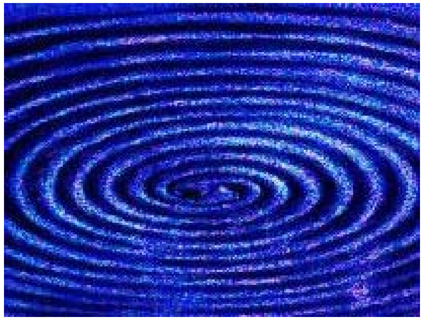
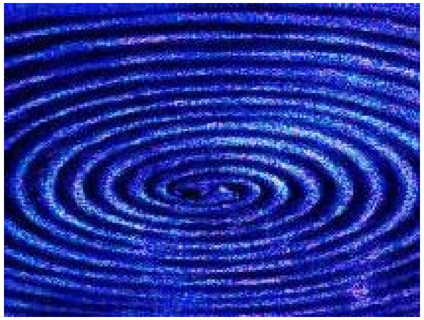


Gravitational Waves and LIGO

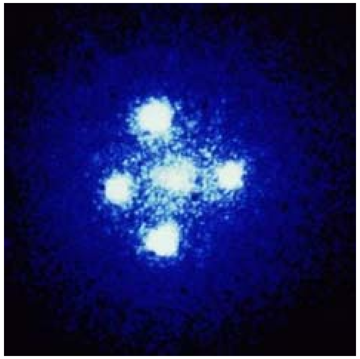
Ray Frey, University of Oregon

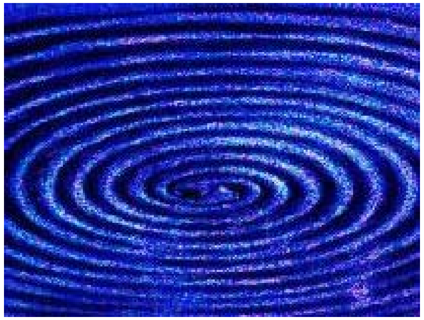
1. GW Physics and Astrophysics
2. How to detect GWs – The experimental challenge
3. Prospects



General Relativity

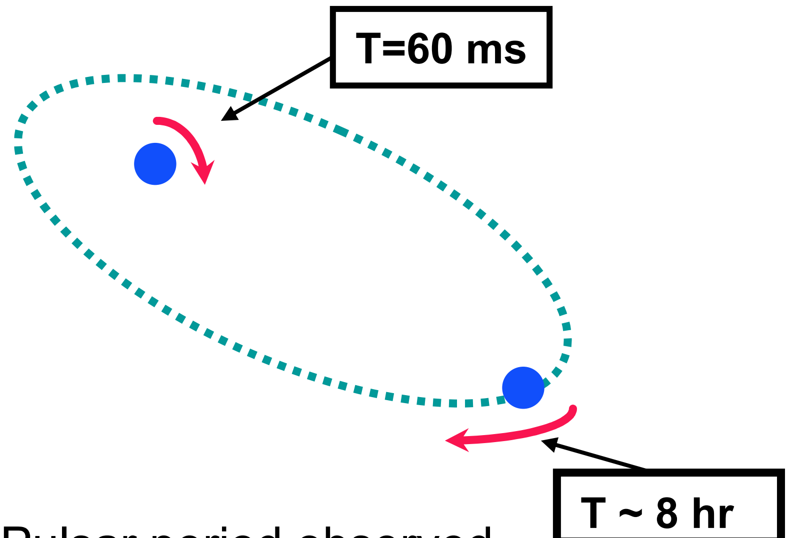
- Some predictions:
  - Gravity influences both mass and energy
    - *e.g.* bending of light in regions with gravitational field
    - 1919 Eddington → Gravitational lensing
  - Many small deviations from Newtonian gravity in "weak" fields
    - Gravitational "redshift" (*e.g.* clocks on satellites are faster)
    - Perihelion advance of mercury
    - Global Positioning System would not work without GR corrections
  - "Strong" field effects
    - Black holes; $R_s = 2GM/c^2$
  - Spacetime structure of universe – evolution of spacetime from Big Bang
  - **And gravitational radiation (gravitational waves) "Ripples in spacetime"**
    - Propagation at c; two polarization states (+,x)





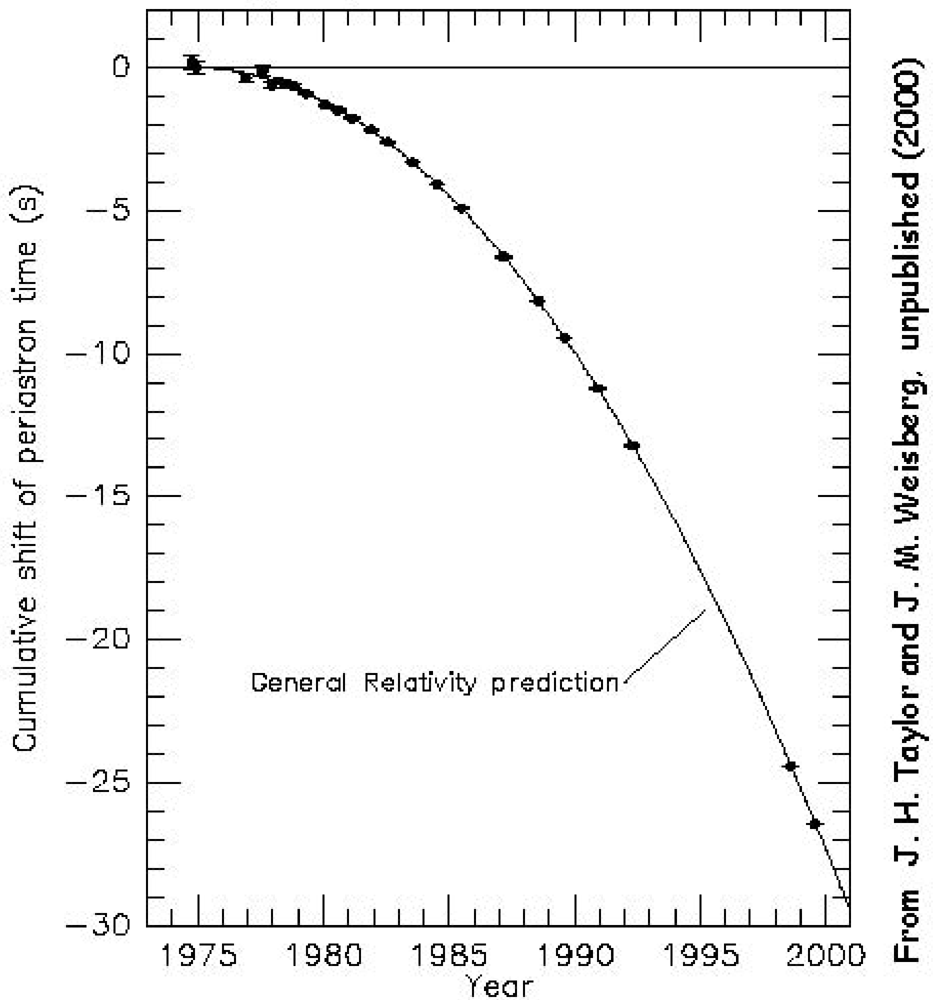
Evidence for Gravitational Waves

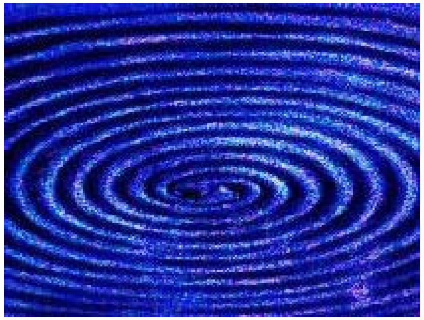
PSR 1913+16 Binary n-star system



Pulsar period observed over 25 years

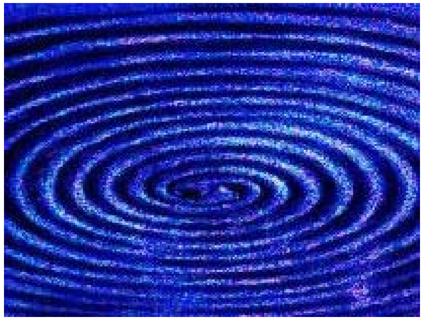
– Taylor and Hulse





GW Science

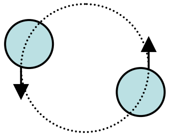
- Goals:
  - Establish GW detection – test General Relativity
  - Use GW as an astrophysical tool
- Unexplored territory!
  - GW revolution like radio astronomy?



GW Sources

- GW emission requires time varying quadrupole moment of mass distribution
- Strain estimate:

$$h \sim \left(\frac{GM}{c^2}\right)\left(\frac{v^2}{c^2}\right)\frac{1}{r}$$

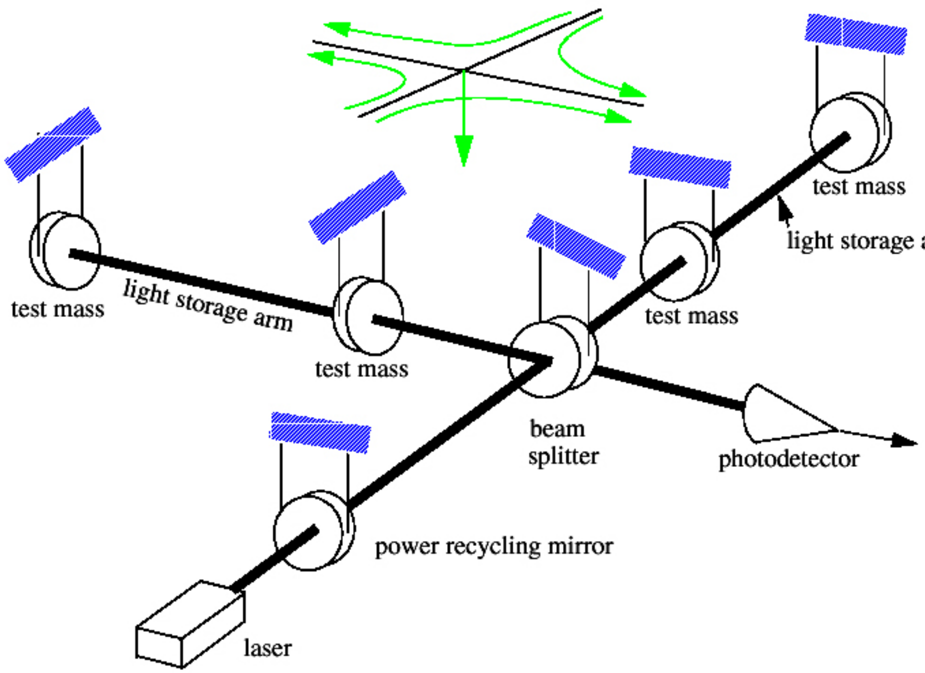


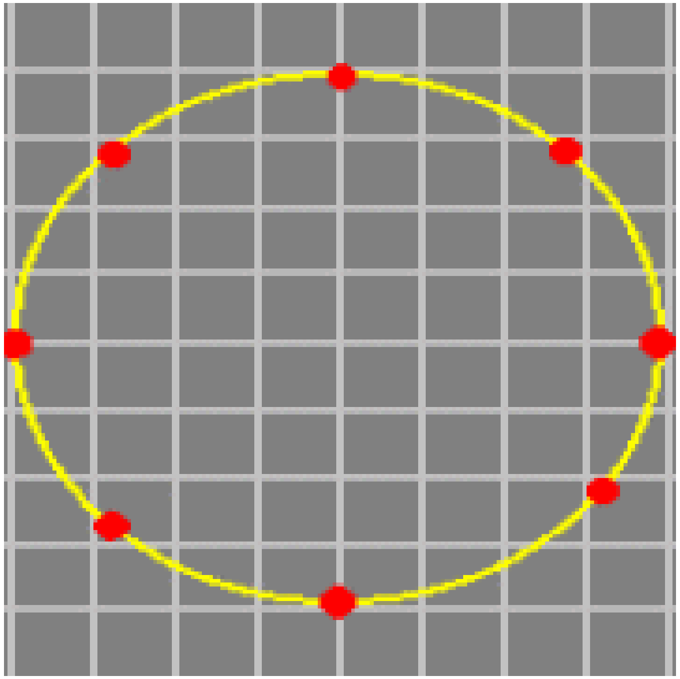
For $1M_\odot \Rightarrow R_s = 2GM_\odot/c^2 = 3$ km

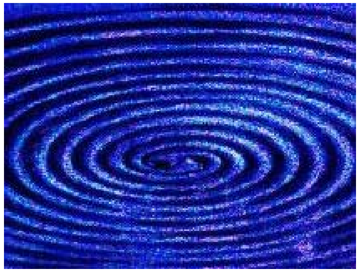
If $v \approx c$, then at $r = 15$ Mpc:

$$h \sim 3 \times 10^{-21}$$

GW Interferometer Principle



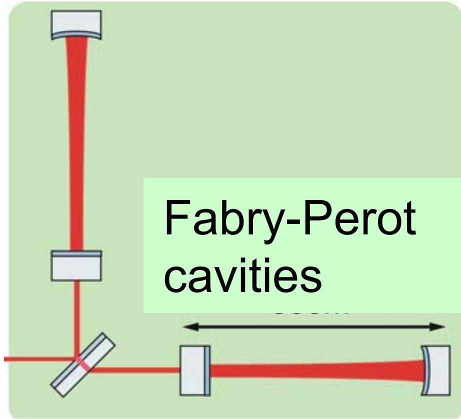




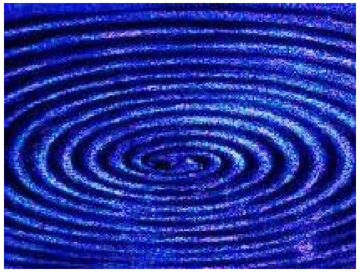
Interferometer sensitivity

- **Strain due to space-time warpage: $h = \delta L / L$**
  - **For $h \approx 10^{-21}$ and $L \approx 1$ km, then $\delta L \approx 10^{-18}$ m**
- **Change in light travel time (one bounce): $\delta t = 2\,\delta L/c = 2hL/c$**
- **Gives change in phase $\delta\Phi = 2\pi f\,\delta t = 4\pi Lh / \lambda$**
  - **$L \approx 100 \times 1$ km**
  - **$\lambda = 1$ μm**
  - **Let $h \approx 10^{-21}$**

$\Rightarrow \delta\Phi \approx 10^{-9}$ rad

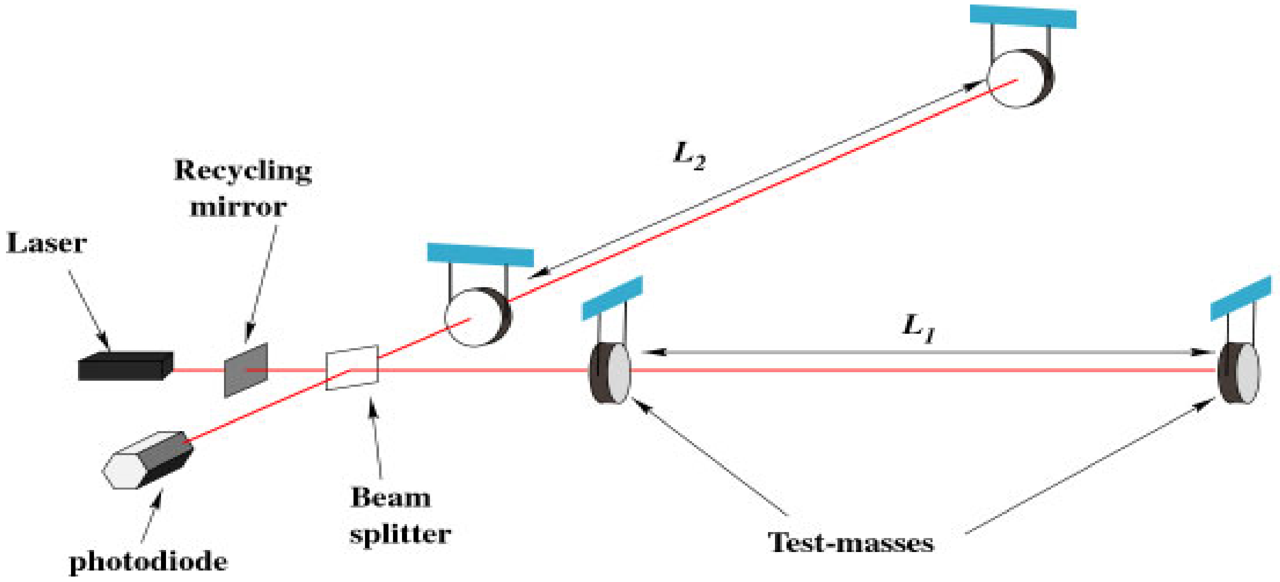


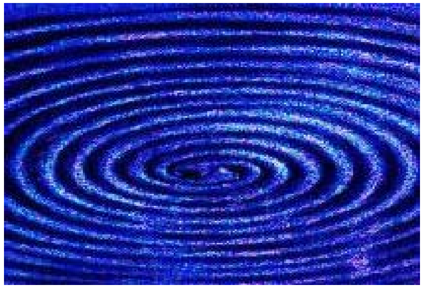
- $\delta\Phi \approx 10^{-7}$ is commonplace
- **Need to improve by factor 100; and in a large system**



Interferometer parameters

- Long baseline ~1 km
- Cavity storage time ~1 ms (~100 bounces)
- High laser power
  - Power recycling (x30)
  - Few watts in; few kW in arms

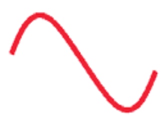




How small is 10^{-18} m ?

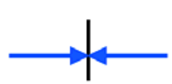
One meter, about 40 inches

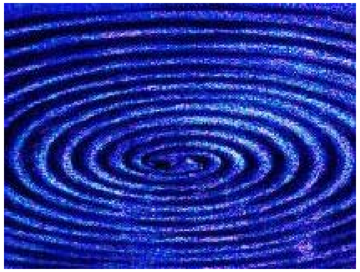
÷10,000  *Human hair, about 100 microns*

÷100  *Wavelength of light, about 1 micron*

÷10,000  *Atomic diameter, 10^{-10} meter*

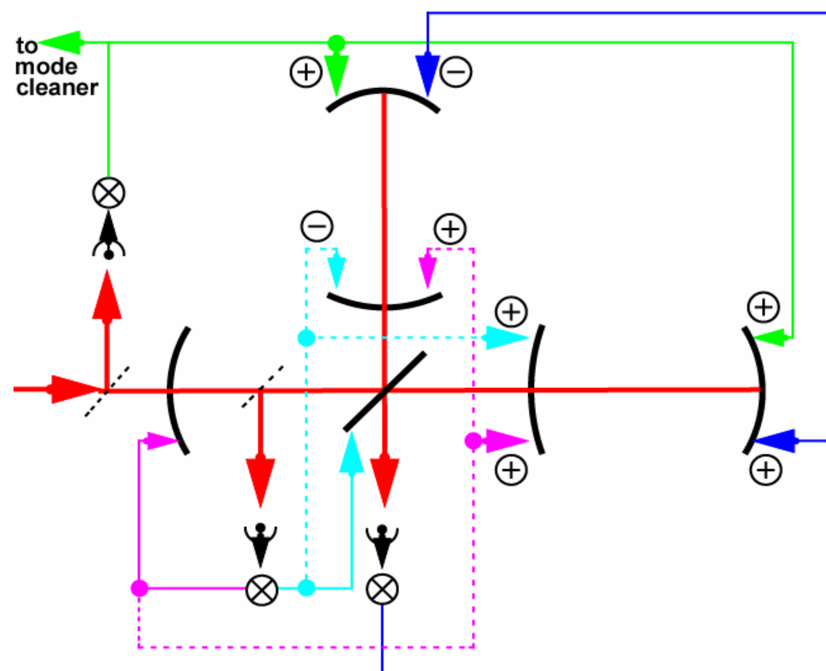
÷100,000  *Nuclear diameter, 10^{-15} meter*

÷1,000  *LIGO sensitivity, 10^{-18} meter*



Experimental features

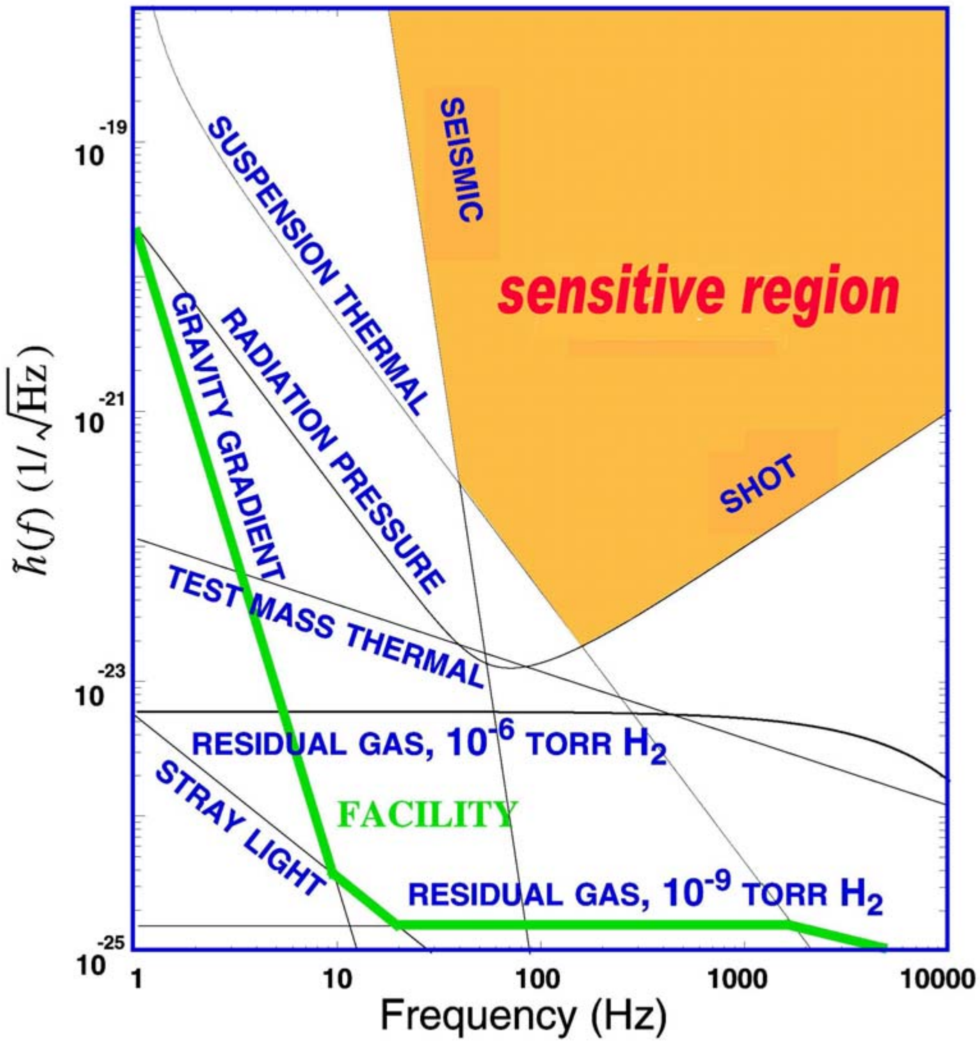
- Extensive use of servo loops
- Null measurements
  - dark fringe kept centered on photodiode
- RF heterodyne measurement of $\delta\Phi$
- Power recycling
- Isolation and monitoring of environment



LIGO length control system

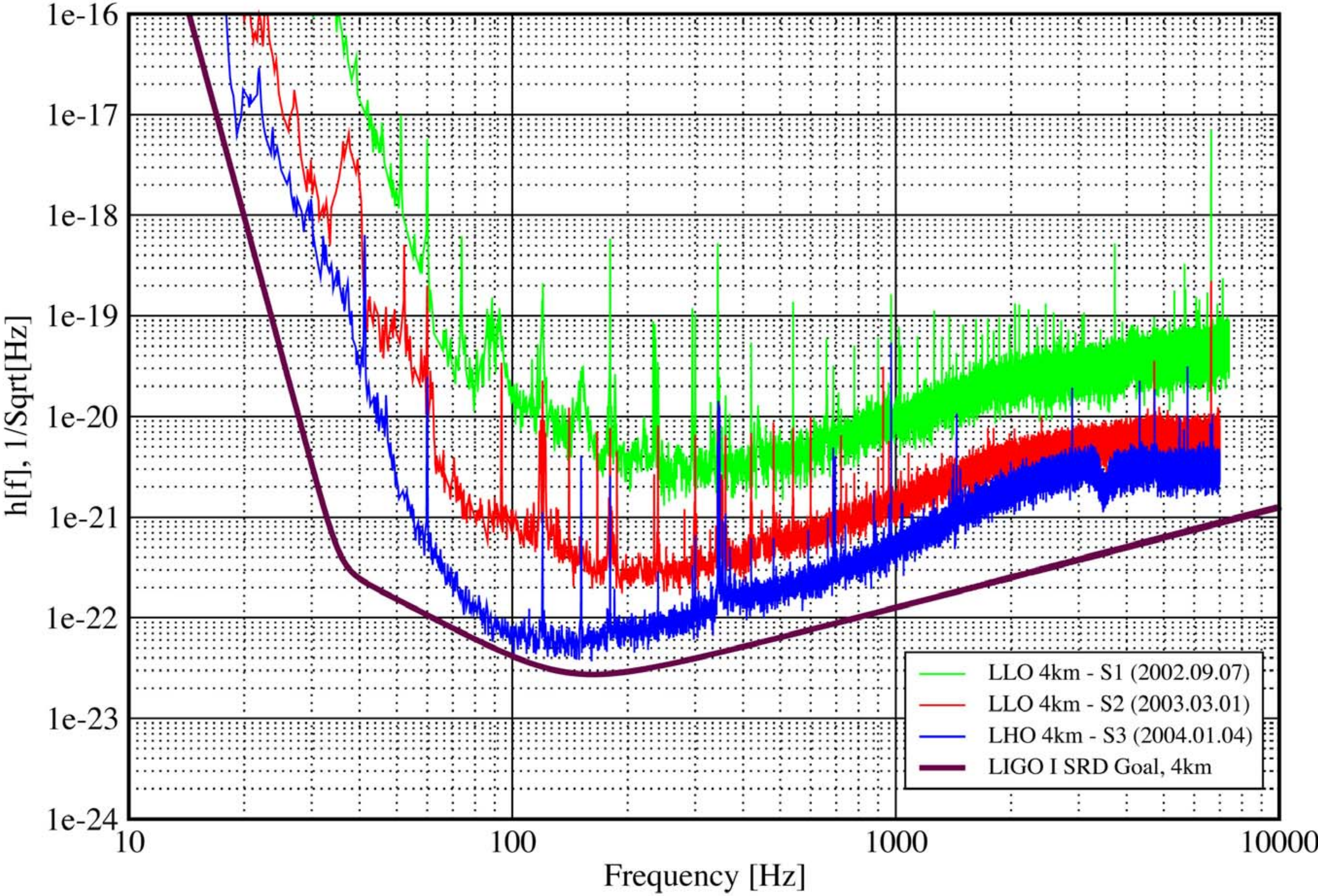
What Limits Sensitivity of Interferometers?

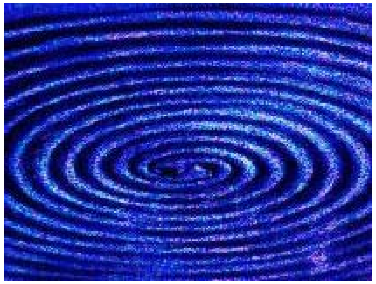
- Seismic noise & vibration limit at low frequencies
- Thermal noise of suspensions and test masses
- Quantum nature of light (Shot Noise) limits at high frequencies
- Limitations of facilities much lower (LIGO)



Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1, S2, S3   LIGO-G030548-02-E

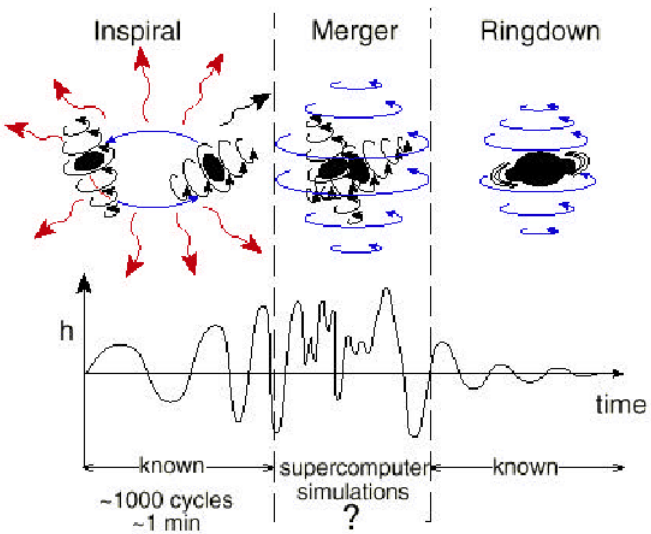


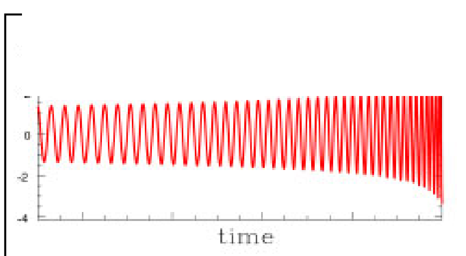


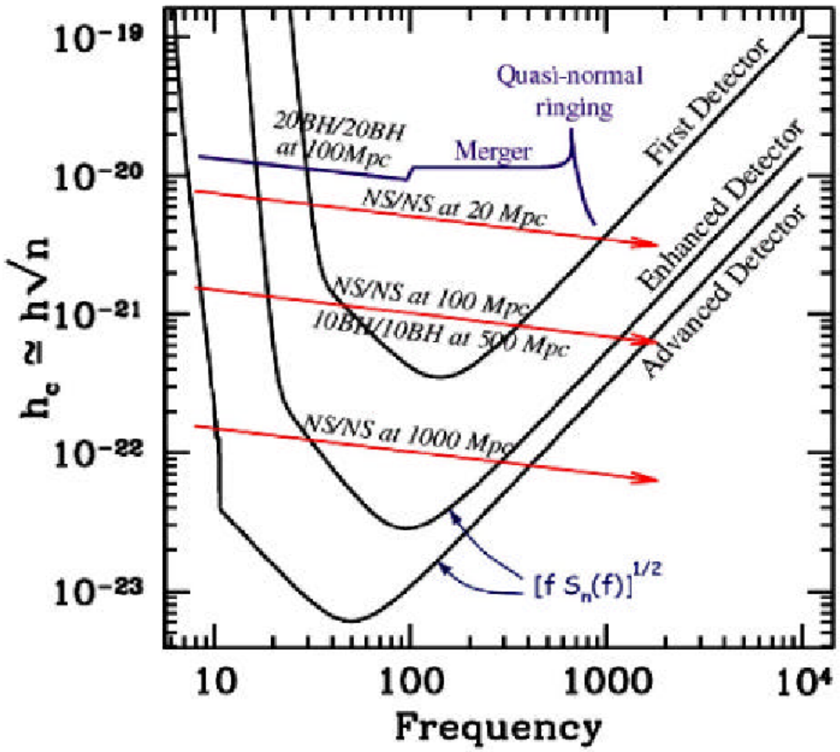
Inspiral sensitivity

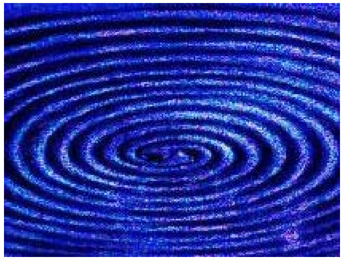
LIGO sensitivity to coalescing binaries

Compact binary mergers



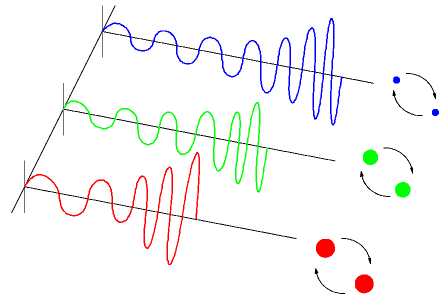




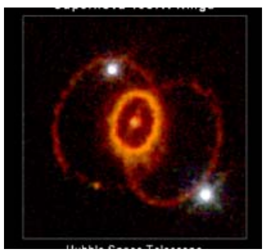


Astrophysical signal types

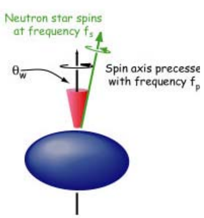
- Compact binary inspiral: *"chirps"*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



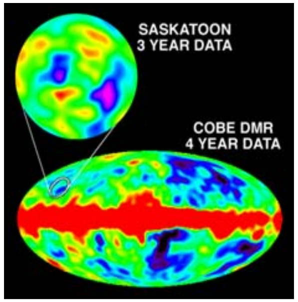
- Supernovae / GRBs: *"bursts"*
  - "unmodelled" search
  - triggered search: coincidence with photon or neutrino detections



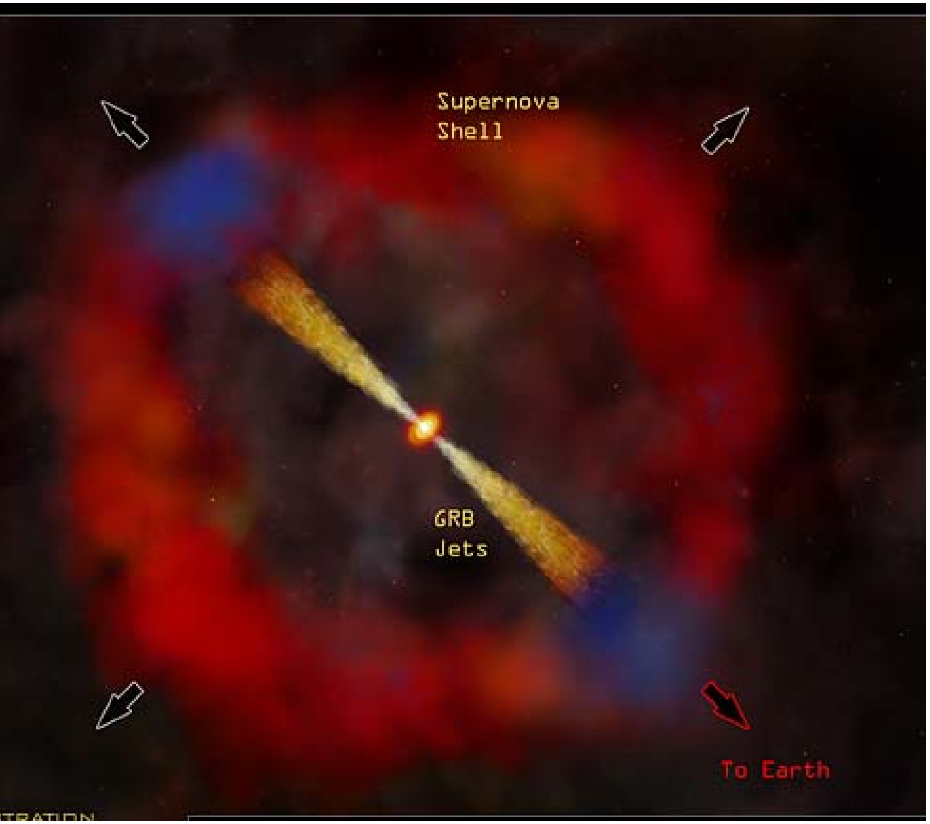
- Pulsars in our galaxy: *"periodic"*
  - observe known neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes



- Cosmological Signals *"stochastic background"*



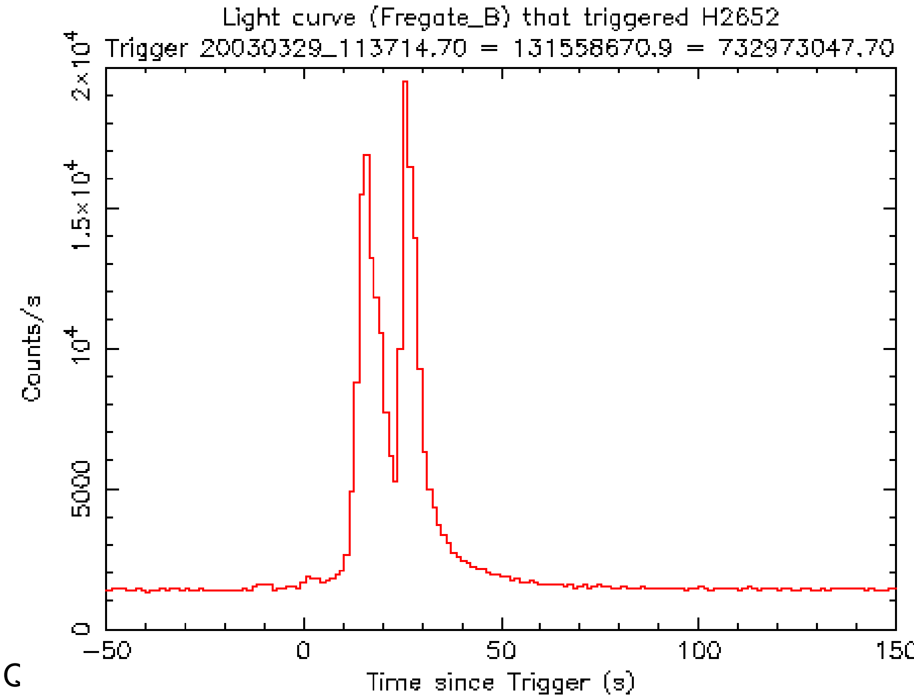
Gamma Ray Bursts

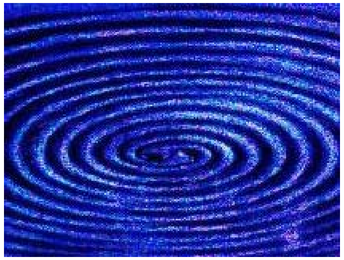


Source: GSFC

GRB030329

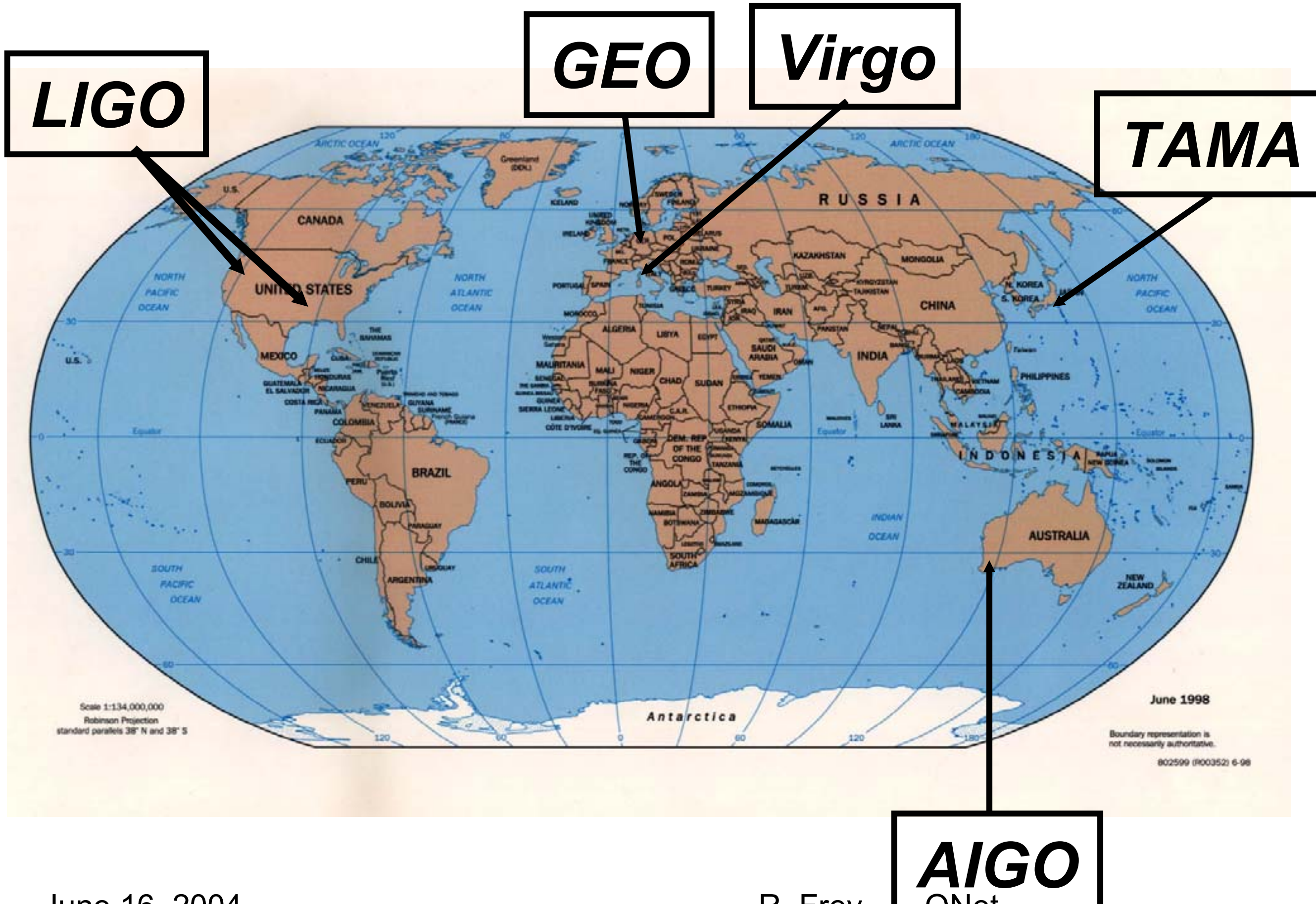
Gamma-ray lightcurve from the HETE-2 spacecraft





An International Network of Interferometers

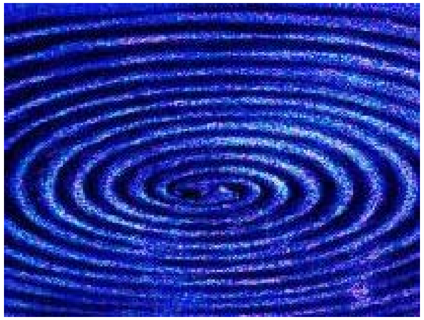
Simultaneously detect signal (within msec)



detection confidence

locate the sources

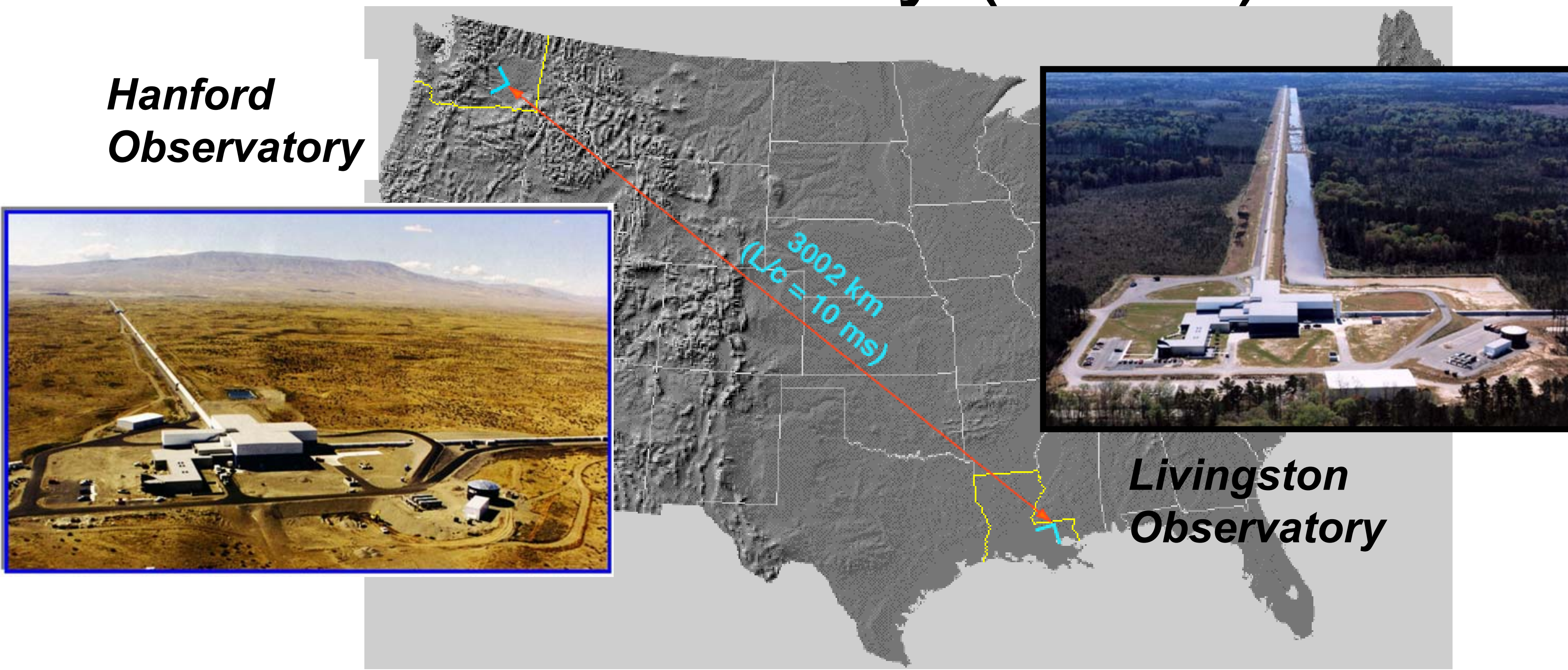
decompose the polarization of gravitational waves



Status of detectors

- LIGO: 2 sites, L=4km
  - Science running interleaved with planned improvements
  - S1 analyses and papers completed (upper limits)
  - S2 and S3 analyses being completed
- VIRGO: L=3km
  - Commissioning full interferometer
  - Advanced suspensions
- GEO: L=0.6km
  - Run with LIGO S1, S3, … (improvements interleaved)
  - Advanced suspensions
- TAMA: L=0.3km
  - Run with LIGO S2, S3, …
- AIGO: R&D facility

Laser Interferometer Gravitational-wave Observatory (LIGO)



Vacuum equipment – corner station

Optic

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5 x 10^{-7}

Internal mode Q's > 2 x 10^{6}

Polishing

Surface uniformity < 1 nm rms

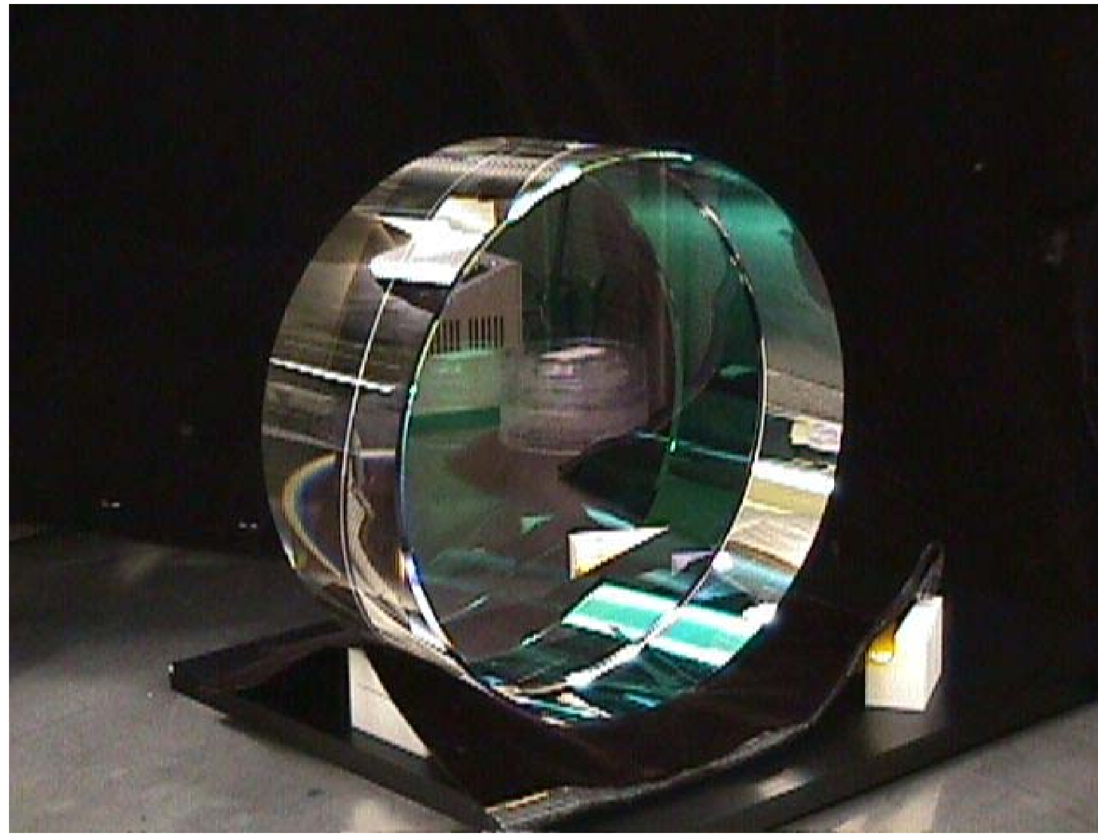
Radii of curvature matched < 3%

Coating

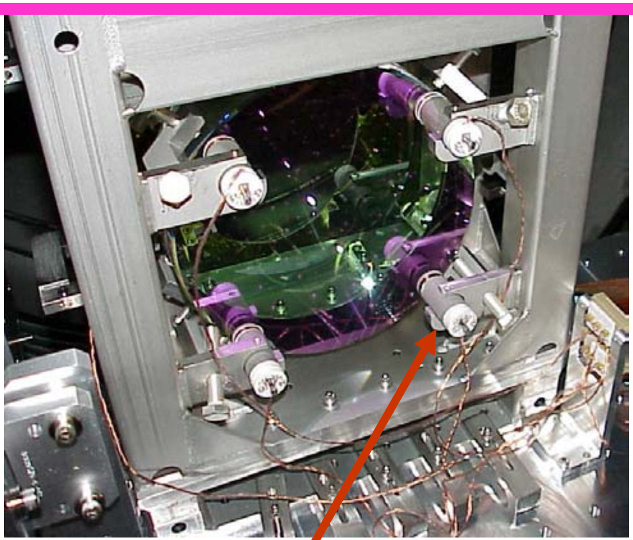
Scatter < 50 ppm

Absorption < 2 ppm

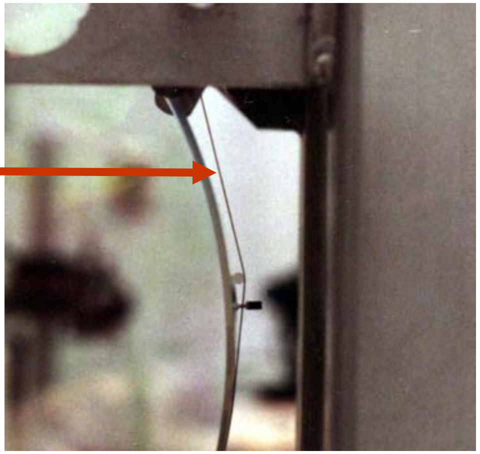
Uniformity <10^{-3}



Core Optics Suspension and Control



Optics suspended as simple pendulums

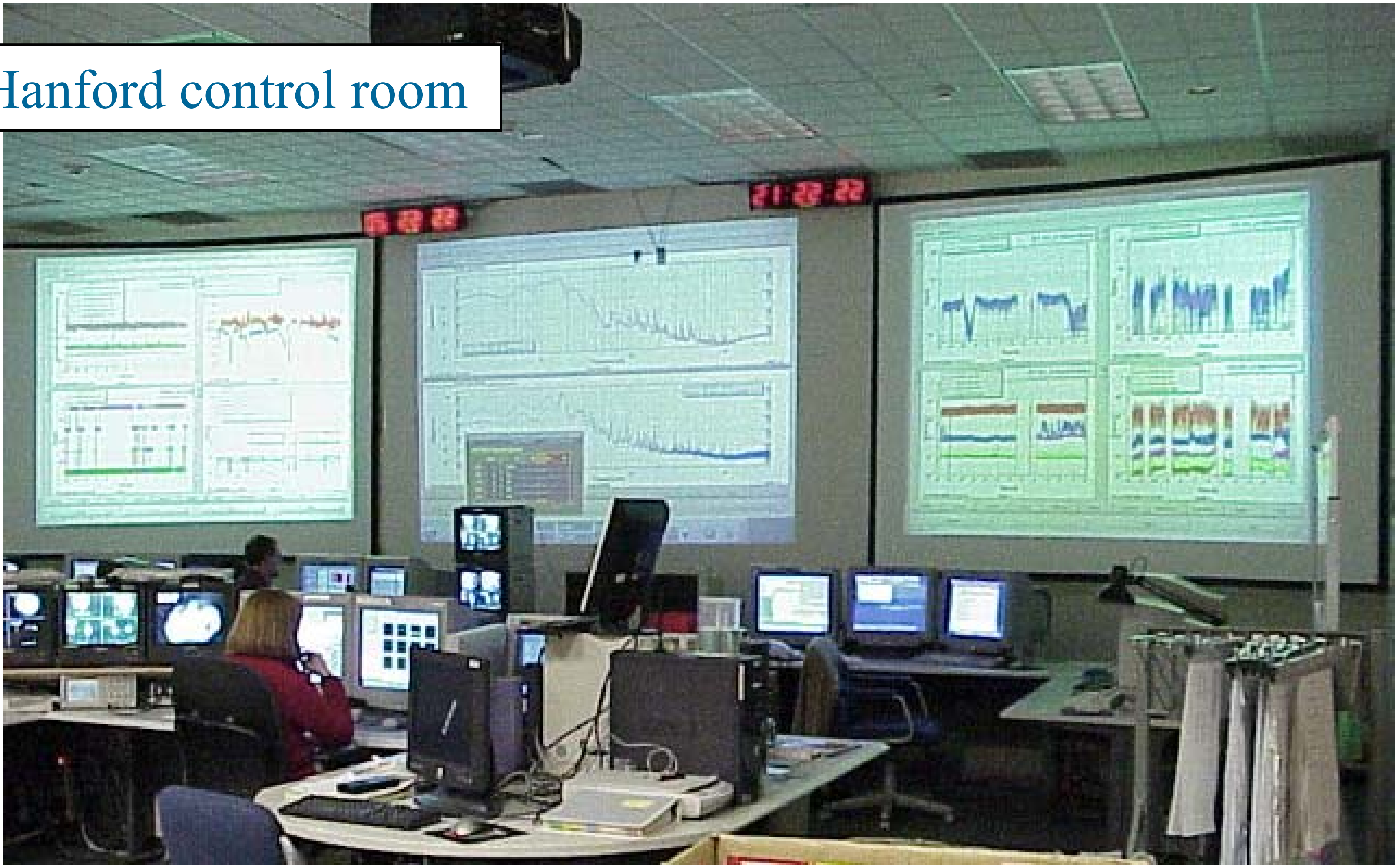


Shadow sensors & coil actuators provide damping and control forces

Mirror is balanced on 30 micron diameter wire to 1/100th degree of arc

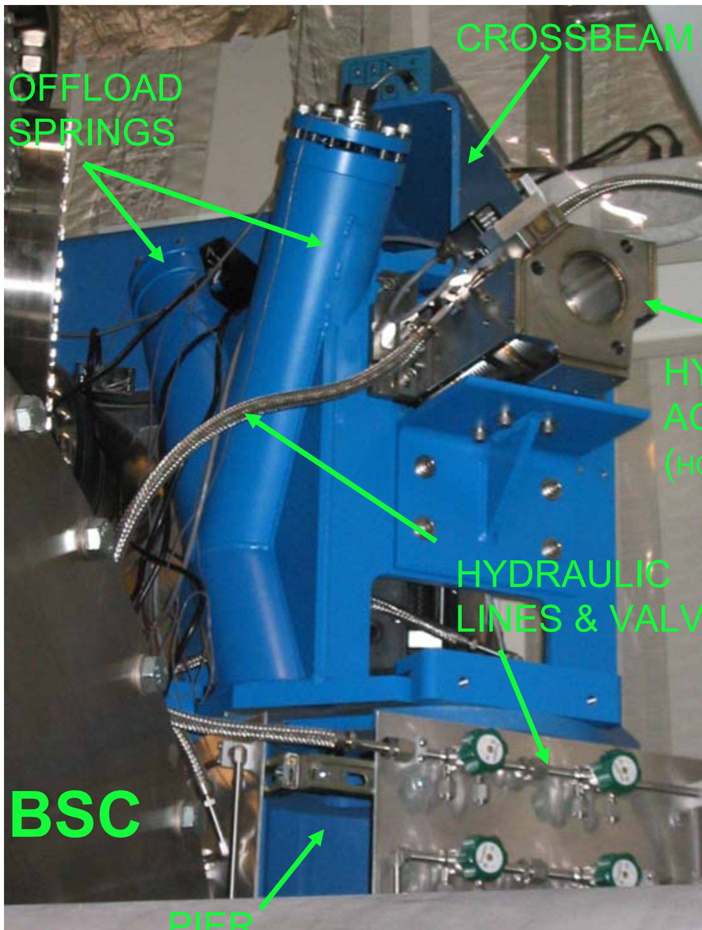
Science Running

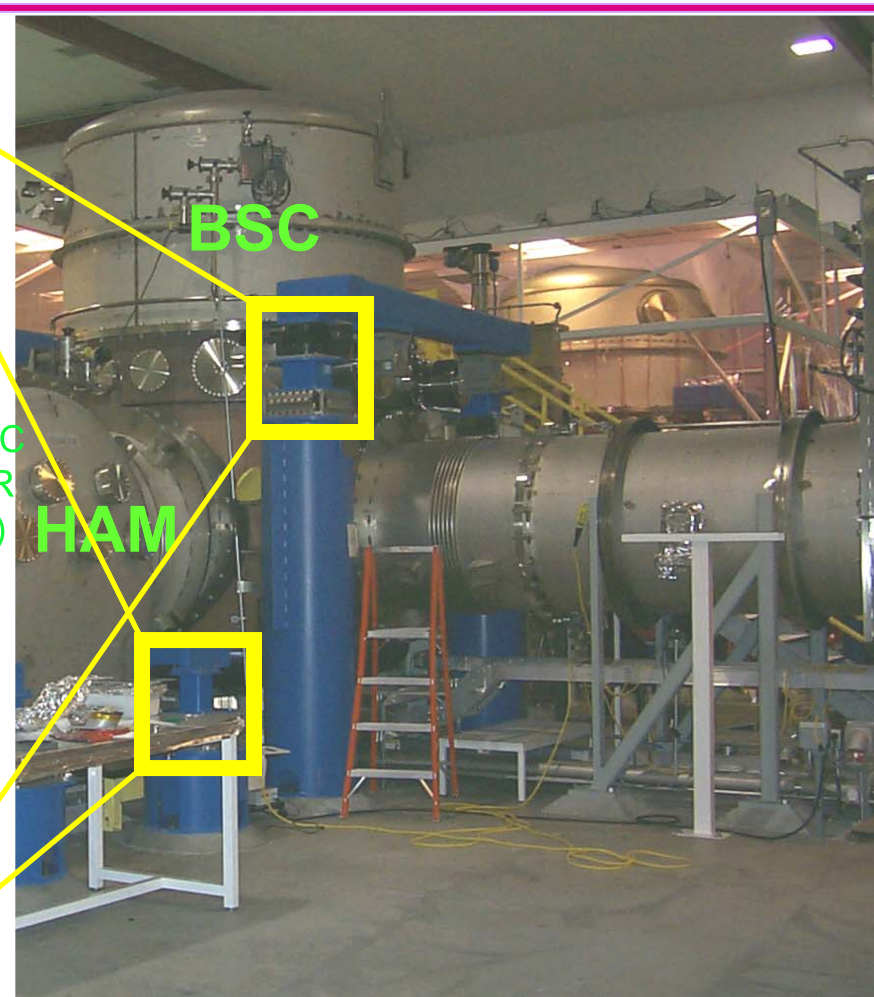
Hanford control room

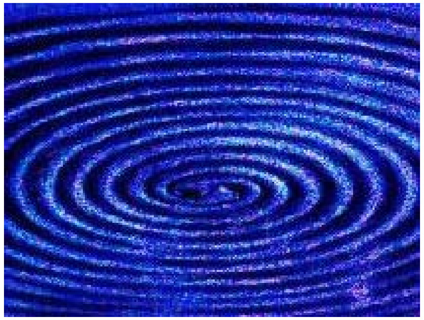


Active Seismic Isolation

Hydraulic External Pre-Isolator (HEPI)

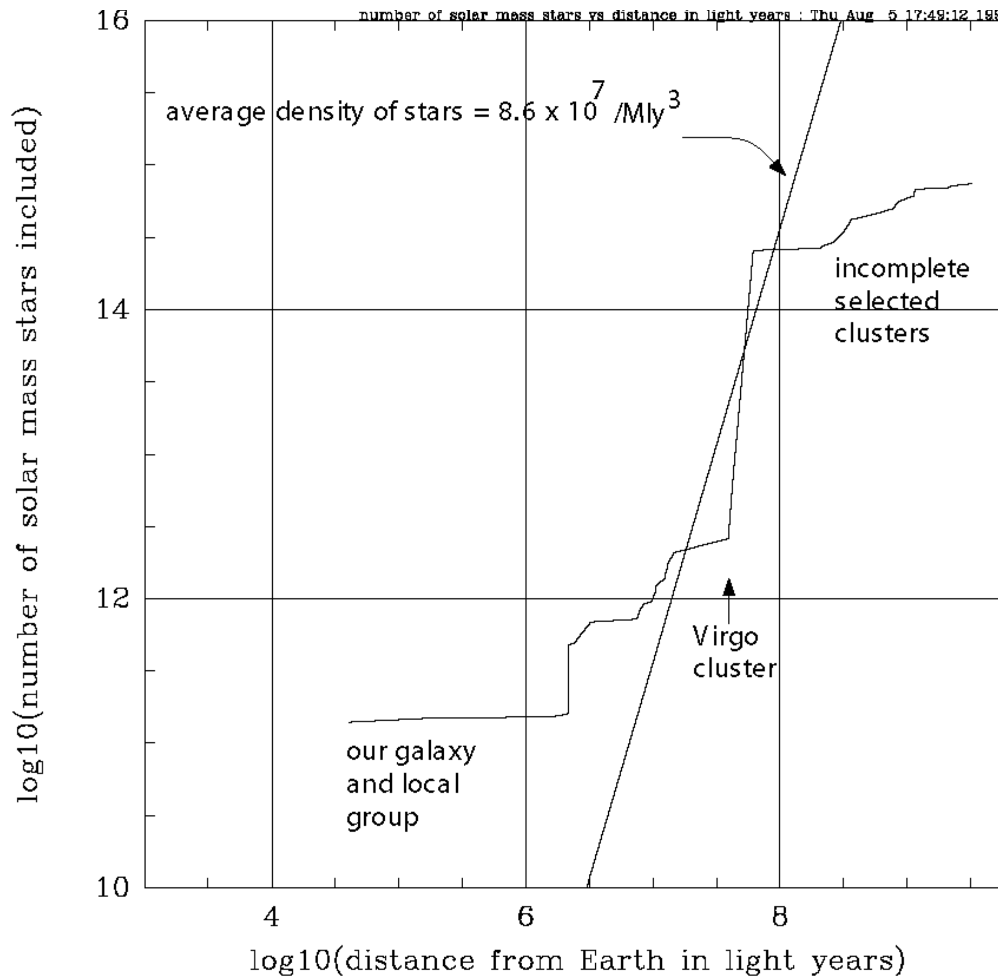






The need for improved sensitivity

- Probe the Virgo cluster and beyond
- Sample cosmologically located sources (eg GRBs) with good statistics
- Advanced LIGO will increase observed space by 10^4



DATA: Cosmology of the Local Group G.Lake
Astrophysical Quantities C.W. Allen

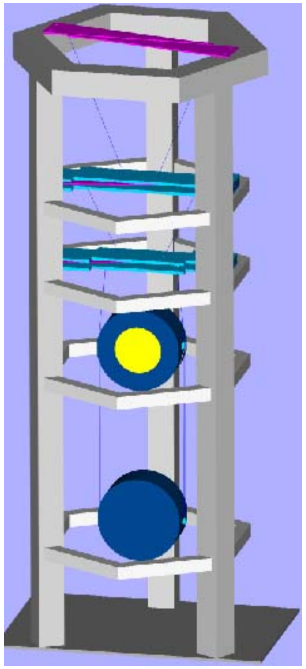
June 16, 2004

Advanced LIGO

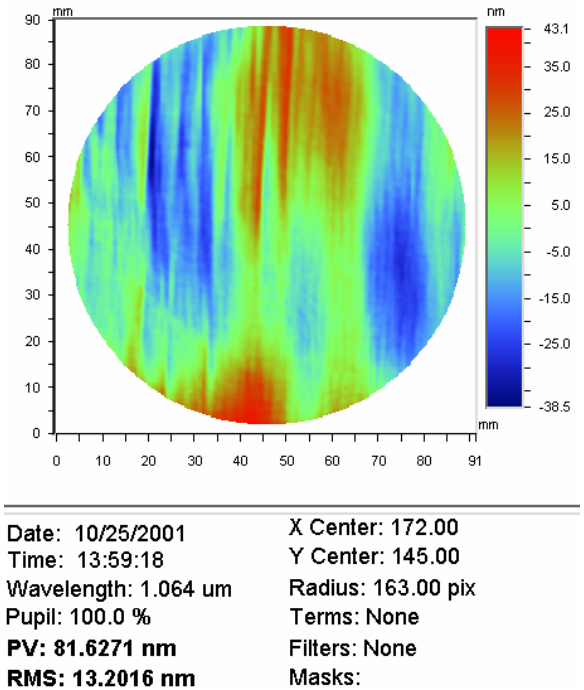
improved subsystems

Multiple Suspensions

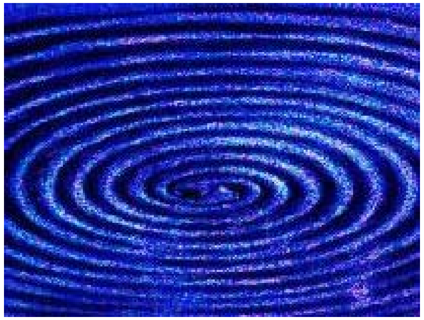
Active Seismic



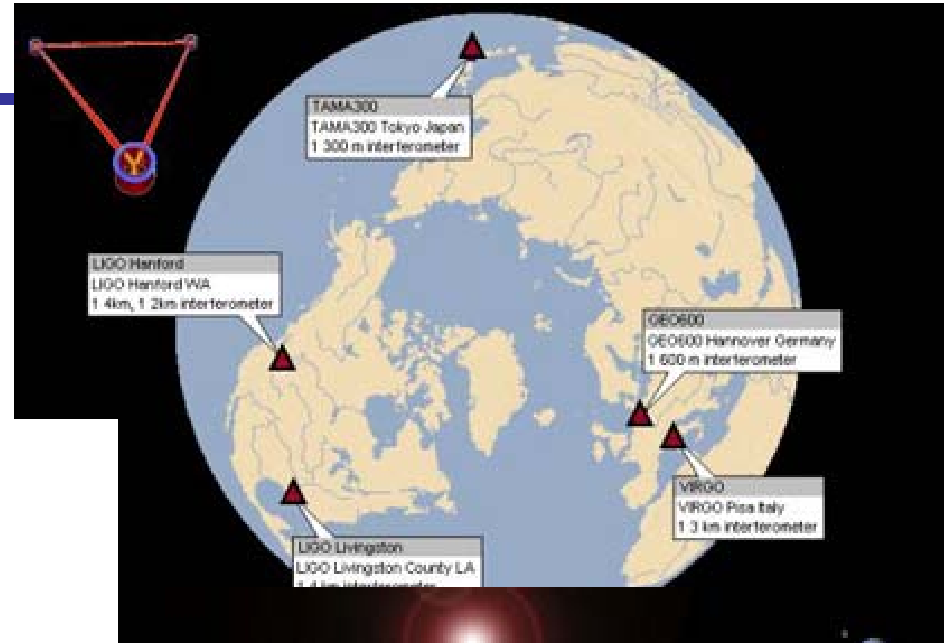
Sapphire Optics



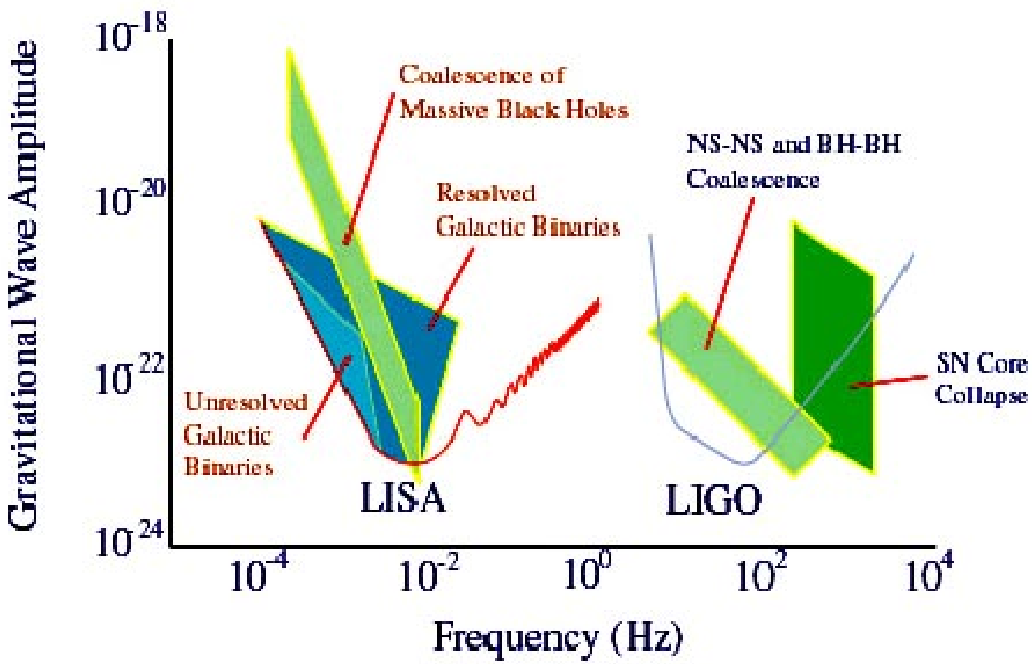
Higher Power Laser



LISA: Interferometers in space



- Can probe low-frequency sources



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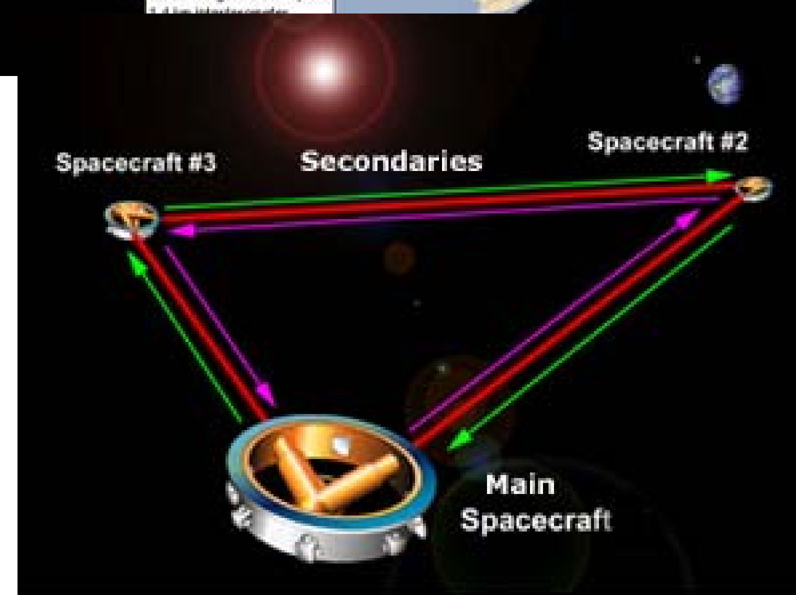
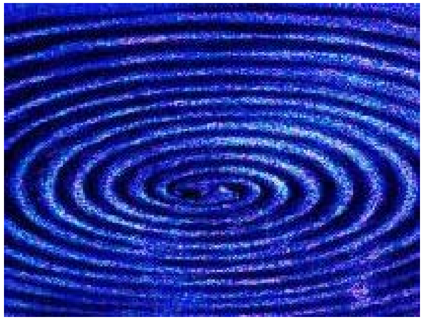
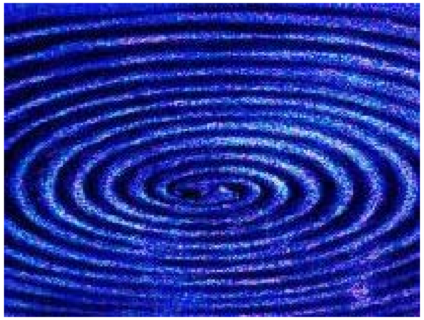




Prospects

- First GW discoveries ??
- Advanced LIGO
  - Plan: Start shutdown for installation ~2007
- Maturation of the field of GW astronomy ??
- LISA



Summary

- Goals:
  - Establish gravitational wave detection – test General Relativity
  - Use GW as an astrophysical tool
- New generation of ground-based GW interferometric detectors turning on well
  - approaching design sensitivity
  - Impressive technological achievement
- Science Running has started
  - GW physics and astrophysics
  - Capable now of seeing sources outside our local group of galaxies
- Major upgrades planned