LIGO: The Search for Gravitational Waves

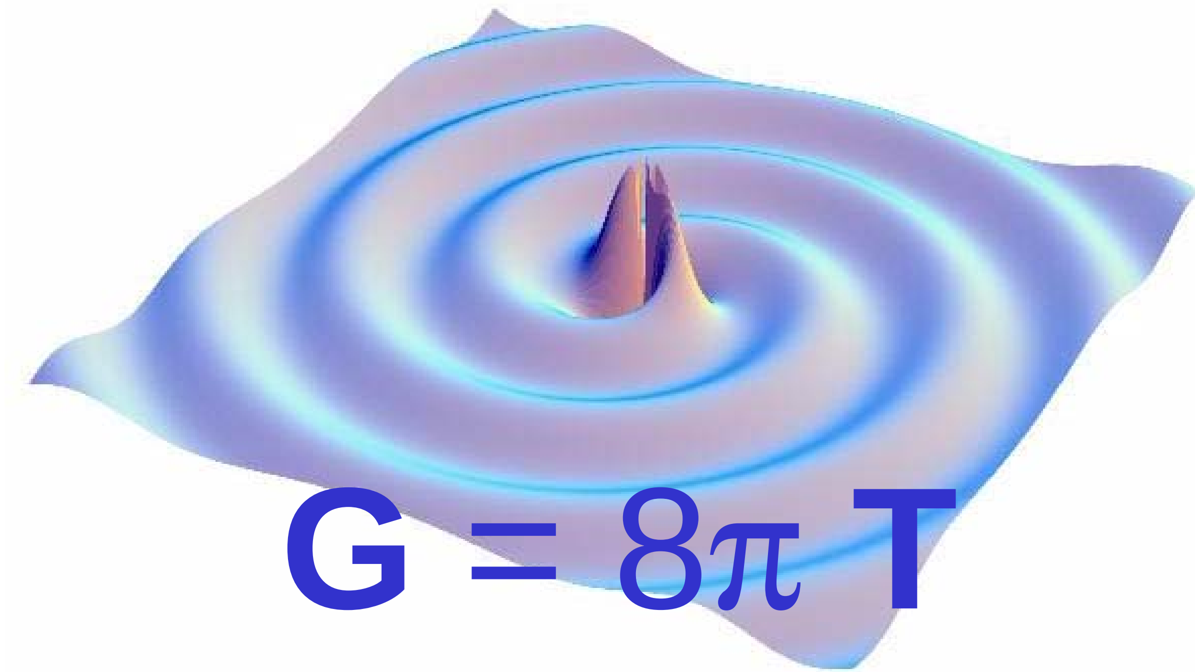
Gregory M. Harry
LIGO Laboratory/Massachusetts Institute of Technology
- On behalf of the LIGO Science Collaboration -

January 21, 2002
Worcester Polytechnic Institute
Department of Physics Colloquium

Overview

- General relativity and gravitational waves
- Sources of gravitational radiation
- Interferometers and LIGO
- Noise and technology
- Next steps
- Current status

Einstein's Theory of Gravity



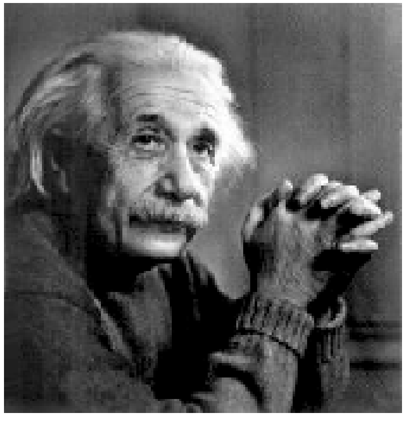
$$G = 8\pi T$$

- Mass tells spacetime how to bend
- Spacetime tells mass how to move

Electromagnetism and Gravity

Electromagnetism

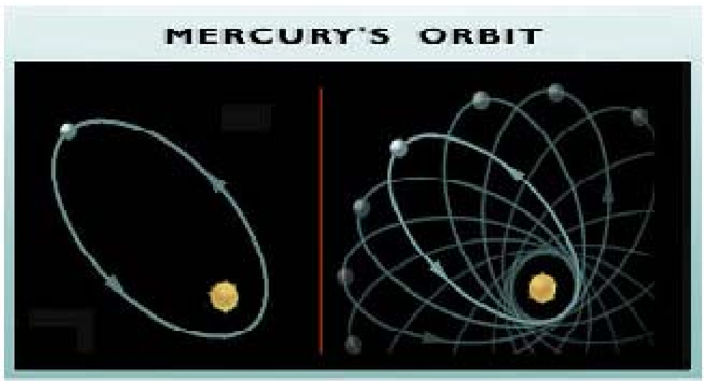
Coulomb → static charge
Maxwell → oscillating fields
Hertz → radio waves



Gravity

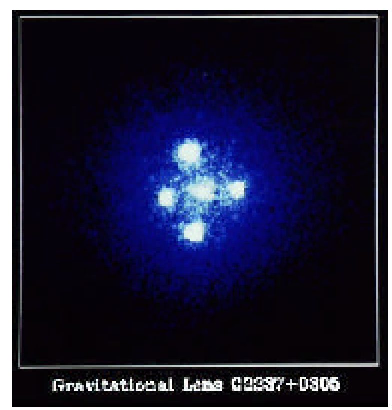
Newton → static masses
Einstein → oscillating spacetime
? → gravitational radiation

Tests of general relativity



Precession of Mercury's orbit

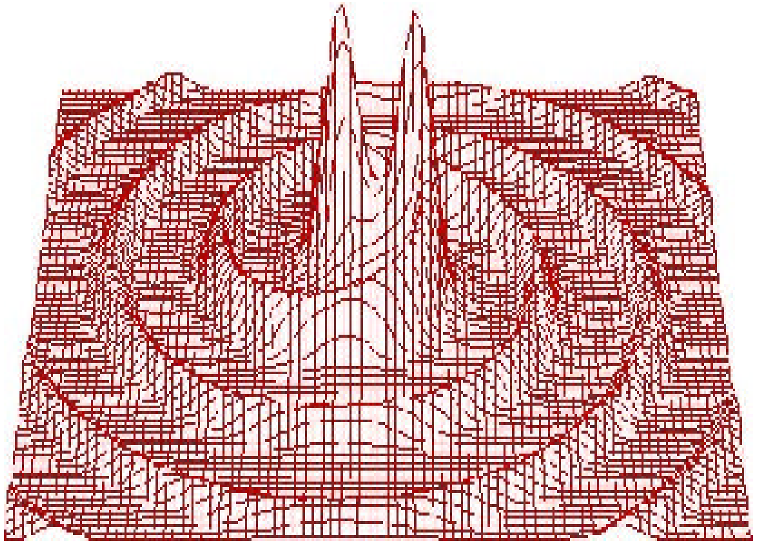
Einstein Cross



Bending of light near massive objects

Gravitational Waves
Generation

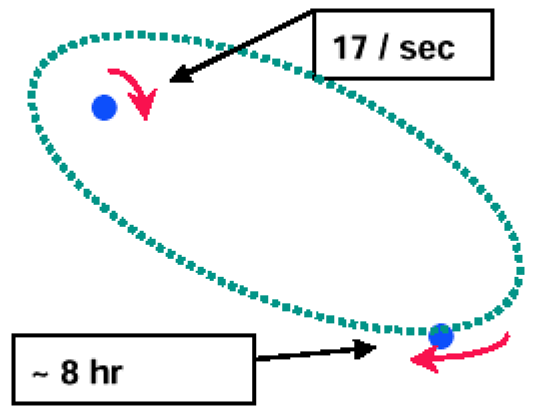
- Effect of mass on spacetime propagates in finite time
- Accelerating masses create spacetime waves
- Waves travel at speed of light, *c*



gravitational radiation from binary inspiral of compact objects

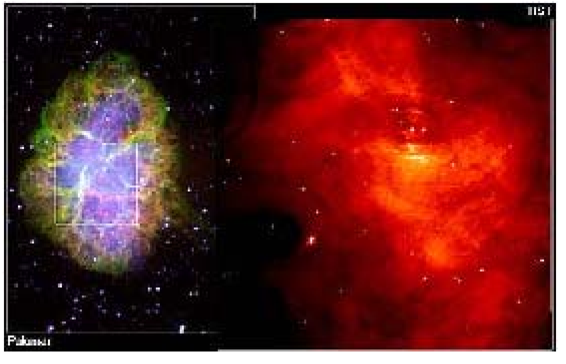
Gravitational Waves
Observation

PSR 1913 + 16 -- Timing of pulsars



Binary Neutron Star System

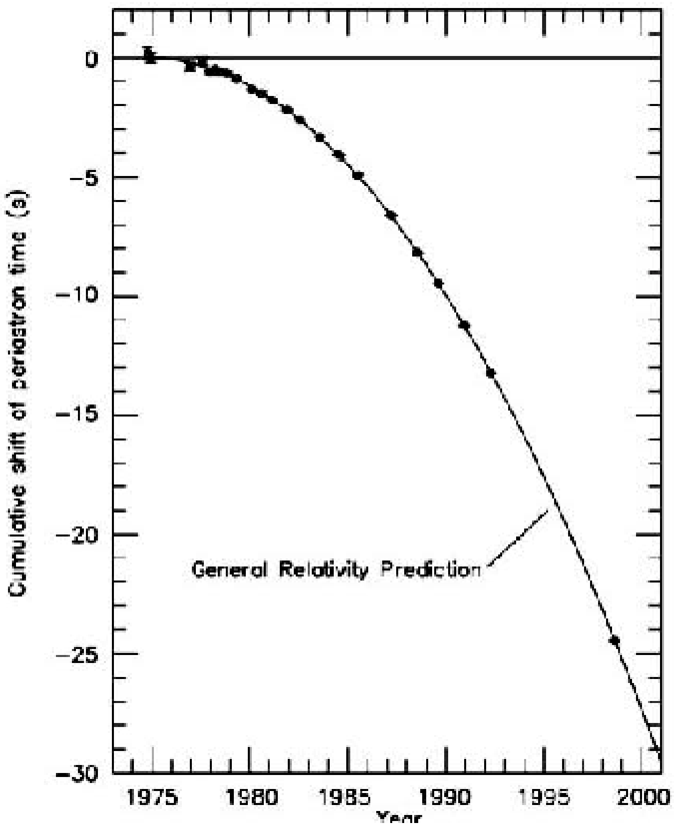
Changing quadrupole moment of system causes emission of gravitational waves.



Energy loss causes orbital period to decrease

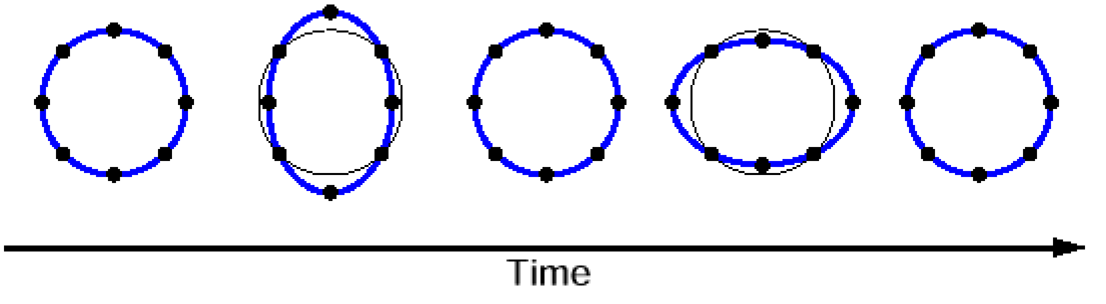
Gravitational Waves
Evidence

- Energy is lost to gravitational waves
- Orbital period decreases
- Deviation grows as predicted by Einstein



Gravitational Waves
Effect on matter

- Freely falling masses move in response to the gravitational wave
- Gravitational wave is a tensor so masses move in both transverse directions



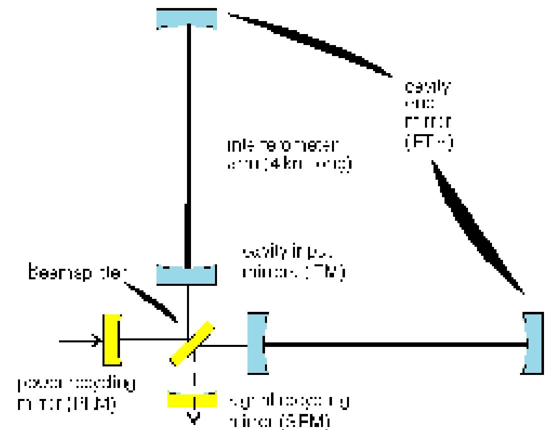
- Two polarizations, X and +
- Amplitude measured in strain, $\Delta L / L$ (= h)

Gravitational Waves
Detectors

Resonant mass antennas

Bars and spheres

Allegro, Explorer, Auriga, Niobe, GRAIL, Schenberg

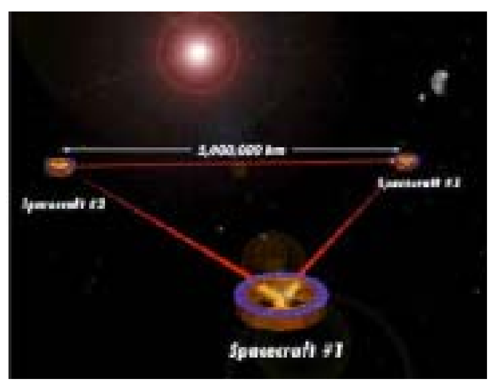


Earth-based interferometers

LIGO, Virgo, GEO, TAMA, advanced LIGO

Space-based interferometers

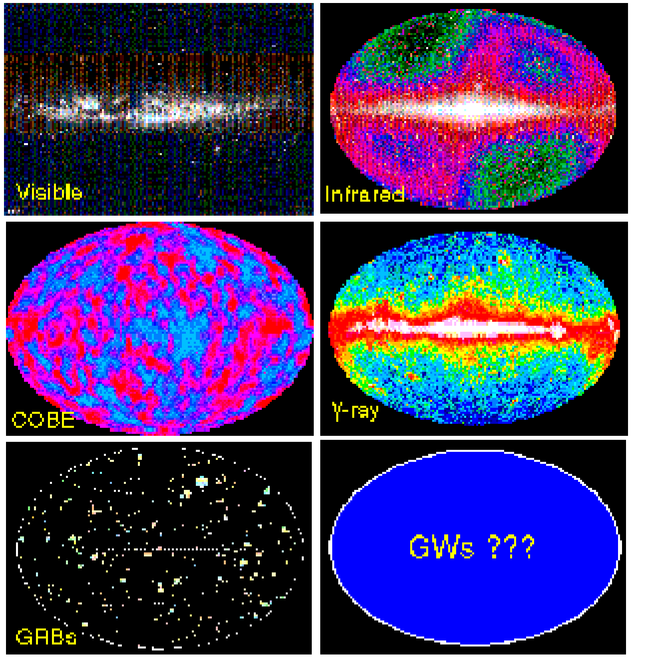
LISA



Sources of Detectable Gravitational Waves

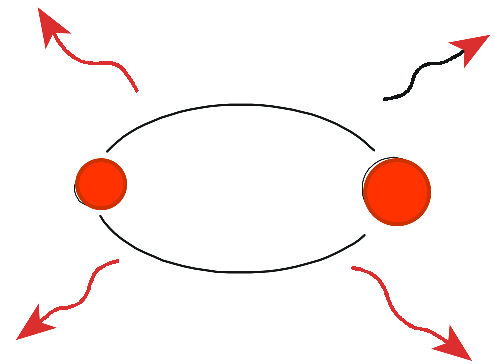
New window on the universe

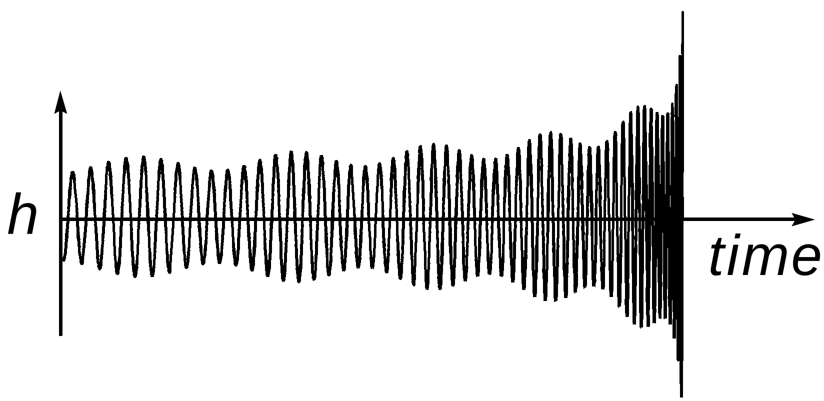
- Inspiraling binary compact objects (neutron star, black hole)
- Supernovae
- Compact body merger
- Stochastic background



Sources
Compact binary inspiral

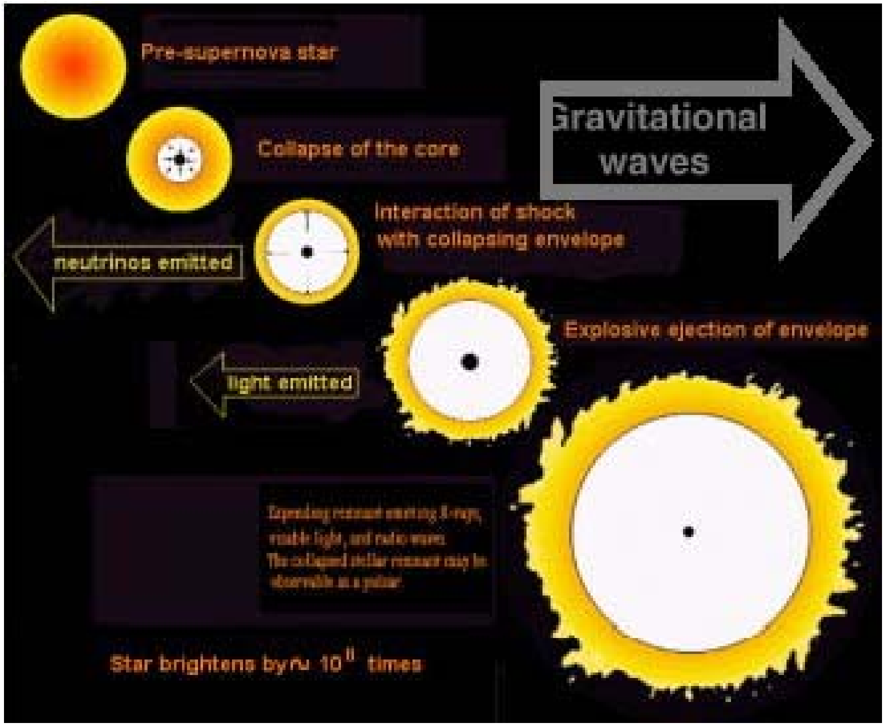
- Black holes and/or neutron stars
- Measure masses, spins, distance, and location
- Waveform modeled analytically
- Correlate with EM counterpart (γ burst ?)





- Rates estimated from known pairs
  - NS/NS
  - Initial LIGO, 1/10 yr
  - Advanced LIGO, 1/month

Sources
Supernovae



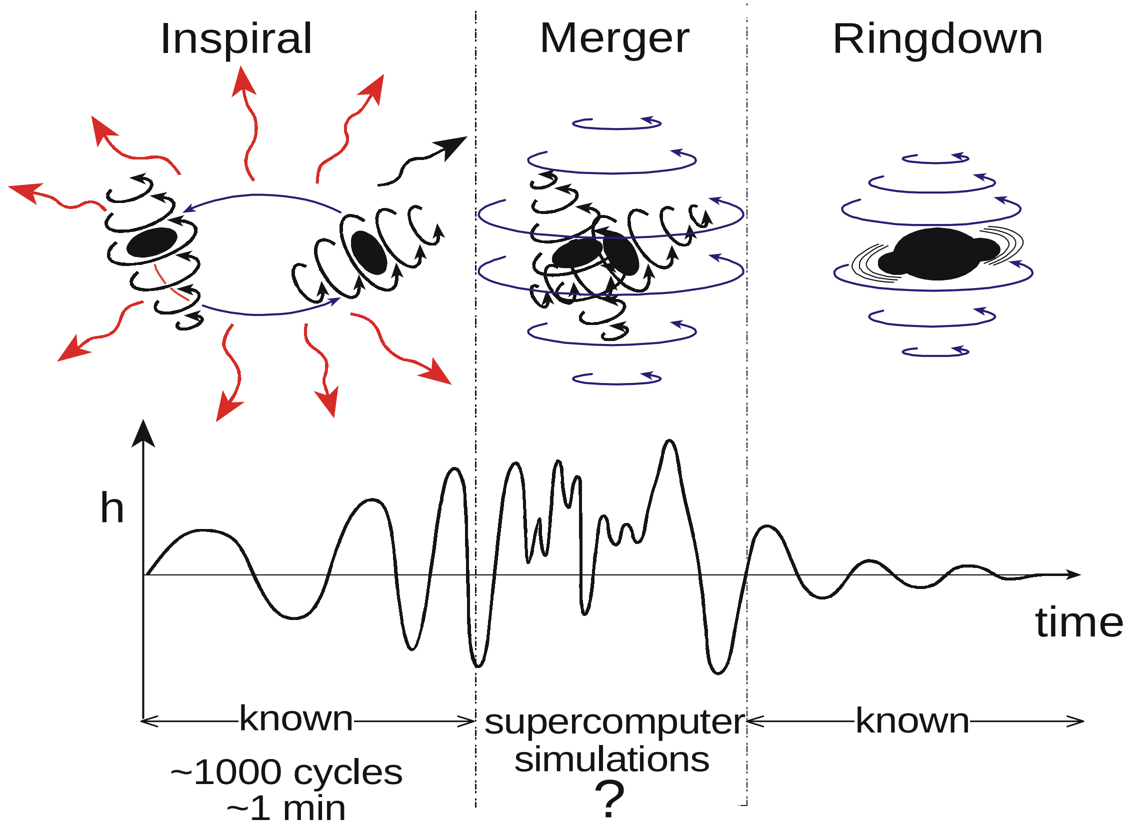
- **Must be non-axisymmetric**
- **Rate uncertain**

~ 3/yr at Virgo Cluster (20 Mpc)

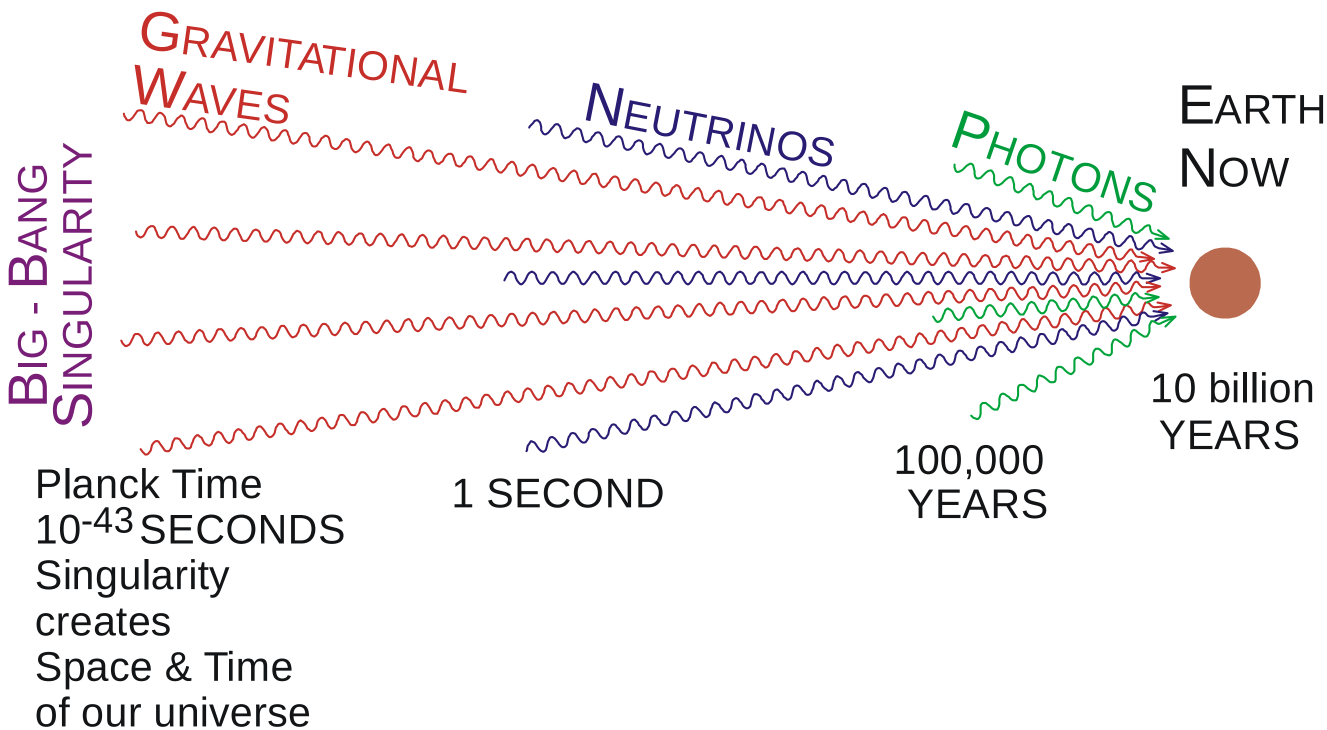
SN1987A

Sources
Compact binary merger

- Black hole formation
- True GR regime
- Uncertain rate
  - BH/BH
  - Initial LIGO, 1/yr (?)
  - Advanced LIGO, 1/hr (?)



Sources
Stochastic background



Cosmic background from Big Bang

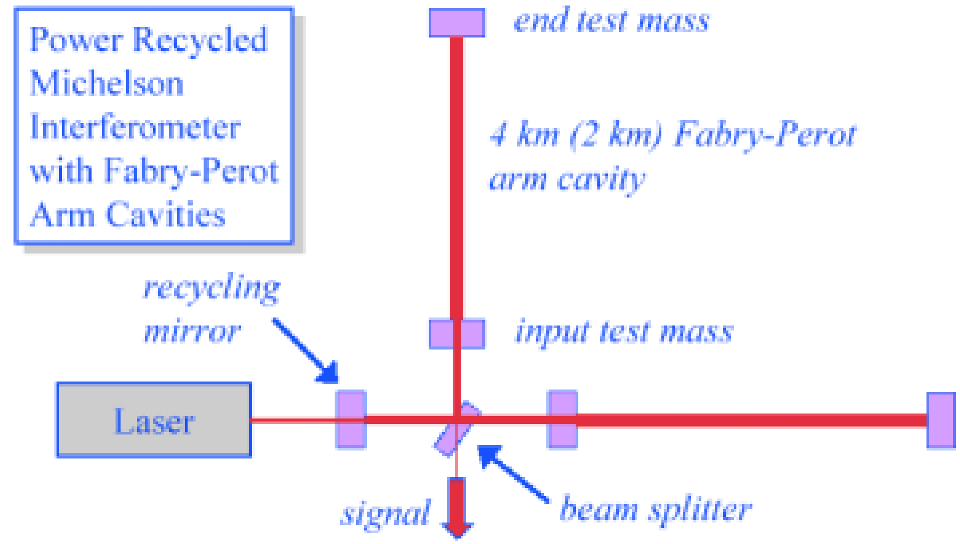
Sources
Unpredicted phenomenon

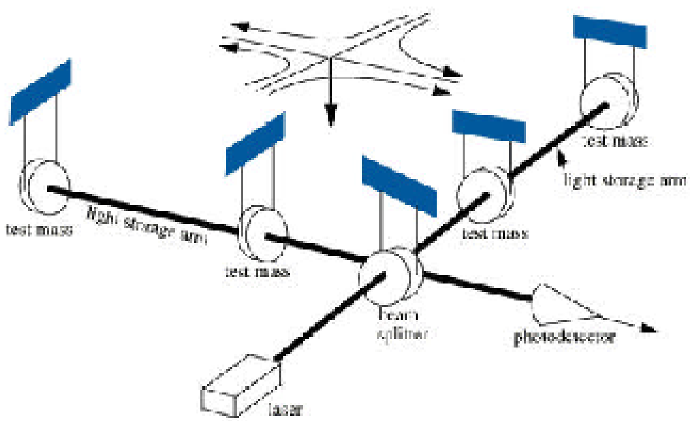
- Big surprises likely

?

LIGO
Interferometry

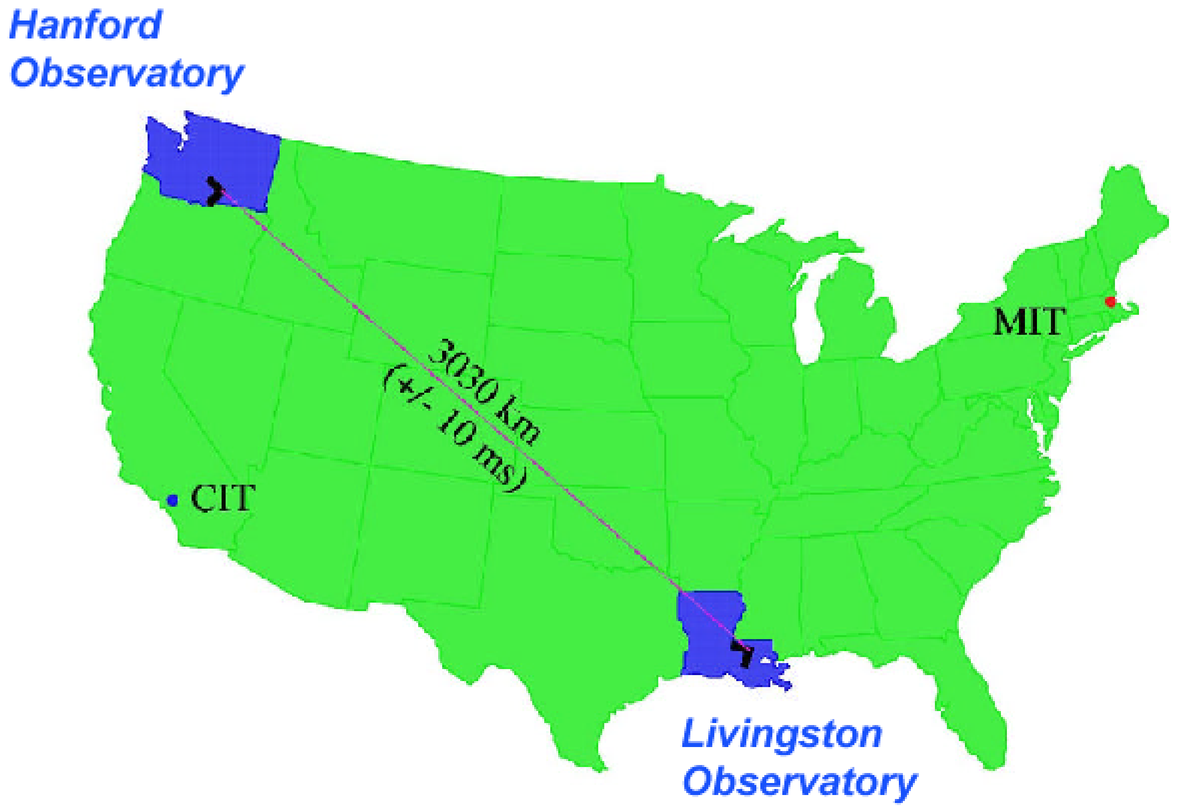
- **4 kilometer long arms**
- **All subsystems designed for low noise**
- **Feedback allows for sensitivity h ~ 10^{-21}**





- **Test mass hangs like pendulum**
- **Approximate freely falling bodies**

LIGO
Two sites



Allows for correlated searches

LIGO
Livingston Louisiana

LIGO
Hanford Washington

LIGO Collaboration

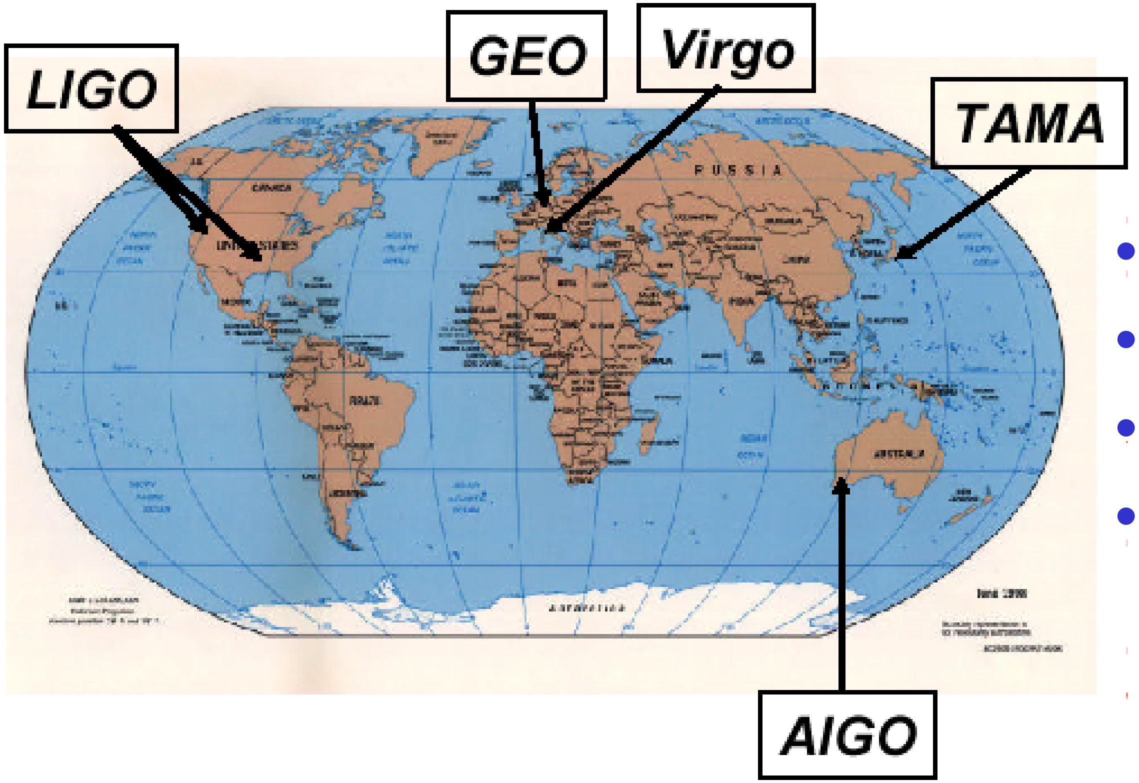
LIGO Scientific Collaboration

LIGO Laboratory

Caltech	LIGO Hanford Observatory
MIT	LIGO Livingston Observatory

ACIGA (Australian Consortium)
Caltech Center for Adv. Computing Research
Caltech Relativity Theory Group
Caltech Experimental Gravity Group
Calif. State U., Dominguez Hills
Carleton College
Cornell U.
U. of Florida
GEO 600 Collaboration (British/German)
Harvard-Smithsonian Center for Astrophysics
Institute of Applied Physics–Nizhny Novgorod
Iowa State U.
IUCAA (India)
JILA – U. of Colorado
Louisiana State U.
Louisiana Tech U.
U. of Michigan
Moscow State U.
National Astronomical Observatory of Japan
U. of Oregon
Penn. State U.
Southern U.
Stanford U.
Syracuse U.
U. of Texas, Brownsville
U. of Wisconsin, Milwaukee

International Network



- Detection confidence
- Source location
- Verify speed *c*
- Determine polarization

Plus bar detectors in Louisiana, Italy, and Australia

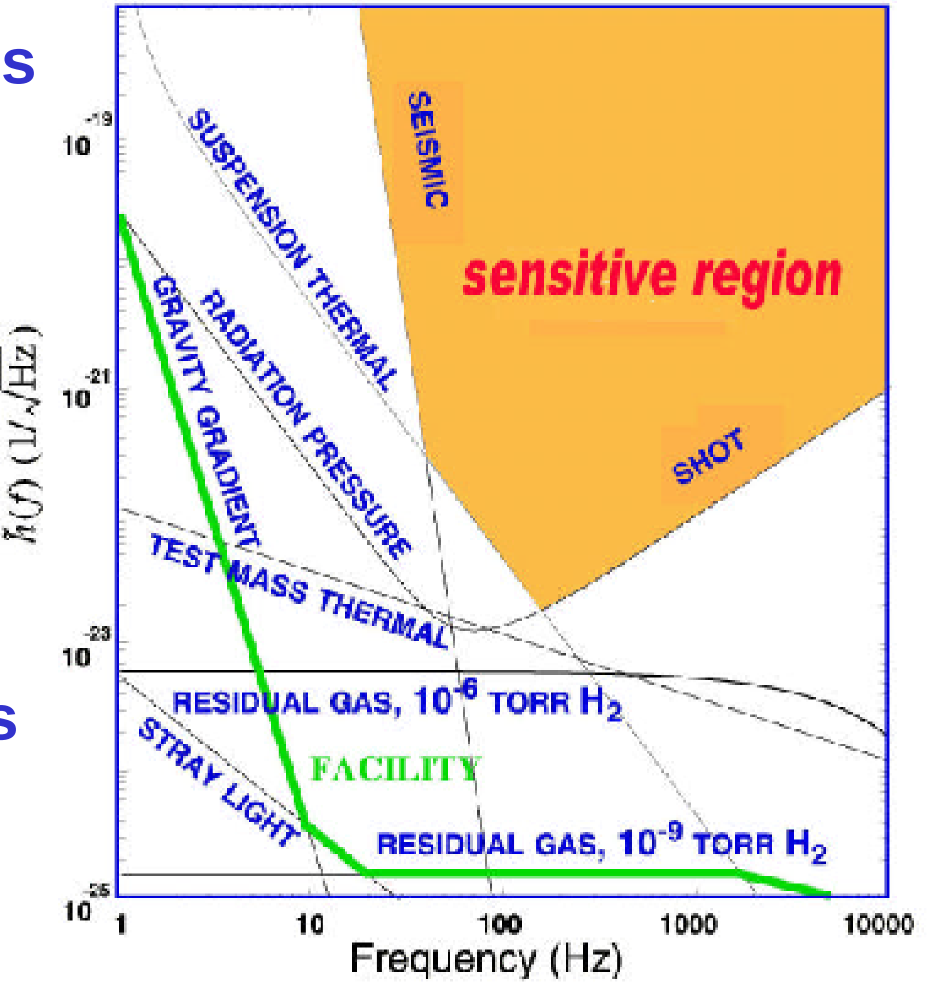
LIGO
Facilities

- Everything under vacuum
- All 4 km beam tube baked out
- Vacuum limited at 10^{-6} torr by water outgassing

Noise
Total noise

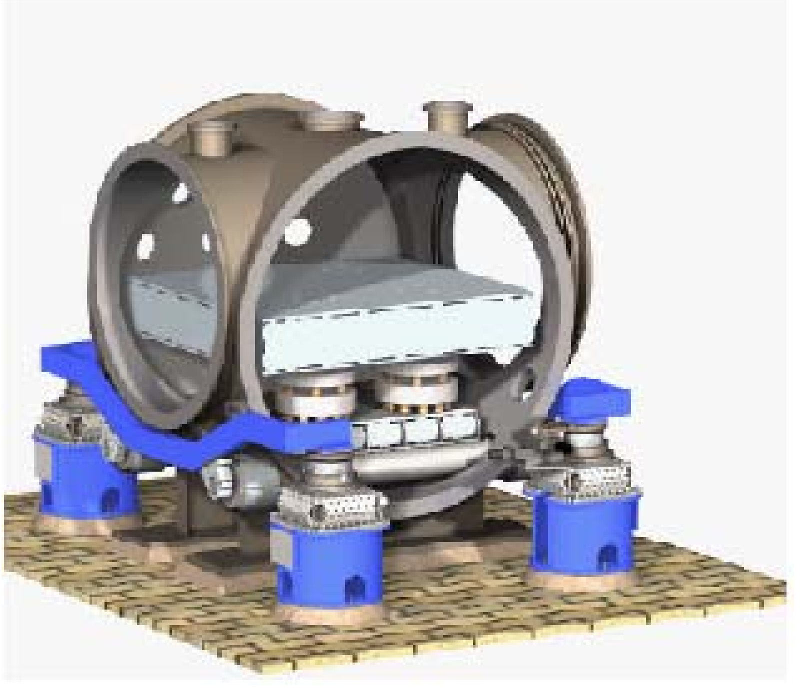
- **Fundamental noise sources**
  - Seismic noise at low frequencies
  - Thermal noise at intermediate frequencies
  - Shot noise at high frequencies

- **Facility limits at lower levels**
  - Gravity gradient
  - Residual gas



Noise
Seismic noise

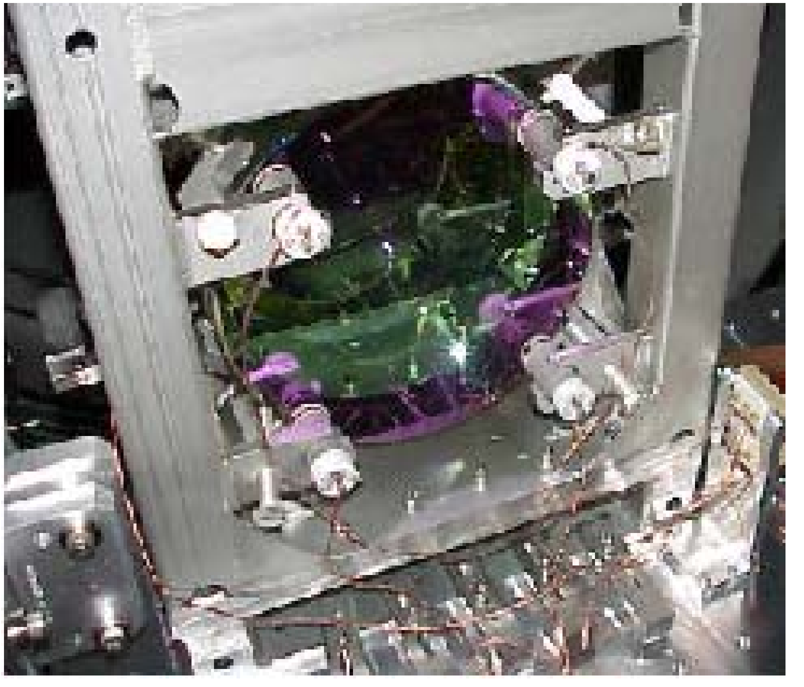
- All optics sit on vibration isolation stacks
- Alternating layers of masses and springs
- Isolate above 40 Hz
- Reduce seismic motion by 4-6 orders of magnitude
- Some compensation for Earth tides



Noise
Thermal noise

- Brownian motion of optics
  - Pendulum mode
  - Internal mirror modes

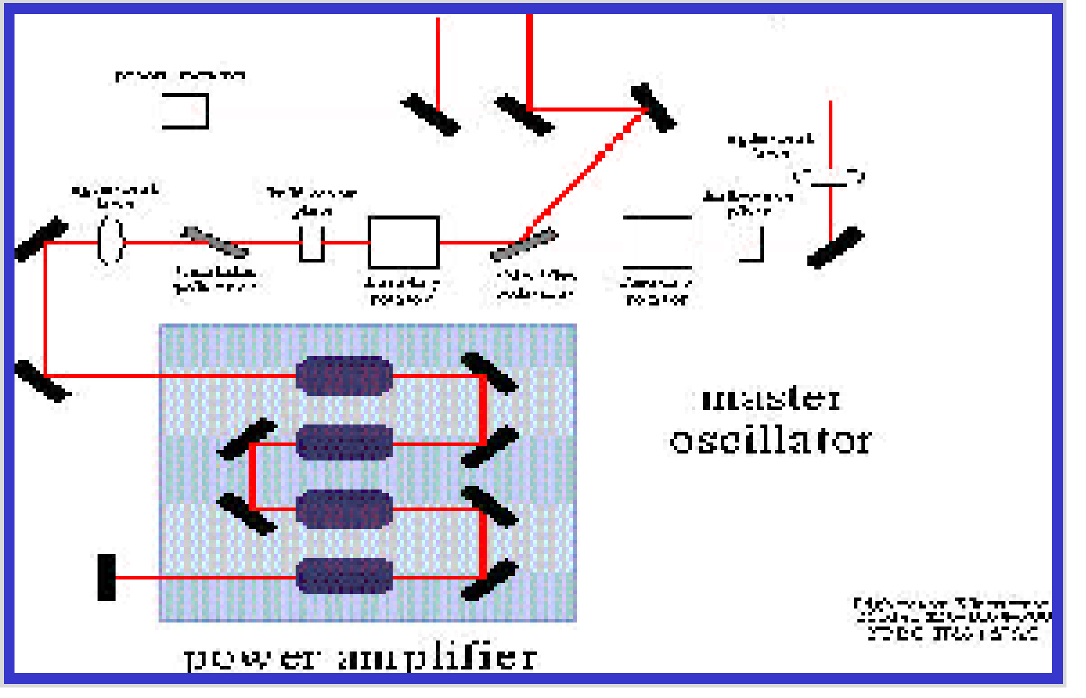
- Use fused silica for mirrors
- Limiting noise source in most sensitive region



Suspended Optic

Noise
Laser

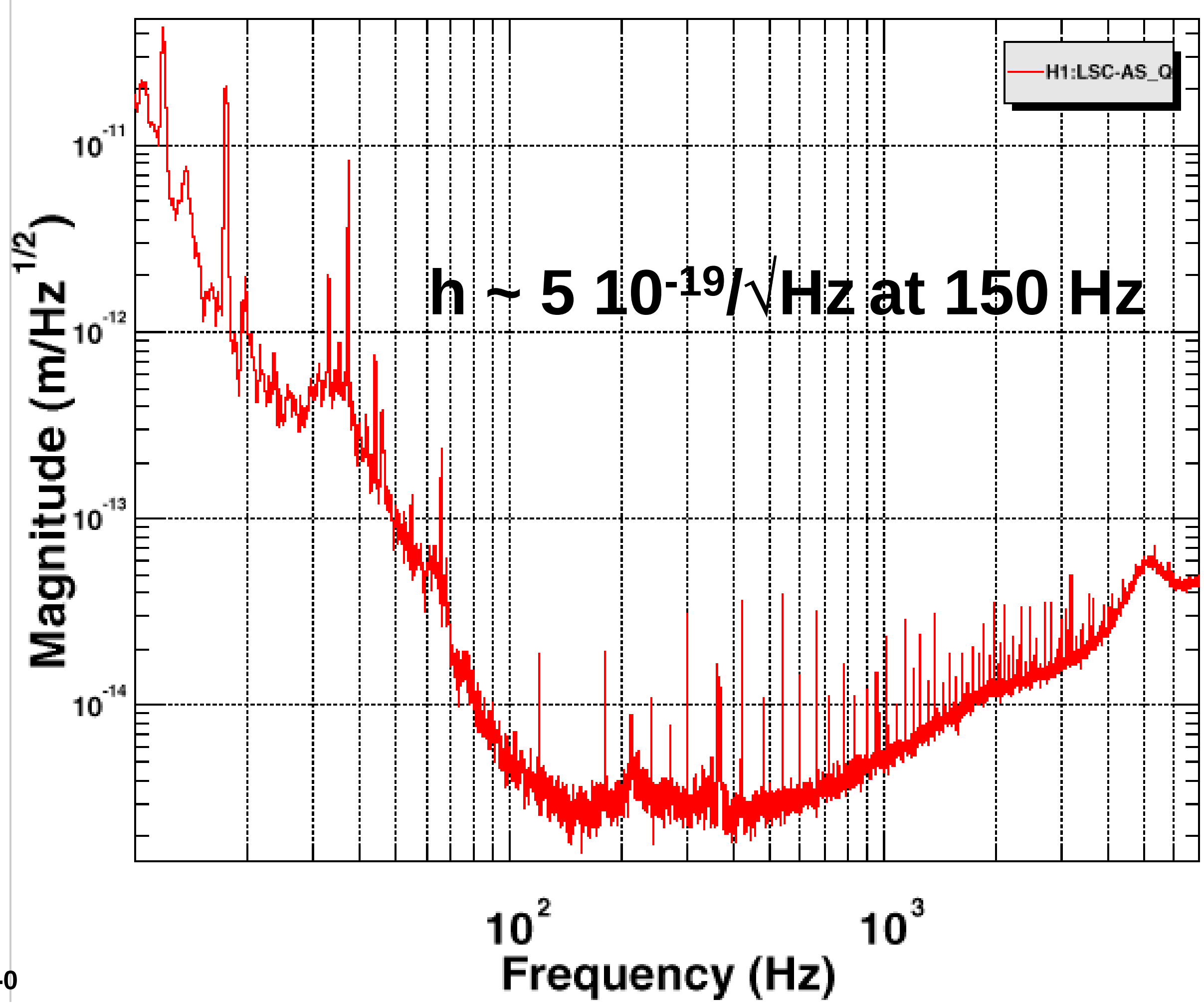
- Nd:YAG
- 1.064 μm
- Use TEM00 mode
- 8 W output power



Down to shot noise limit

Noise
Current status

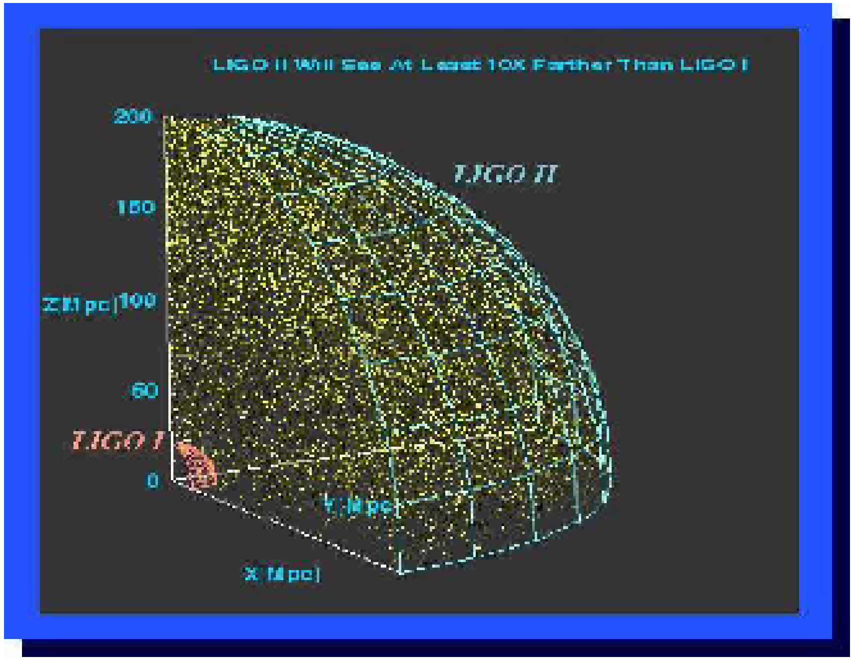
4k calibrated noise curve



Engineering run
January 30, 2001
LIGO Hanford

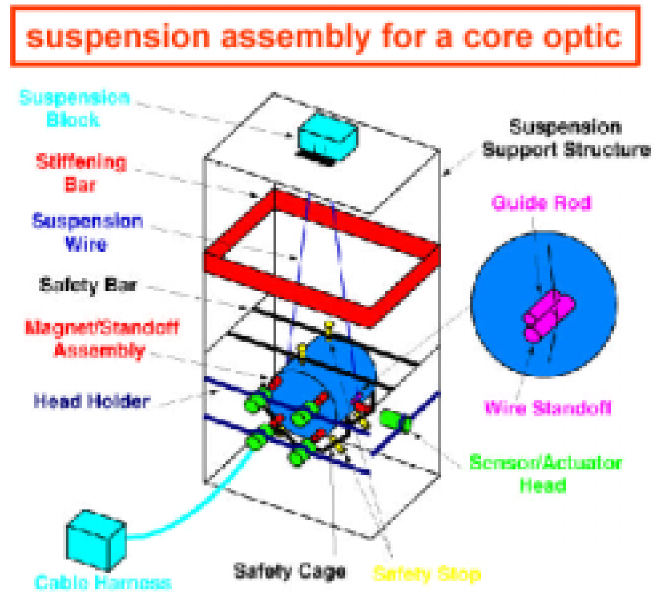
Advanced LIGO
Plans

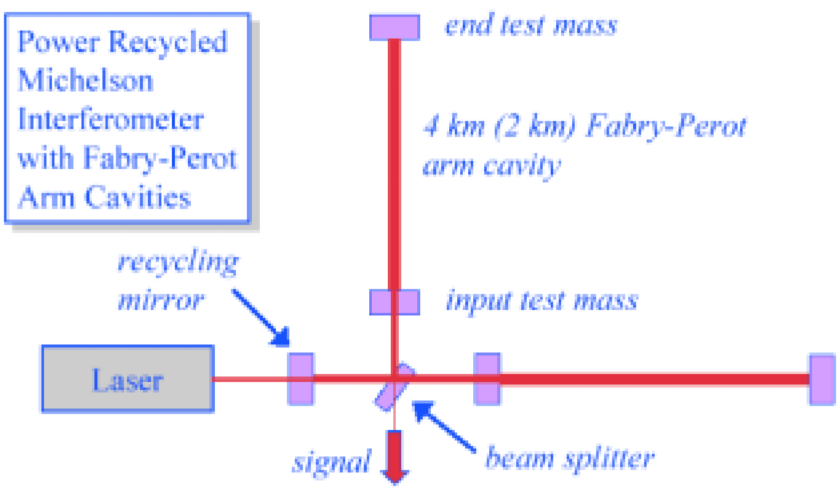
- “See” out to 200 Mpc
- Technology research going on now
- Prototype work beginning
- Begin installation 2006+
- Begin taking data 2008+



Advanced LIGO
Improvements

- Seismic isolation to 10 Hz
- Sapphire optics for lower thermal noise
- Silica ribbon suspensions

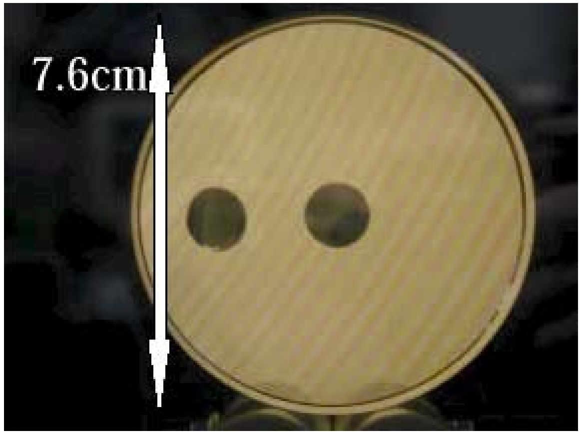




- Higher laser power 180 W
- Signal recycling mirror

Advanced LIGO
Research

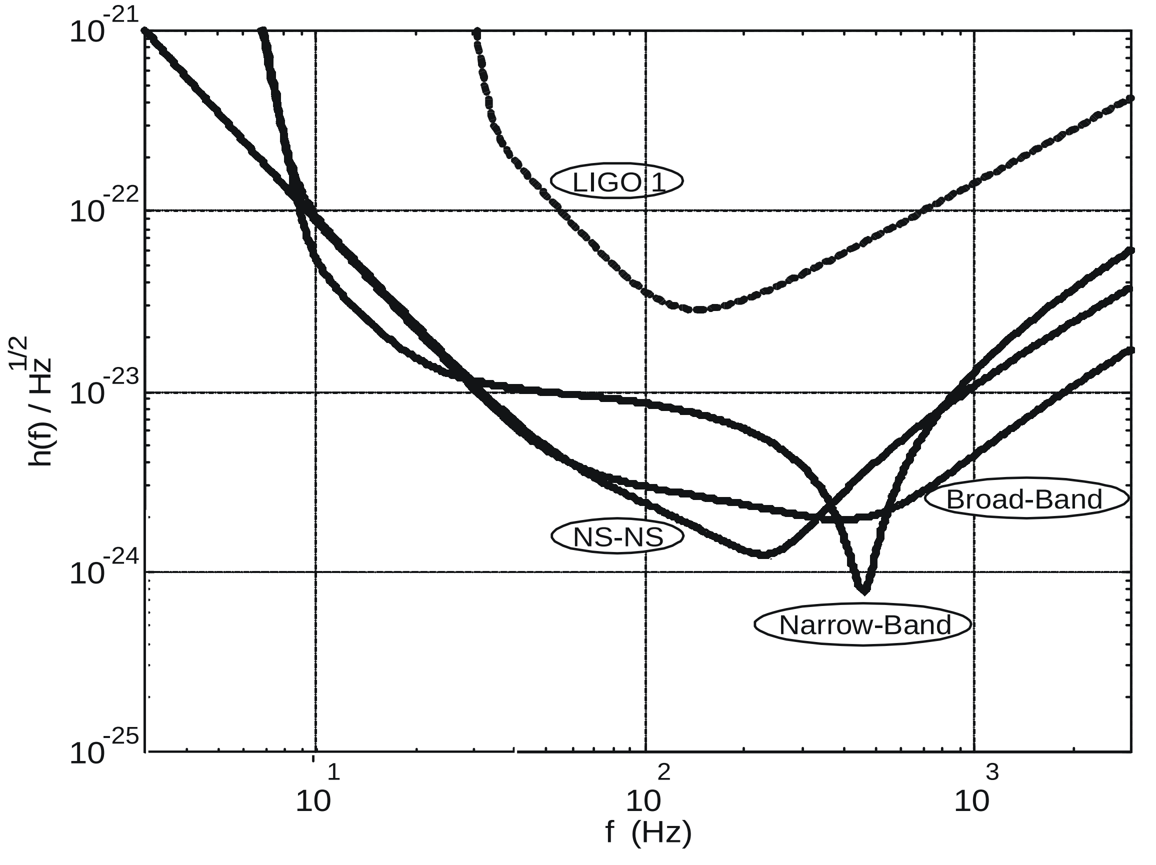
- Seismic isolation testing
- Laser development
- Silica ribbon suspensions
- Sapphire properties
  - Thermal noise
  - Optical absorption



Prototypes

- 40 m interferometer
- Thermal noise interferometer
- LASTI

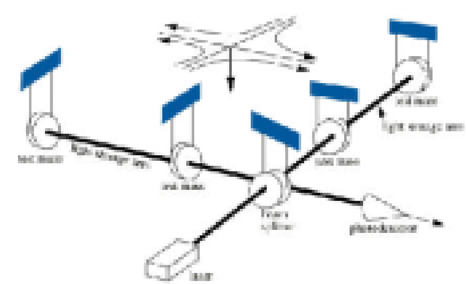
Advanced LIGO
Sensitivity



Signal recycling mirror allows tuning for particular sources

Gravitational wave detection
Current status

- Completing commissioning of initial LIGO
- ~ 10^4 improvement needed in noise
- Plans developing for data analysis
    - Science runs
    - Upper limits with engineering data
- Advanced LIGO R&D progressing
    - Laboratory experiments with technology
    - Prototype development



Gravitational wave detection
Future plans

- Science run with initial LIGO – summer 2002 ?
- Install advanced LIGO ~ 2006
- DETECT GRAVITATIONAL WAVES !!!
    - Possible with initial LIGO
    - Likely with advanced LIGO
- Further upgrades to LIGO – cryoLIGO 2012?
- Space-based interferometers - LISA