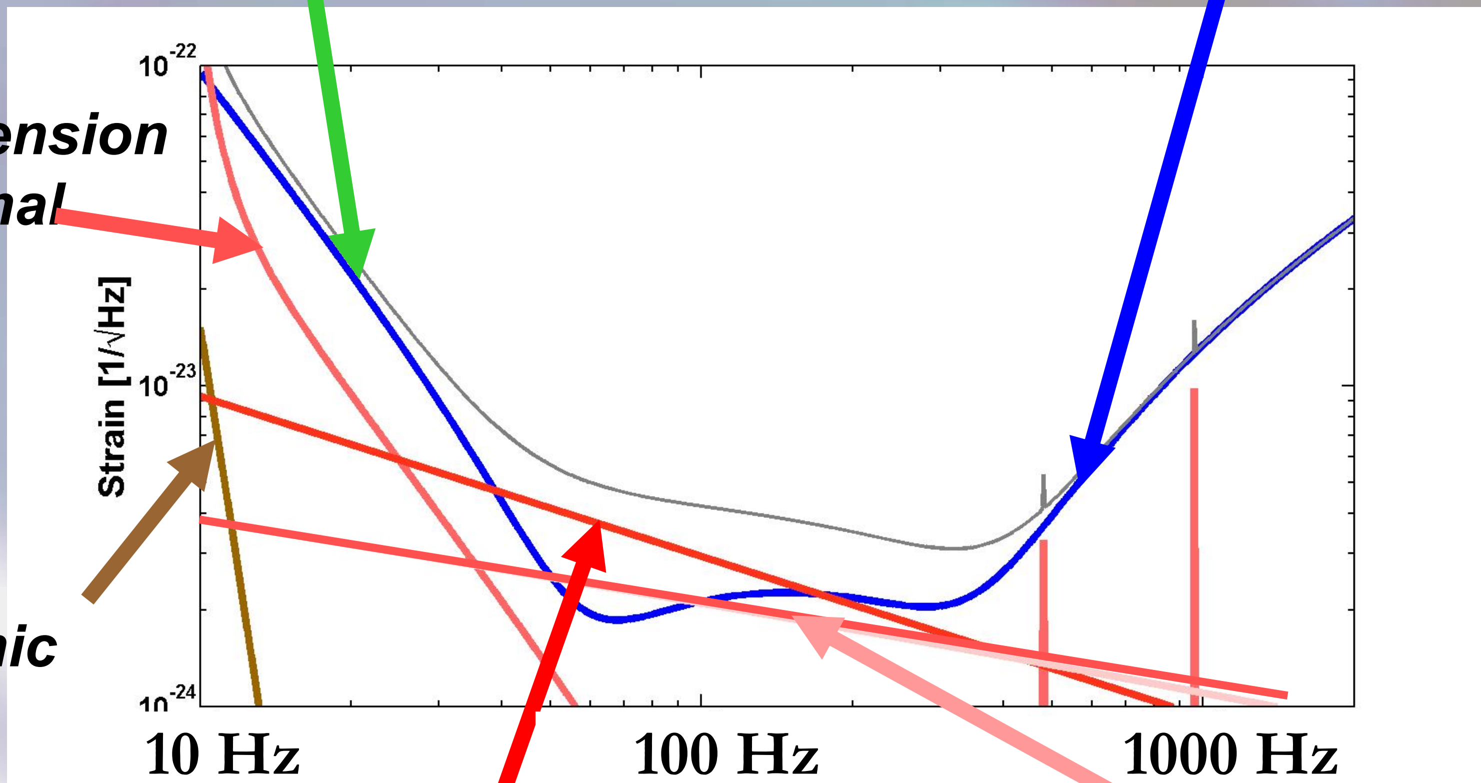
Noise in Advanced LIGO

Indirect Laser Noise – Radiation Pressure

Direct Laser Noise – Shot Noise

Suspension Thermal Noise

Seismic Noise

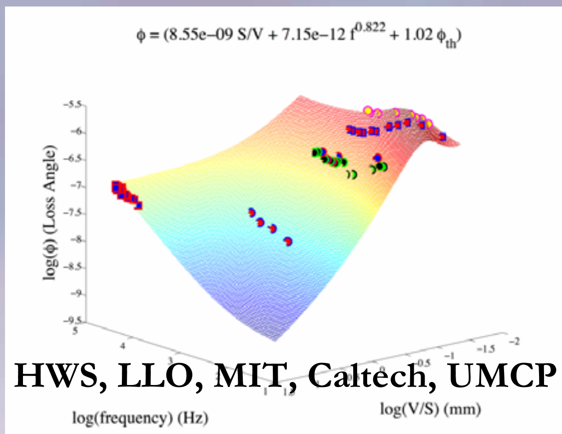


Coating Thermal Noise - Brownian

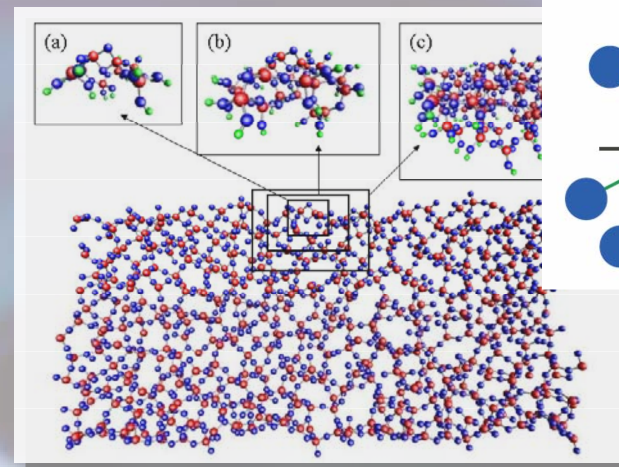
Coating Thermal Noise – Thermo-optic

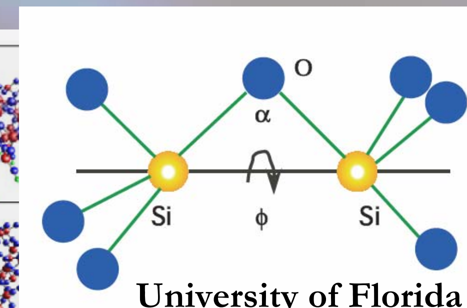
Thermal Noise Research

LIGO Collaboration: Theory and Modeling

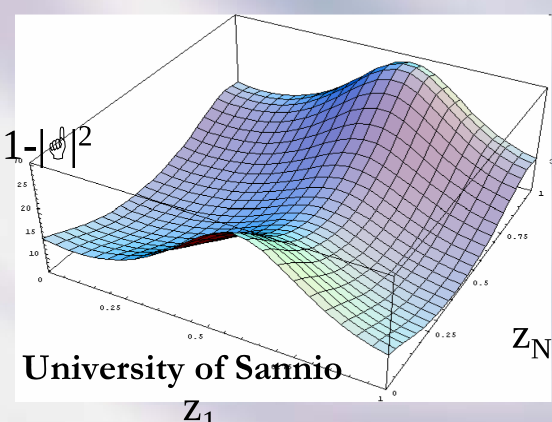


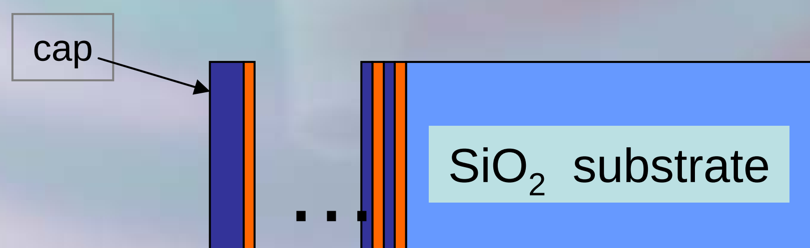
Theory and Data for Mechanical Loss in Fused Silica





Molecular Level Modelling of Mechanical Loss





Coating Design Optimization to Minimize Thermal Noise

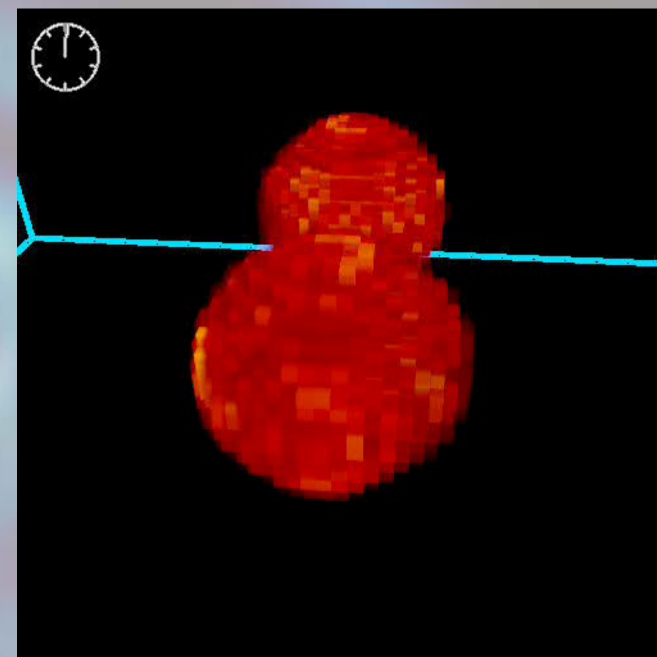
Astronomical Sources

Compact Binary Inspirals

- **Two objects in mutual orbit**
  - **High mass and high velocity**
  - **High velocity when objects close**

    high density
- **Typical astronomical objects**
  - **Black Holes**
  - **Neutron stars**
  - **White dwarfs**
- **Neutron stars - “standard candle”**
- **In human audio band**

Numerical Model of Inspiral

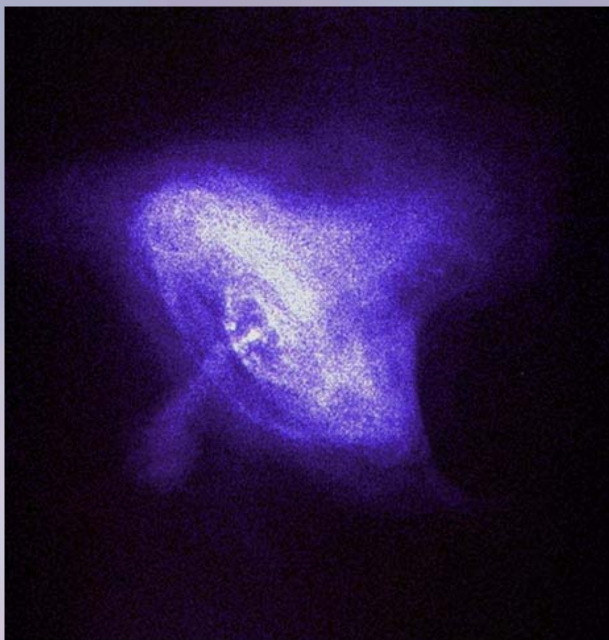


Black Hole Inspiral and Coalescence

Astronomical Sources

Periodic Sources

X-ray Image of Crab Pulsar



- **Rapidly rotating compact body**
  - **Pulsar (rotating neutron star)**
  - **Low mass X-ray binary**
- **Must have some asymmetry**
  - **Sphere not quadrupolar**

Artists Conception of Accretion

- **Asymmetry could be due to:**
  - **Accreting material**
  - **Small mountain**
  - **Magnetic effect**

Astronomical Sources

Bursts

Artists Conception of Supernova

- **Catastrophic events**
  - 10s of solar masses
- **Sources not well understood**
  - No theoretical model
  - Cannot use optimal search routine
- **Two categories:**
  - Triggered – seen by other telescopes
    - Supernova (must be asymmetric)
    - Gamma ray bursts
    - Neutrino events (w/ IceCube)
  - Untriggered – gravitational wave signature only
    - Unseen supernova
    - Accretion onto black holes
    - Merger of compact bodies
    - Cosmic strings

Astronomical Sources

Stochastic Background

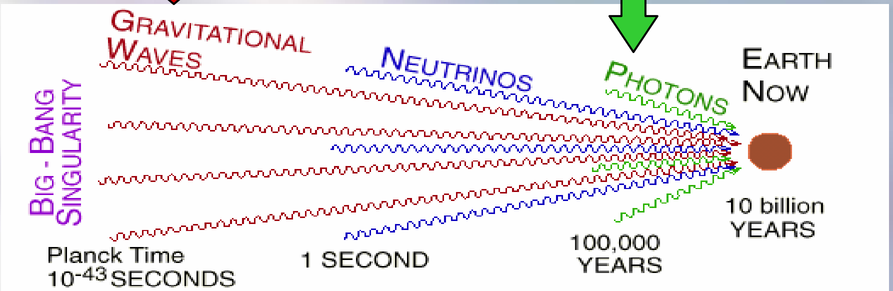
Big Bang

- Similar to cosmic microwave background
- Probe closer to beginning
- Tests of inflation, quantum gravity, etc.

Artists Conception of Big Bang

cosmic gravitational-wave background (10^{-22}s)

cosmic microwave background (10^{+12}s)



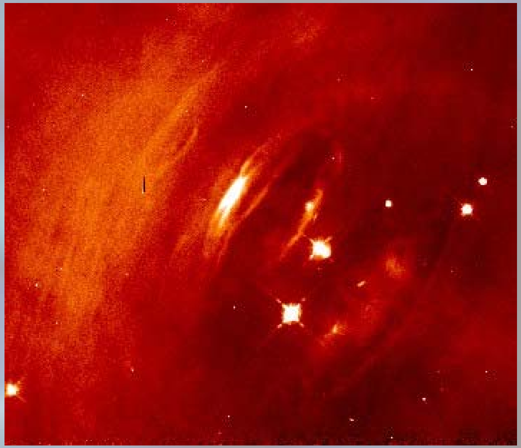
Nearby Sources

- Unresolved background of burst type sources
- Distant supernova, mergers, accretions, etc.

Upper Limits

Supernova and Pulsars

Hubble Image of Crab Pulsar



Supernova

- Sensitive to about 10 kpc
  - Very model dependent
- *LIMIT* of 0.15/day
  - Expect about 1/50 years

Artists Conception of Supernova

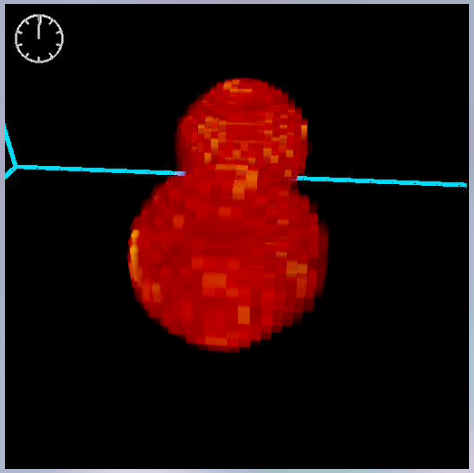
Pulsars

- Upper limits on 78 pulsars
  - *NO* signal seen
  - Eccentricity ε limit as low as 10^{-6}
- Targeted sky location
- Unknown neutron stars

Upper Limits

Inspirals and Stochastic Point Sources

Numerical Model of Inspiral

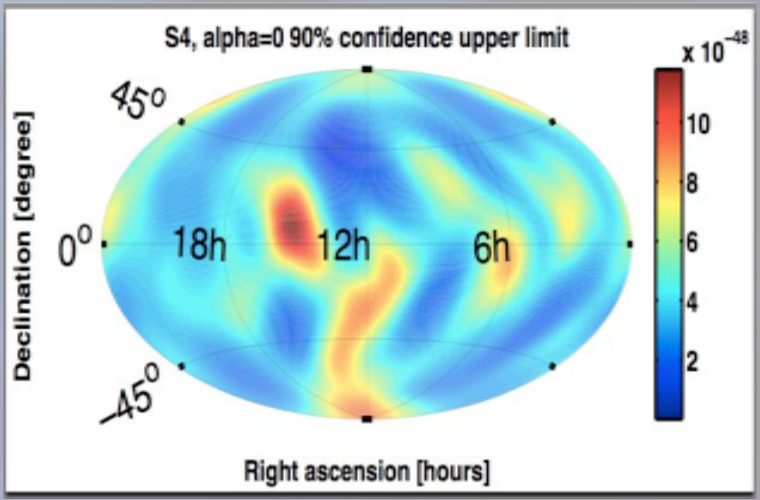


Inspiral Upper Limits

- Neutron stars rate
  - < 2/yr/Milky Way-like Galaxy
- Black hole rate
  - < 1/yr/Milky Way-like Galaxy

Stochastic Search

- Stochastic whole sky map
  - *NO* point sources found
- Correlations with other detectors
  - Virgo in Europe
  - Allegro bar detector in Louisiana



Stochastic Map of Sky

Other Applications

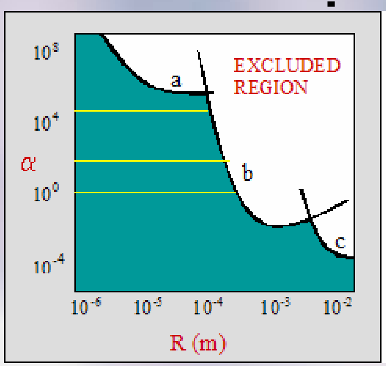
Quantum Experiments

• Reaching standard quantum limit

Sensor development

• Cooling macroscopic objects to quantum ground state

Quantum entanglement in macroscopic objects



Laboratory Gravity Measurements

• Suspension thermal noise limits sensitivity

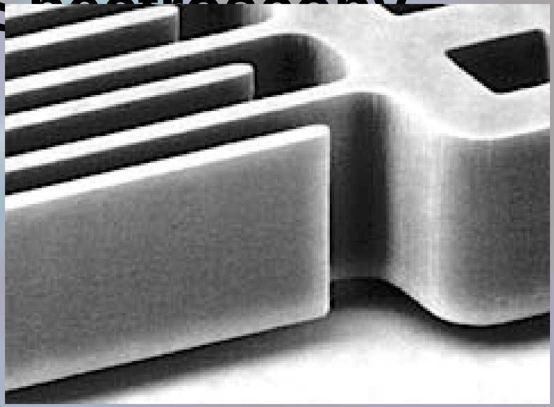
Frequency Stabilization

• Optical frequency combs

John Hall at NIST

• Metrology

• Spectroscopy

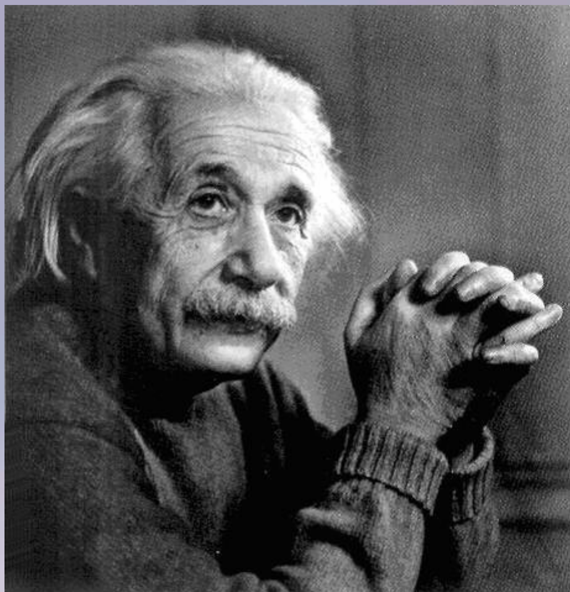


MEMS (Micro-Electro Mechanical Systems)

• Accelerometers

• Gyroscopes

• Seismometers



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