Gearing Up for Gravitational Waves: Commissioning LIGO

Reported on behalf of LIGO colleagues by

Fred Raab,

LIGO Hanford Observatory

LIGO-G020224-00-W

Laser Interferometer Gravitational-wave Observatory

LIGO Mission: To sense the distortions of spacetime, known as gravitational waves, created by cosmic cataclysms and to exploit this new sense for astrophysical studies

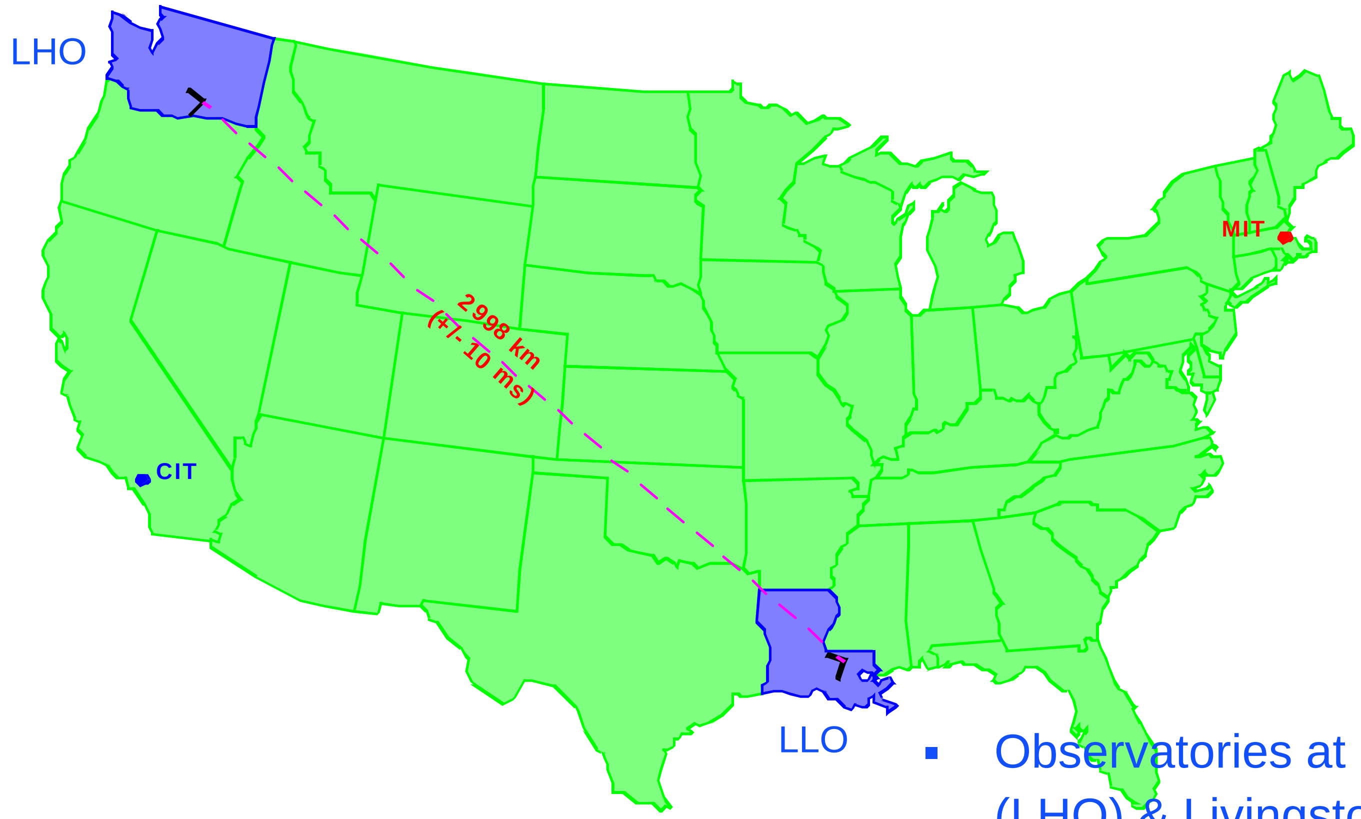
In other words: If the last 400 years of astronomy were about “seeing” a silent movie of the universe, then LIGO hopes to deliver the “sound track” using observatories that function like large terrestrial microphones.

Aerial Views of LIGO Facilities

LIGO Hanford Observatory
(LHO)

LIGO Livingston Observatory
(LLO)

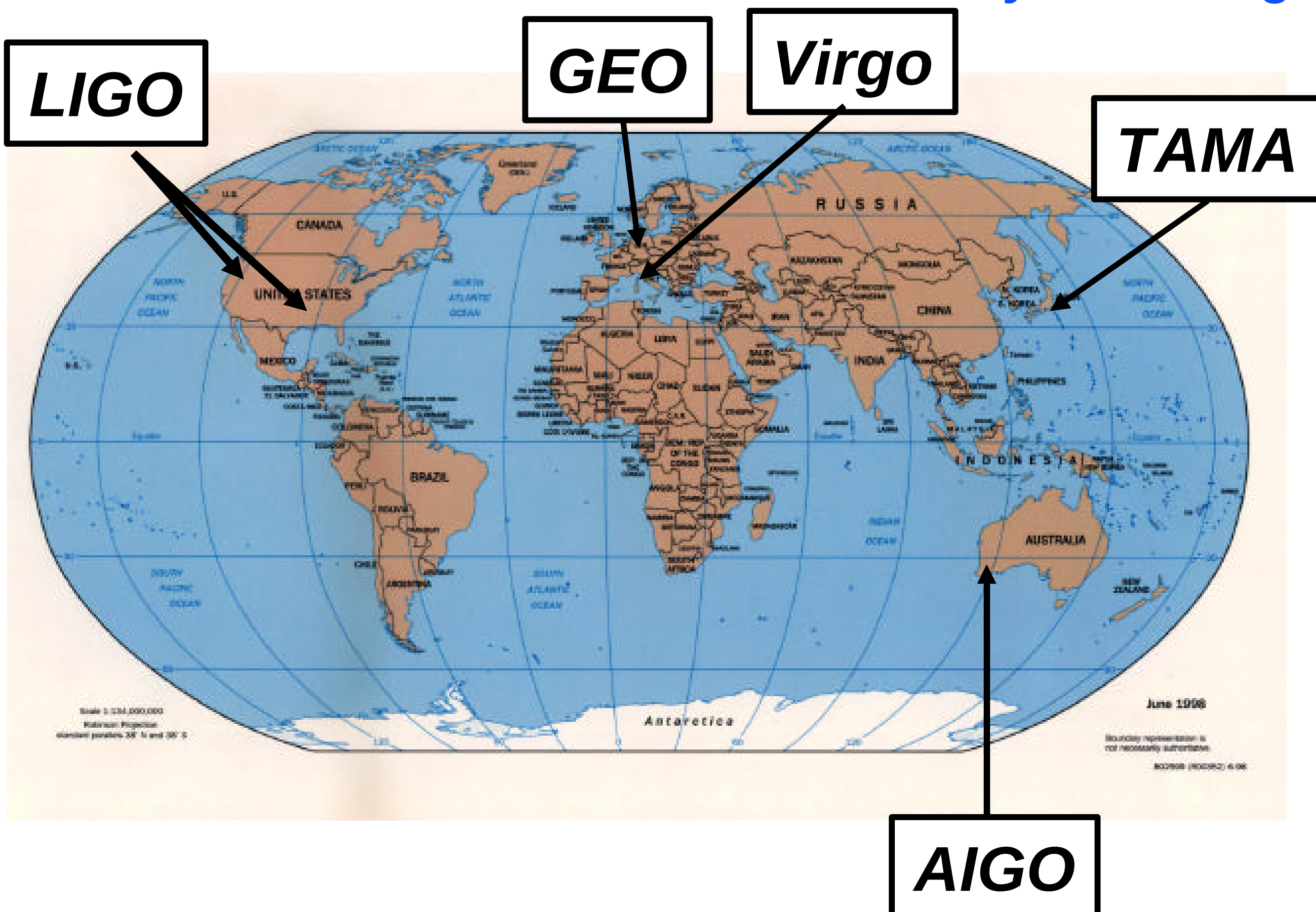
The Four Corners of the LIGO Laboratory



- Observatories at Hanford, WA (LHO) & Livingston, LA (LLO)
- Support Facilities @ Caltech & MIT campuses

Part of Future International GW Detector Network

Simultaneously detect signal (within msec)



detection confidence

locate the sources

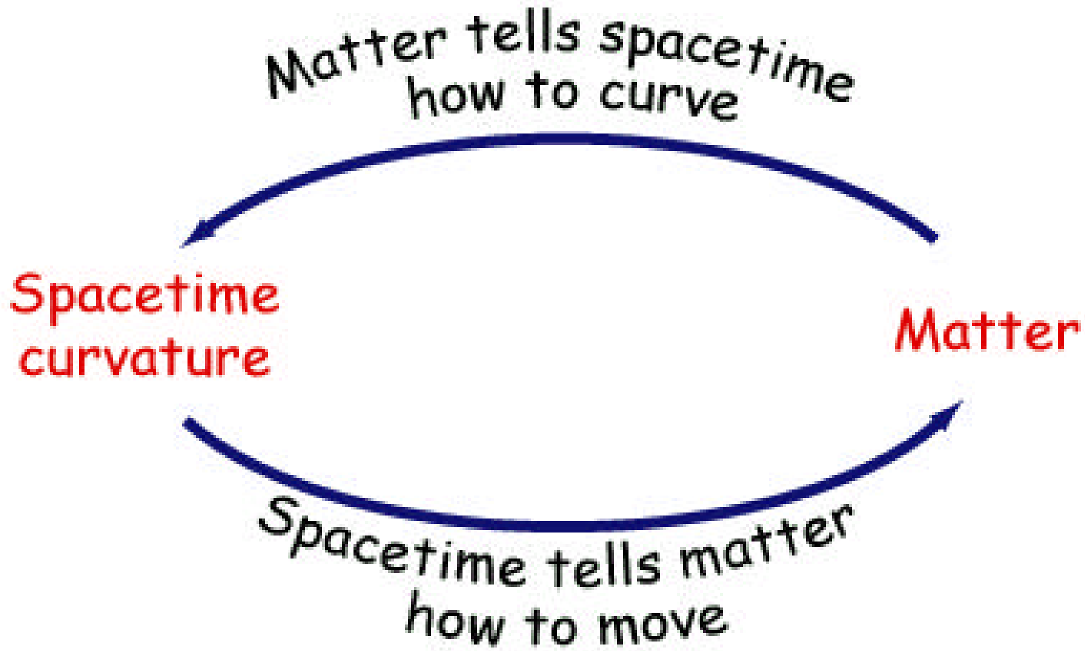
decompose the polarization of gravitational waves

LIGO Laboratory & Science Collaboration

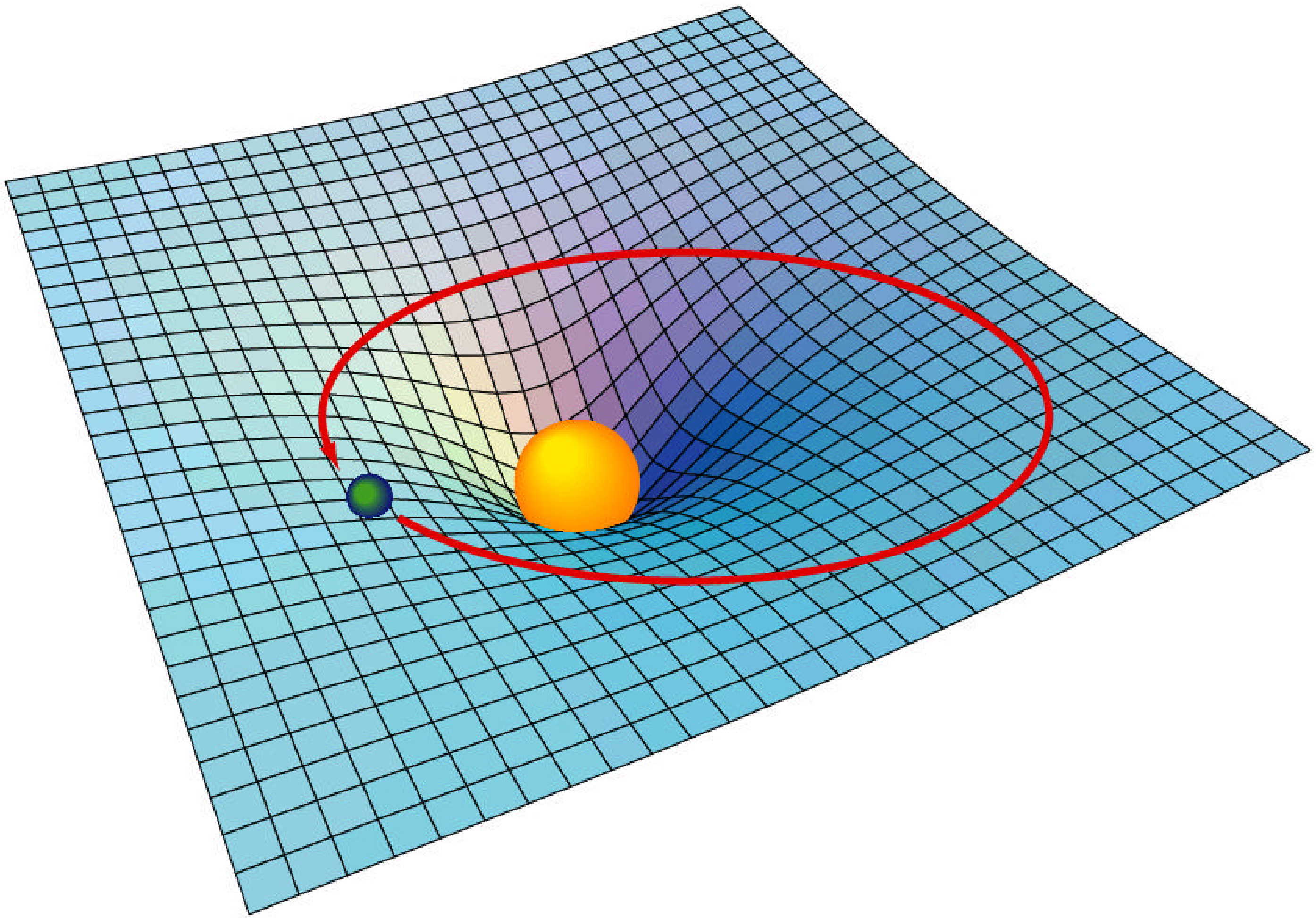
- LIGO Laboratory (Caltech/MIT) runs observatories and research/support facilities at Caltech/MIT
- LIGO Science Collaboration is the body that defines and pursues LIGO science goals
  - » >300 members worldwide (including LIGO Lab personnel)
  - » Includes GEO600 members & data sharing
  - » Working groups in detector technology advancement, detector characterization and astrophysical analyses
  - » Memoranda of understanding define duties and access to LIGO data

WSU is newest collaboration member institution

John Wheeler's Summary of General Relativity Theory

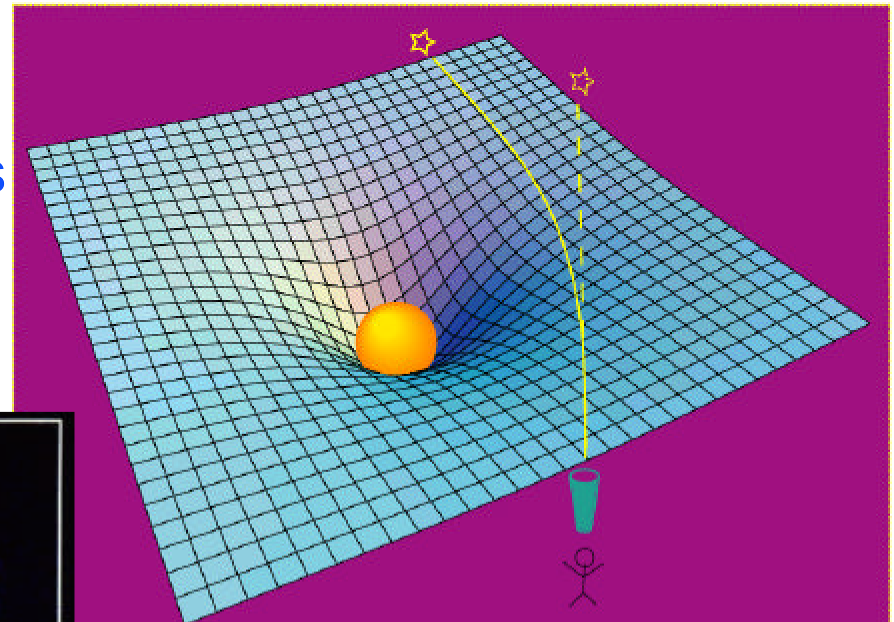


General Relativity: A Picture Worth a Thousand Words



Statics of Spacetime: A New Wrinkle on Equivalence

Not only the path of matter, but even the path of light is affected by gravity from massive objects



A massive object shifts apparent position of a star

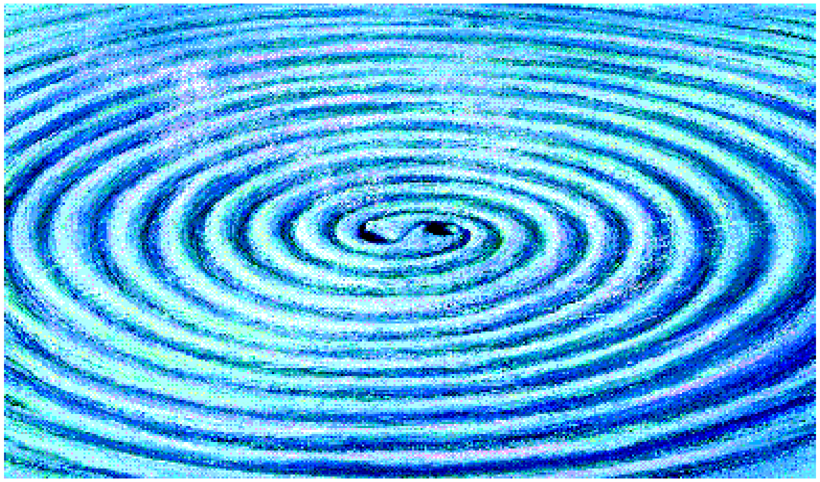
Einstein Cross

Photo credit: NASA and ESA

Dynamics of Spacetime: Gravitational Waves

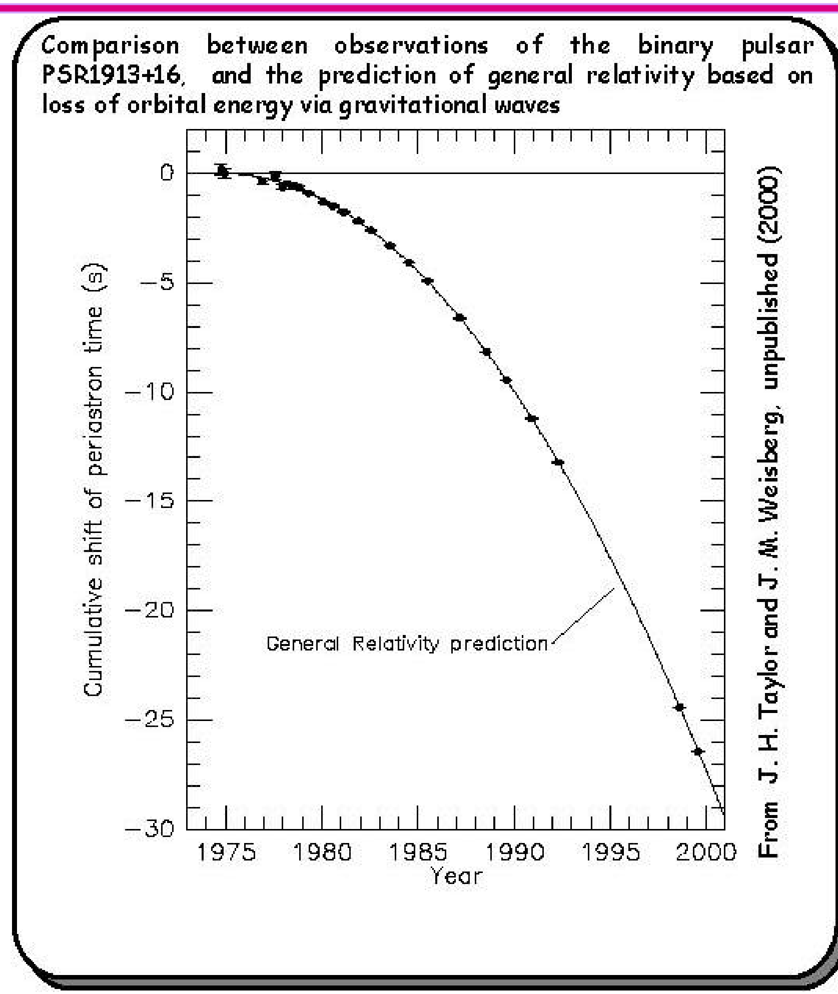
Gravitational waves are ripples in space when it is stirred up by rapid motions of large concentrations of matter or energy; they move at the speed of light

Rendering of space stirred by two orbiting black holes:



Detection of Energy Loss Caused By Gravitational Radiation

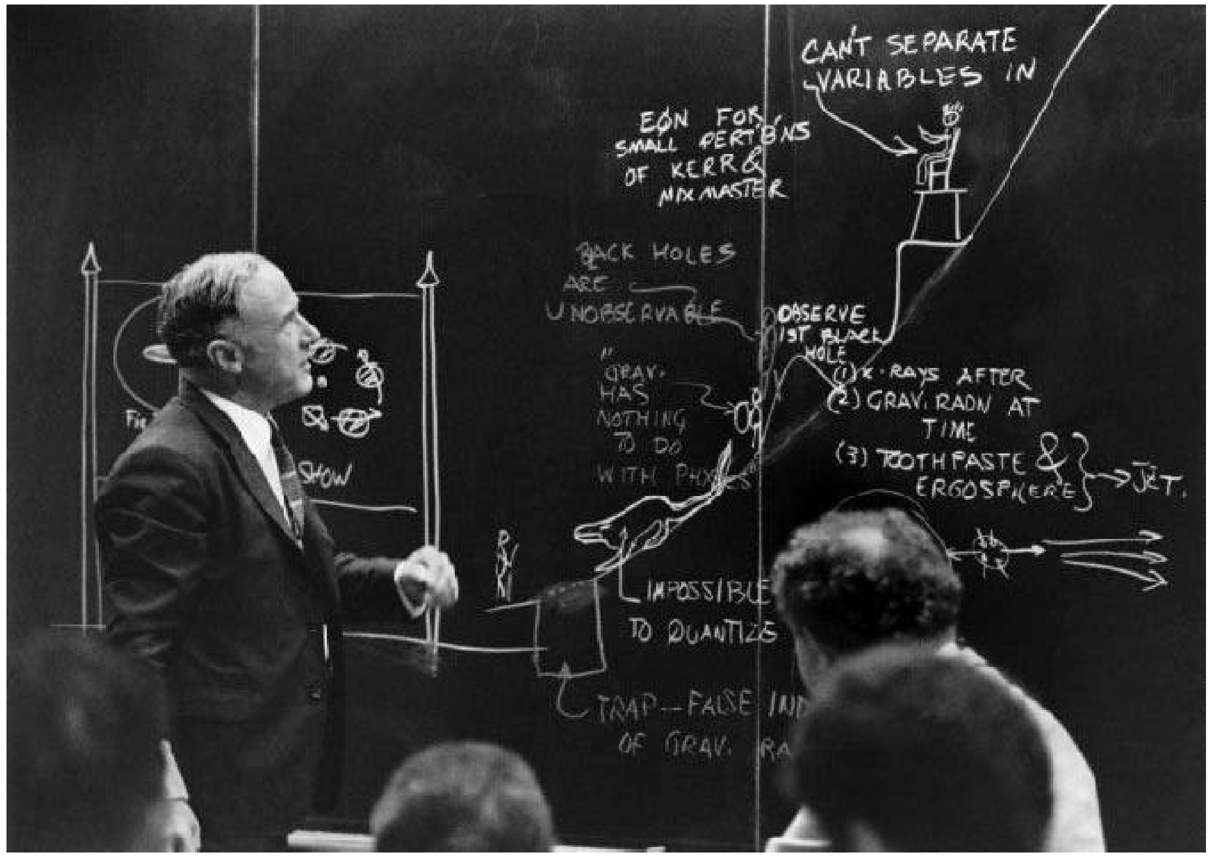
- In 1974, J. Taylor and R. Hulse discovered a pulsar orbiting a companion neutron star. This "binary pulsar" provides some of the best tests of General Relativity. Theory predicts the orbital period of 8 hours should change as energy is carried away by gravitational waves.
- Taylor and Hulse were awarded the 1993 Nobel Prize for Physics for this work.



Gravitational Collapse and Its Outcomes Present Opportunities

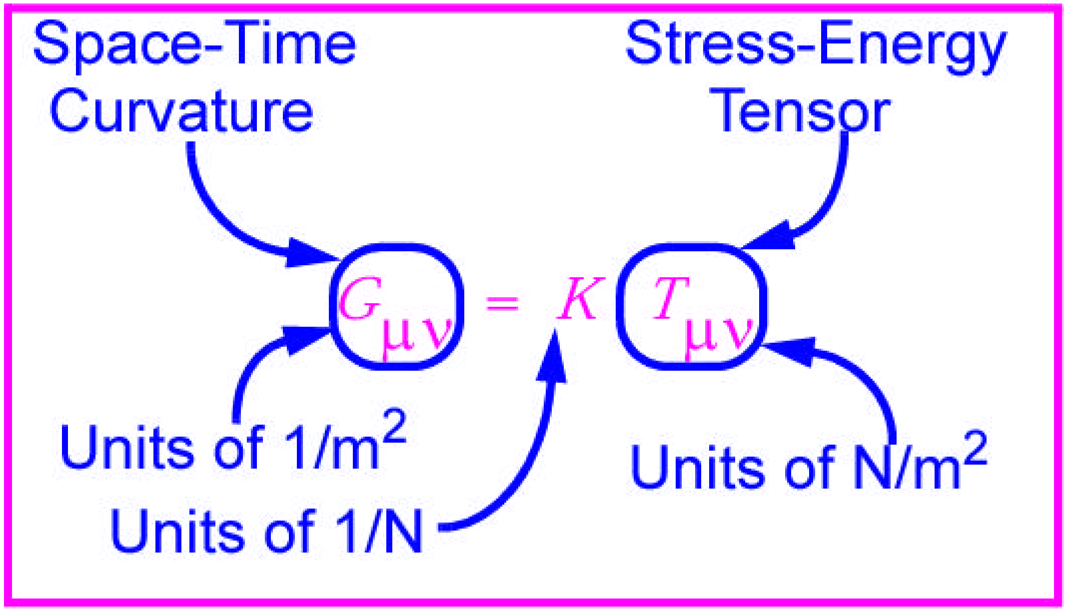
f_{GW} > few Hz accessible from earth

f_{GW} < several kHz interesting for compact objects



Photograph by Robert Matthews, Courtesy of Princeton University (1971)

Spacetime is Stiff!



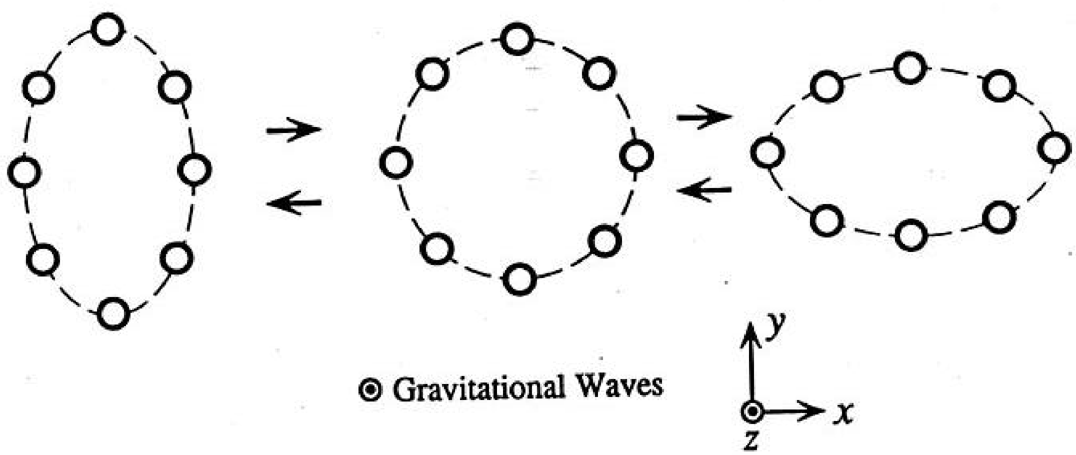
- $K \sim [G/c^4]$ is lowest order combination of G, c with units of 1/N

=> Wave can carry huge energy with miniscule amplitude!

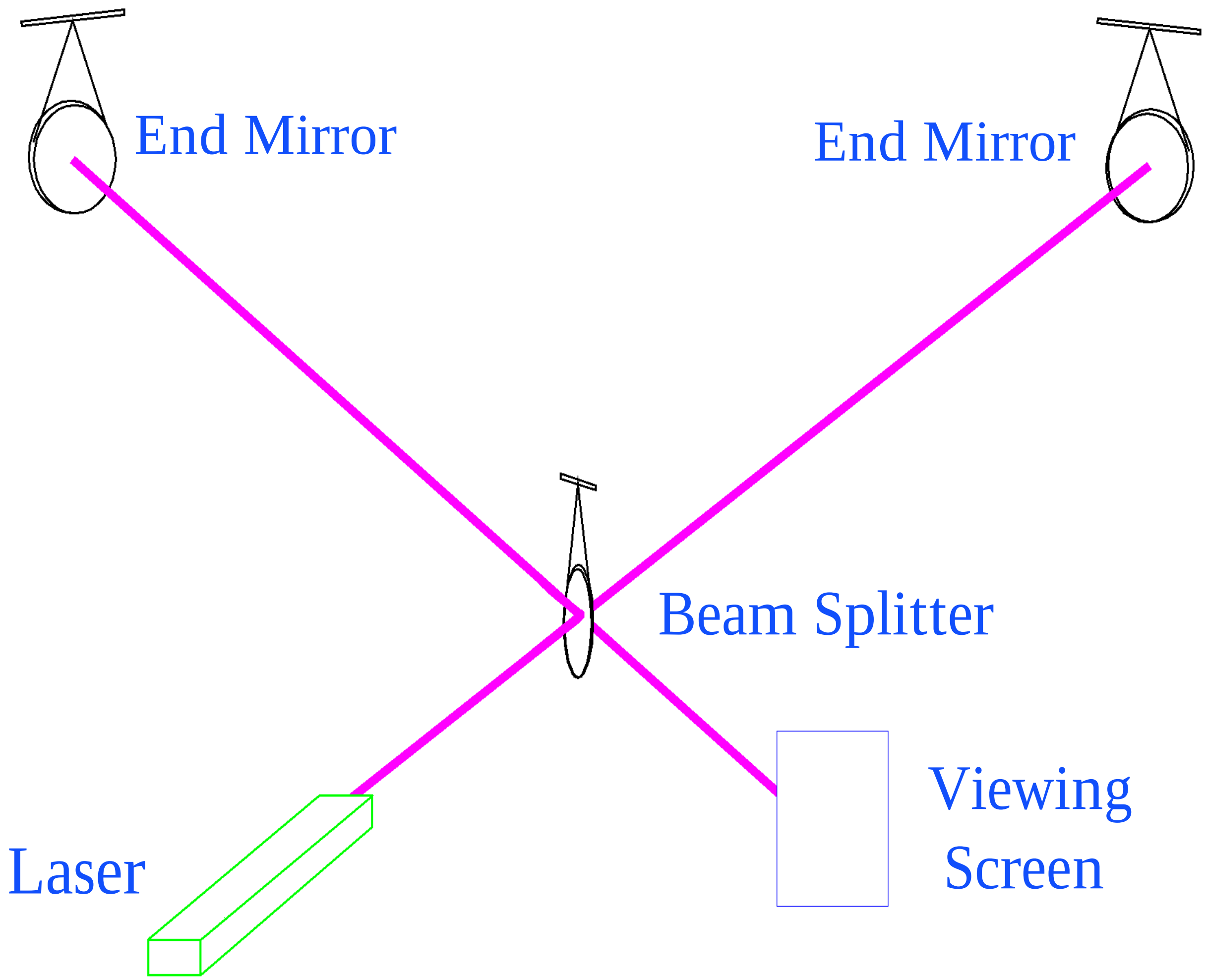
$$h \sim (G/c^4)\,(E_{NS}/r)$$

Important Signature of Gravitational Waves

Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.

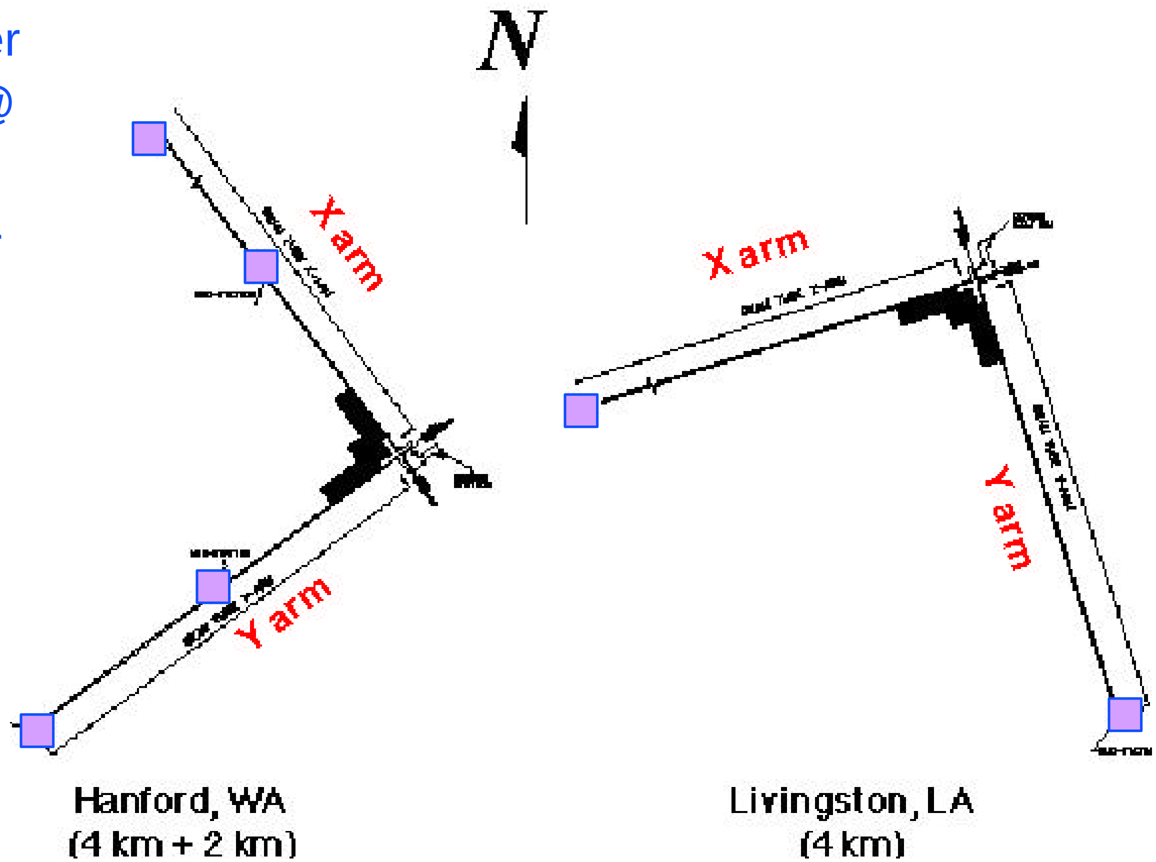


Sketch of a Michelson Interferometer



Configuration of LIGO Observatories

- 2-km & 4-km laser interferometers @ Hanford
- Single 4-km laser interferometer @ Livingston



Observatory Facilities

- Hanford and Livingston Lab facilities available starting 1997-8
- 16 km beam tube with 1.2-m diameter
- Beam-tube foundations in plane ~ 1 cm
- Turbo roughing with ion pumps for steady state

- Large experimental halls compatible with Class-3000 environment; portable enclosures around open chambers compatible with Class-100
- Some support buildings/laboratories still under construction

Beam Tube Bakeout

- Method: Insulate tube and drive ~2000 amps from end to end

Beam Tube Bakeout Results

Postbake measurements of module X1 at Hanford

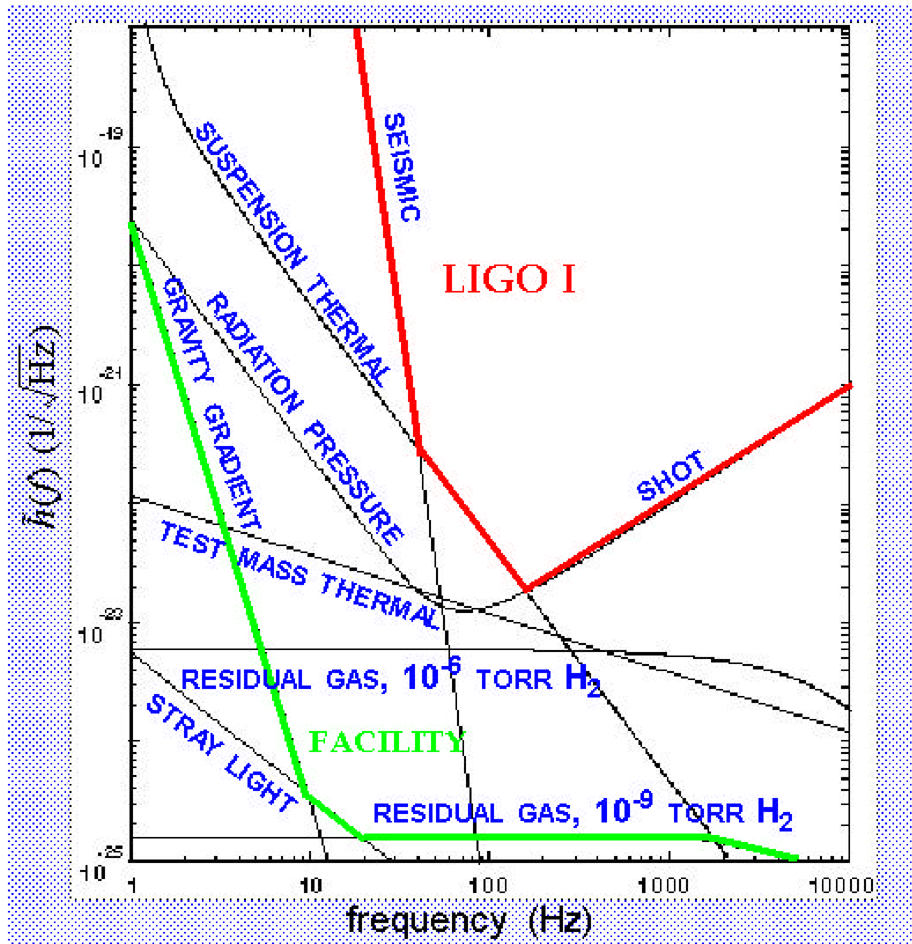
March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

molecule	Outgassing rate @ 10C	pressure@ 10C	outgassing rate @ 23C	pressure@ 23C
	torr liters/sec/cm^2	torr	torr liters/sec/cm^2	torr
H_2	1.6×10^{-14}	1.0×10^{-9}	5.2×10^{-14}	3.4×10^{-9}
CH_4	$< 2 \times 10^{-20}$	$< 3.4 \times 10^{-13}$	$< 8.8 \times 10^{-20}$	$< 1.5 \times 10^{-12}$
H_2O	$< 3 \times 10^{-19}$	$< 5.2 \times 10^{-13}$	$< 1.3 \times 10^{-18}$	$< 2.3 \times 10^{-12}$
N_2	$< 9 \times 10^{-19}$ **	$< 1.5 \times 10^{-13}$		
CO	$< 1.3 \times 10^{-18}$	$< 1.7 \times 10^{-13}$	$< 5.7 \times 10^{-18}$	$< 7 \times 10^{-13}$
O_2	$< 1.2 \times 10^{-20}$	$< 2.3 \times 10^{-14}$		
A	$< 2.5 \times 10^{-20}$	$< 3.6 \times 10^{-14}$		
CO_2	$< 6.5 \times 10^{-20}$	$< 1.2 \times 10^{-13}$	$< 2.9 \times 10^{-19}$	$< 5.2 \times 10^{-13}$

LIGO I Detector Being Commissioned

- LIGO I has evolved from design principles successfully demonstrated in 40-m & phase noise interferometer test beds
- Design effort sought to optimize reliability (up time) and data accessibility
- Facilities and vacuum system designs provide an environment suitable for the most aggressive detector specifications imaginable in future.



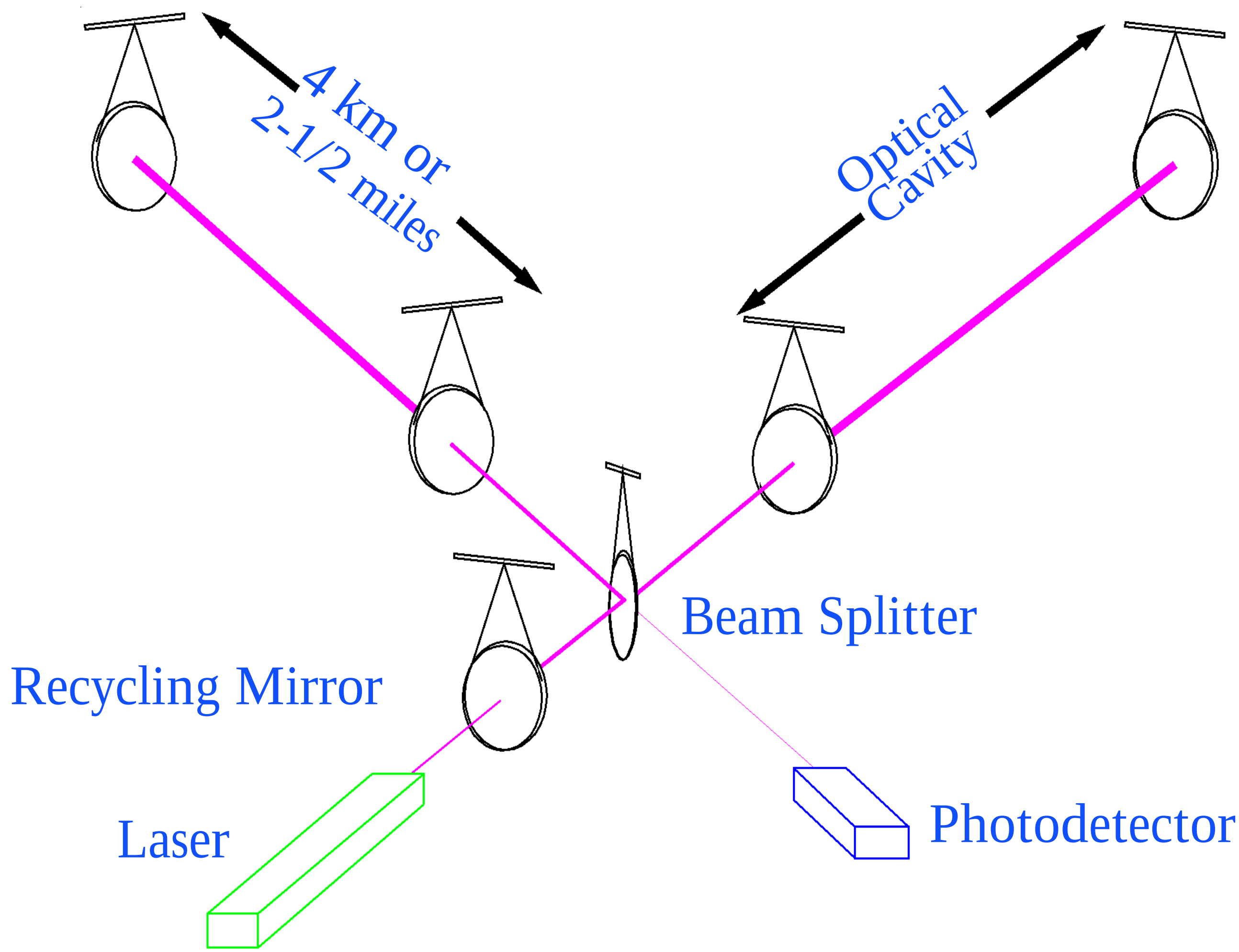
Engineering Challenges

- Detect strains comparable to seeing distance from sun to nearest star changing by a hair's breadth
- Over 4000-meter baseline, mirrors will move 1/1000th the diameter of a proton
- Need to resolve optical phase shifts of 1 ppb with confidence
- Design mechanical structures so atomic vibrations dominate background motion of mirror surfaces, but do not obscure GW signals

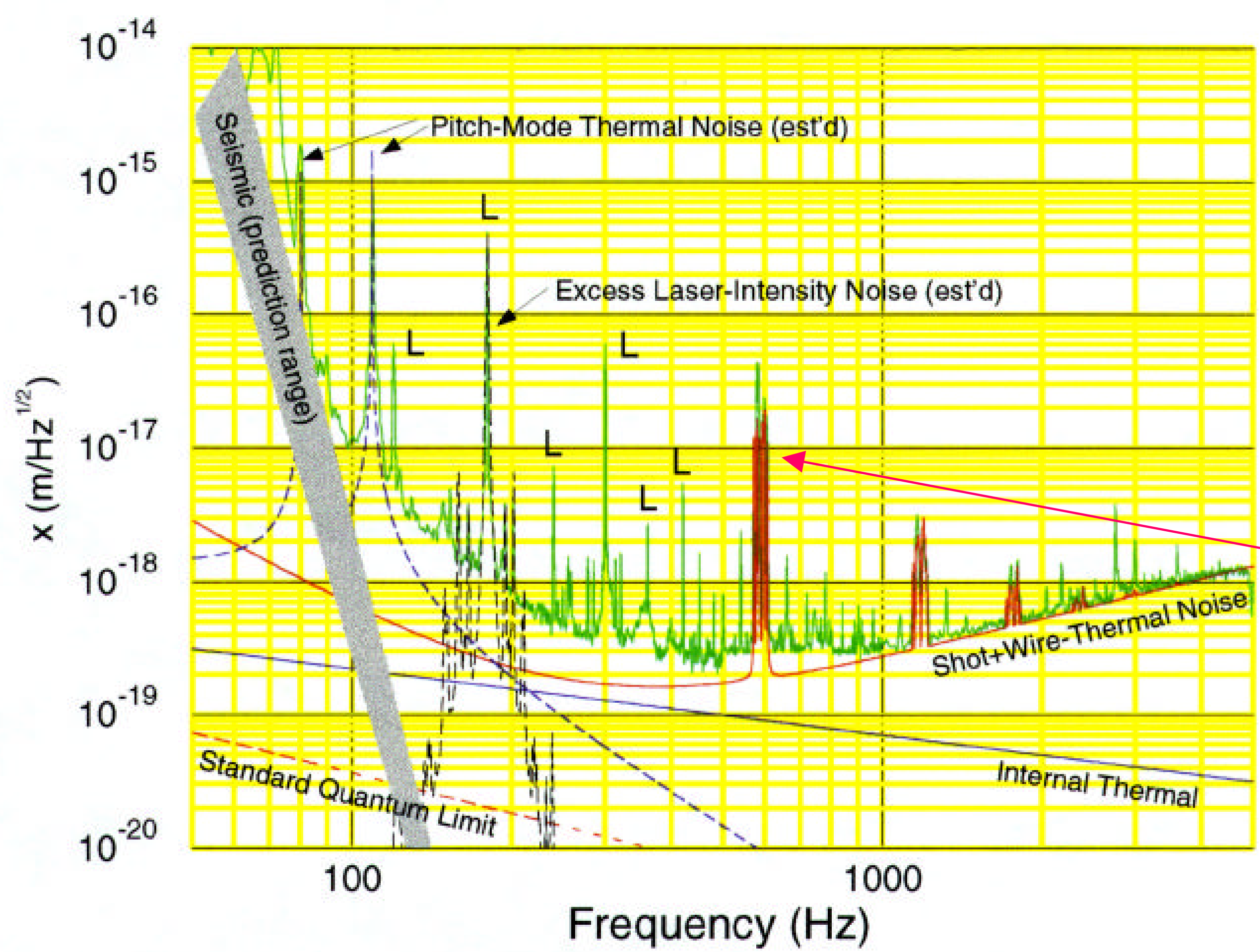
Optical Demands on Laser Light

- expected strains ~ milli-fermis (10^{-18} m) over kilometers
- sensing with wavelength of light ~ 10^{-6} meters
- fringe separation ~ 10^{-6} meters
- use arm cavities to narrow fringe by ~ 100
- split resultant fringe by ~ 10^{10}
  - » Requires high signal/noise ratio, hence high power in arms
  - » Power recycling provides efficient use of laser light
- Laser frequency control to 10^{-7} Hz/Hz$^{-1/2}$
- Laser amplitude stability to 10^{-8} Hz$^{-1/2}$

Fabry-Perot-Michelson with Power Recycling



Design for Low Background Spec'd From Prototype Operation



For Example:
Noise-Equivalent Displacement of 40-meter Interferometer (ca1994)

~ 50 milliFermi RMS for each violin mode

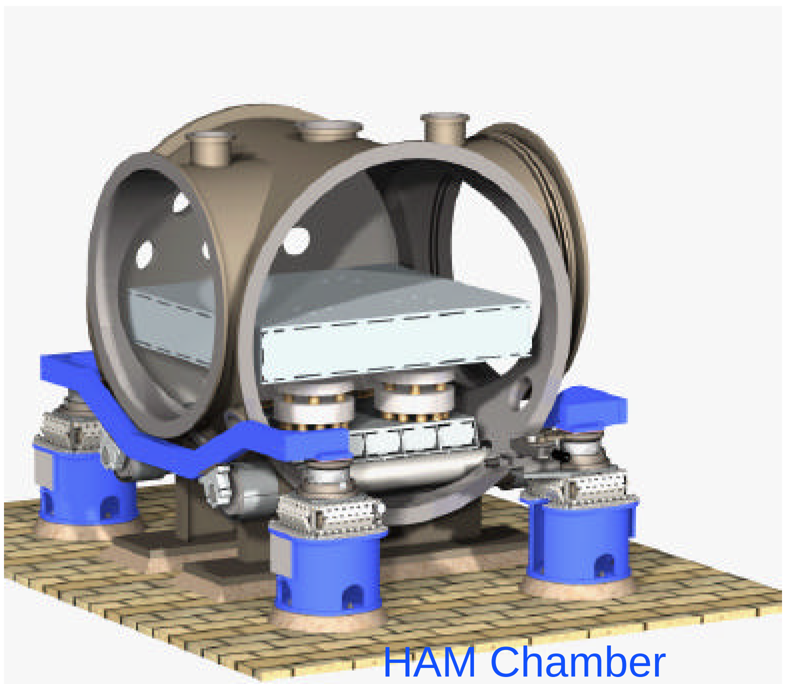
Vacuum Chambers Provide Quiet Homes for Mirrors

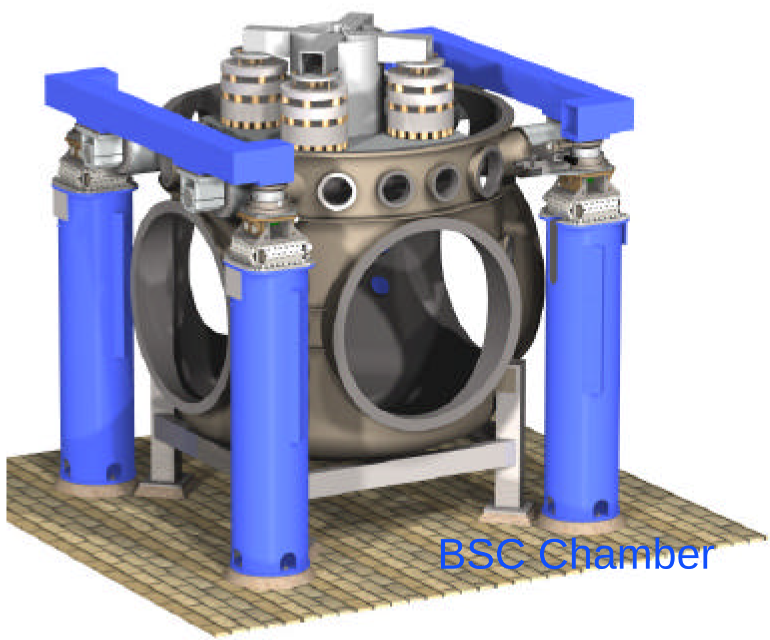
View inside Corner Station

Standing at vertex beam splitter

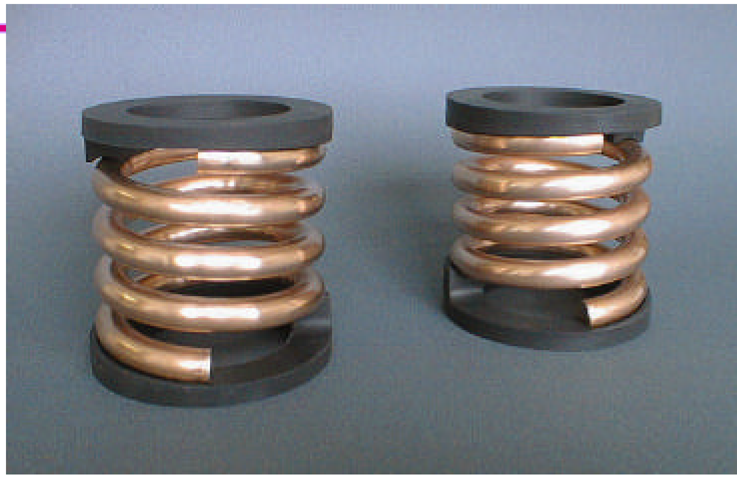
Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Little or no attenuation below 10Hz
» Large range actuation for initial alignment and drift compensation
» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

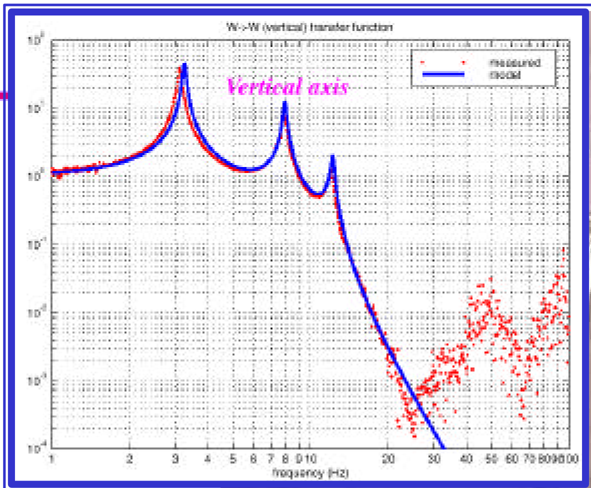




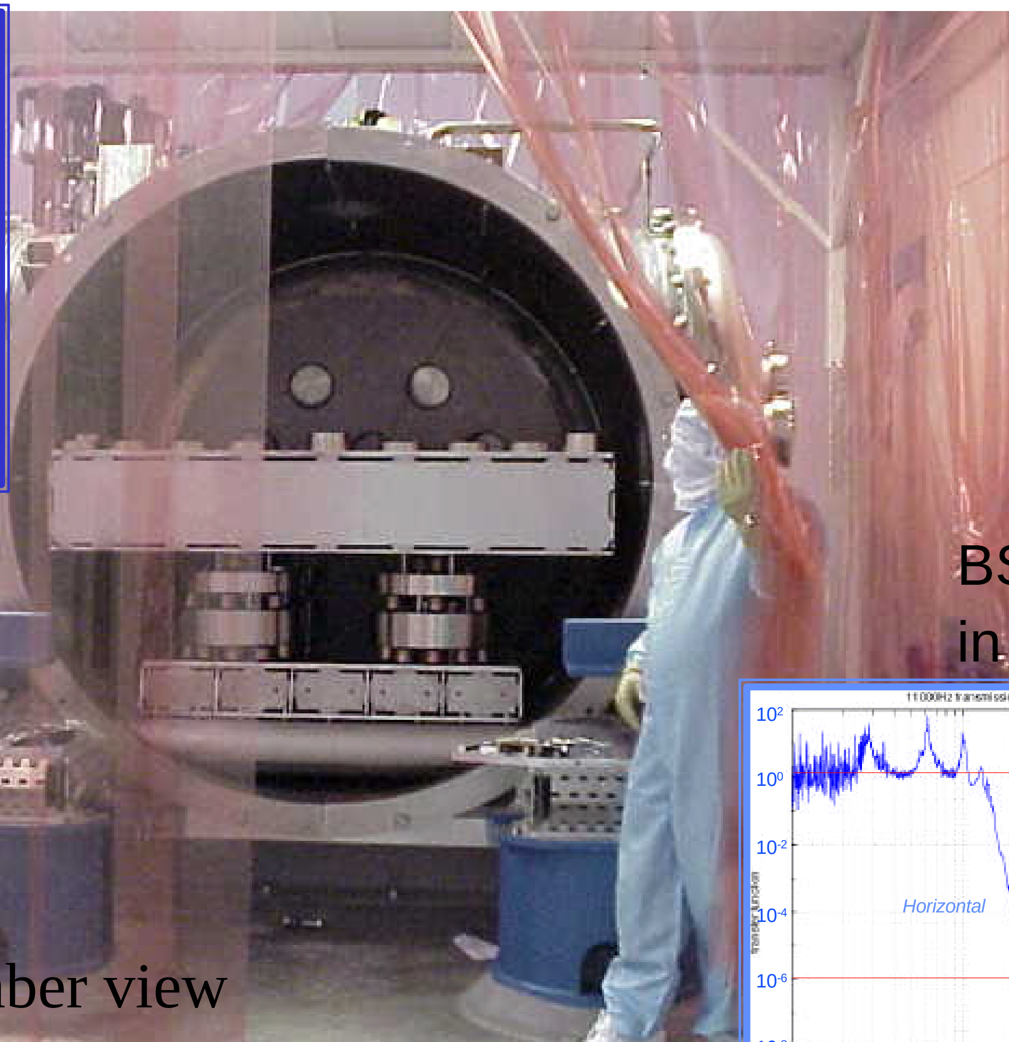
Seismic Isolation – Springs and Masses



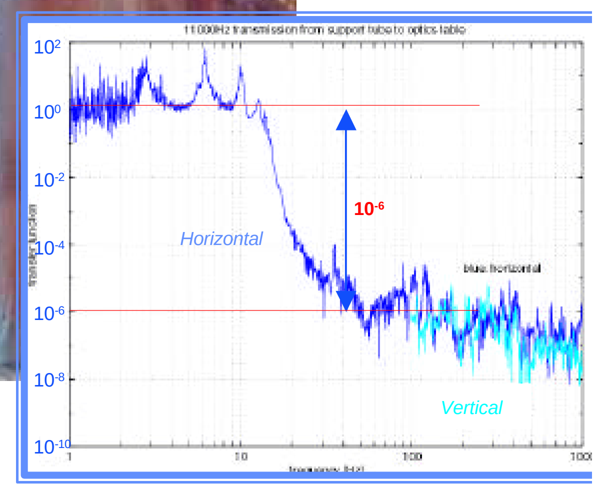
Seismic System Performance



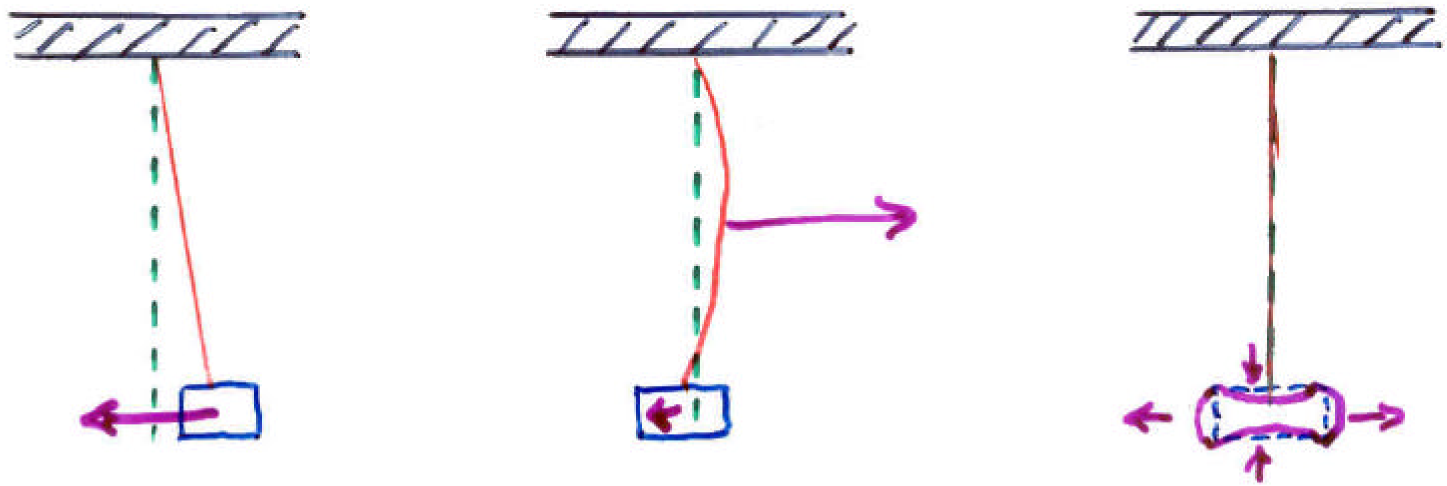
HAM stack
in air



BSC stack
in vacuum



Thermal Noise ~ k_BT/mode

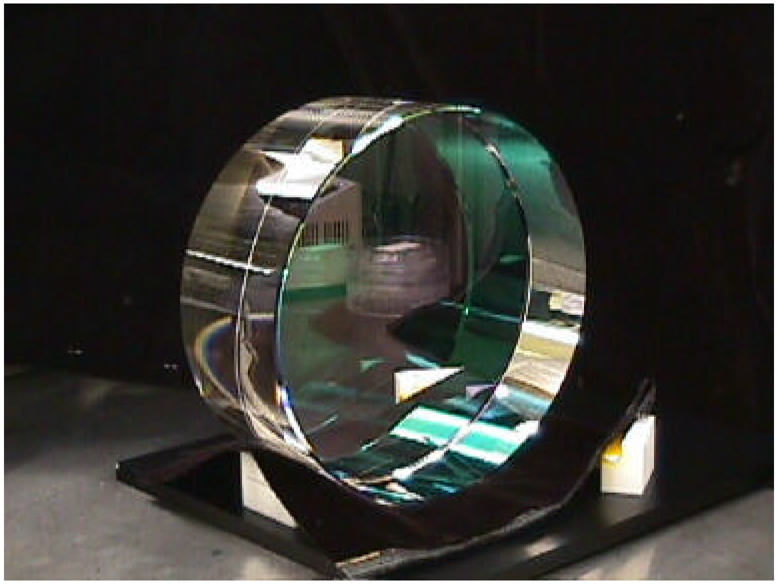


pendulum mode	violin mode	test mass vibrational mode
$x_{rms} \approx 10^{-11}$ m	$x_{rms} \approx 5\times10^{-17}$ m	$x_{rms} \approx 5\times10^{-16}$ m
f < 1 Hz	f ~ 350 Hz	f ≥ 10 kHz

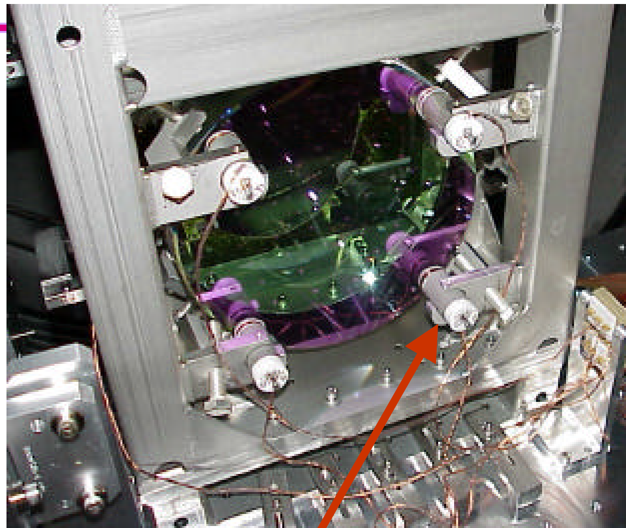
Strategy: Compress energy into narrow resonance outside band of interest ⇒ require high mechanical Q, low friction

Mirrors (a.k.a. Test Masses) for Initial LIGO Interferometers

- 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}
- Production involved 6 companies, NIST, and LIGO



Core Optics Suspension and Control

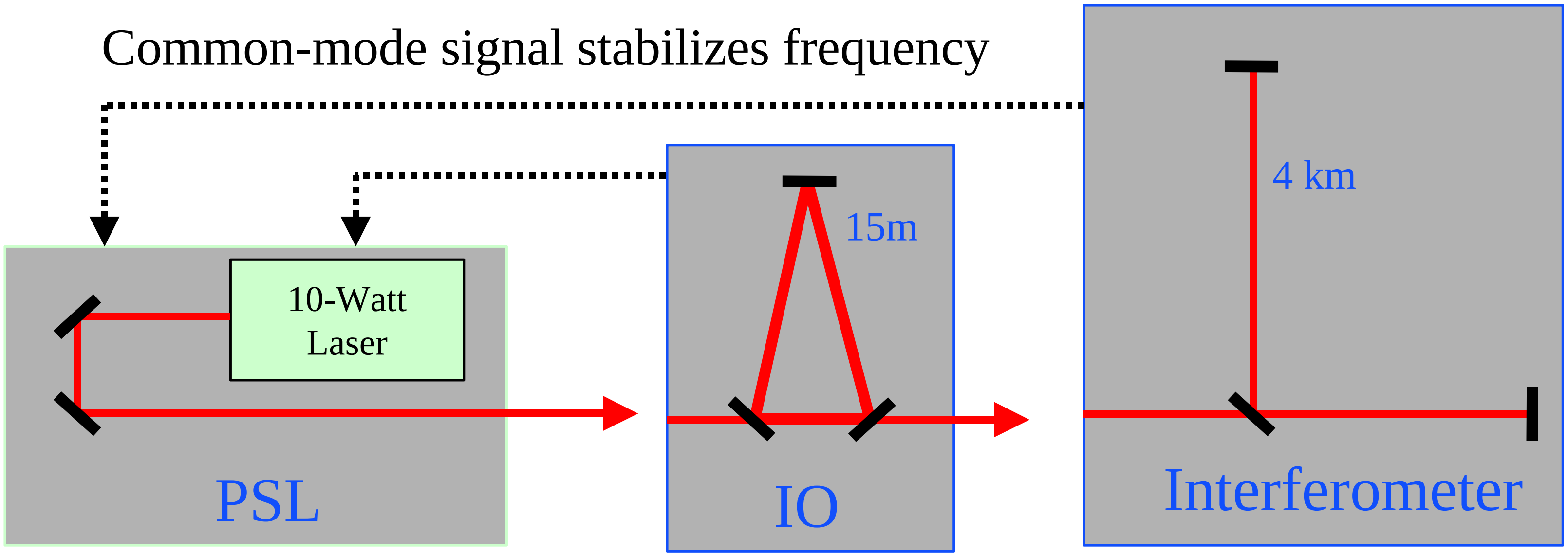


Optics suspended as simple pendulums

Local sensors/actuators provide damping and control forces

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

Frequency Stabilization of the Light Employs Three Stages

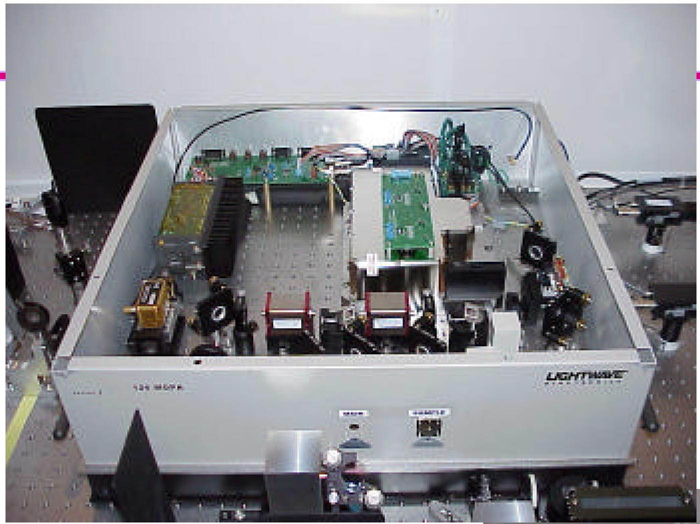


Pre-stabilized laser

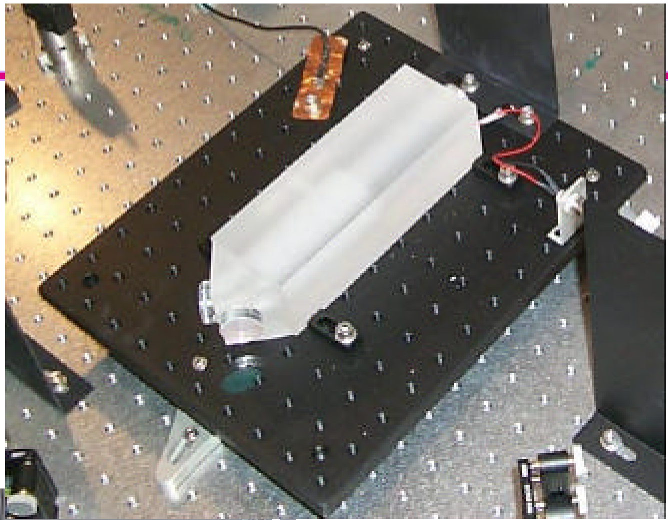
"Mode-cleaner" cavity cleans up laser light

Differential signal carries GW info

Pre-stabilized Laser (PSL)



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

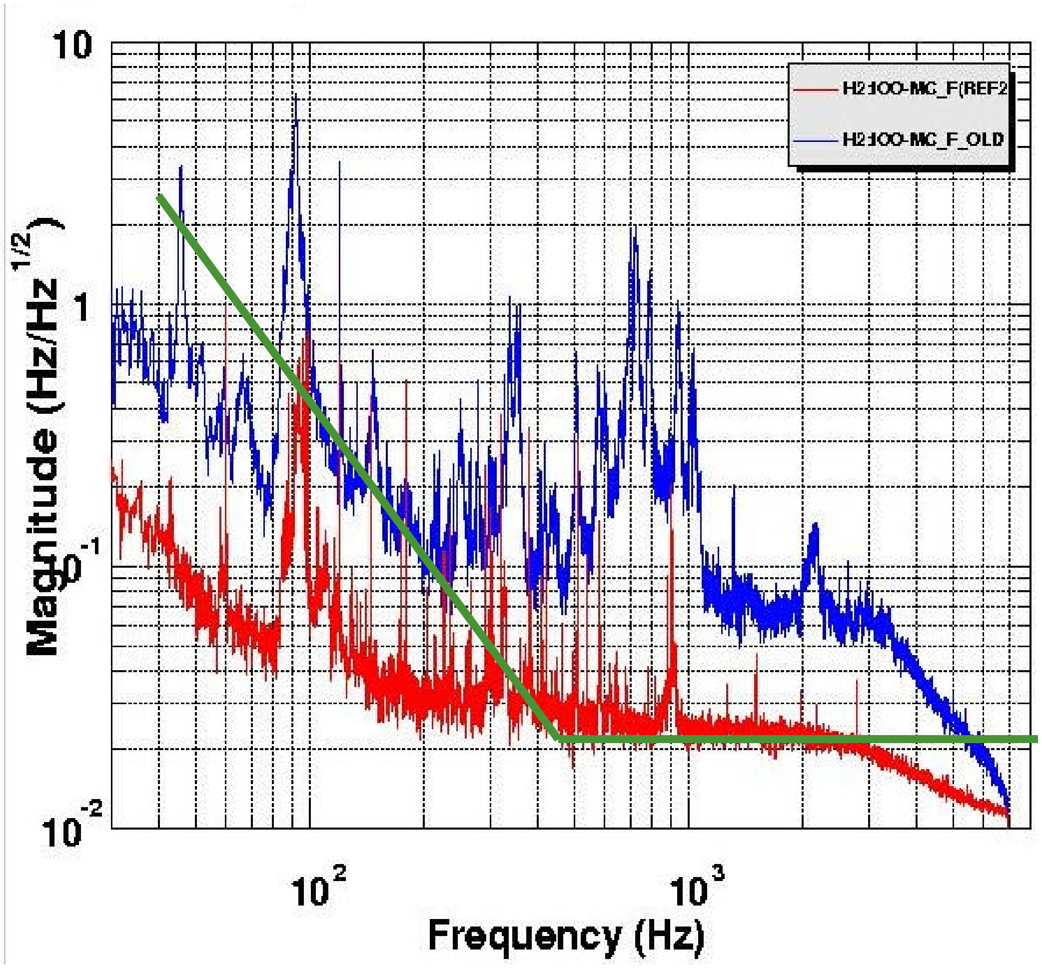


Cavity for
defining beam geometry,
joint development with
Stanford

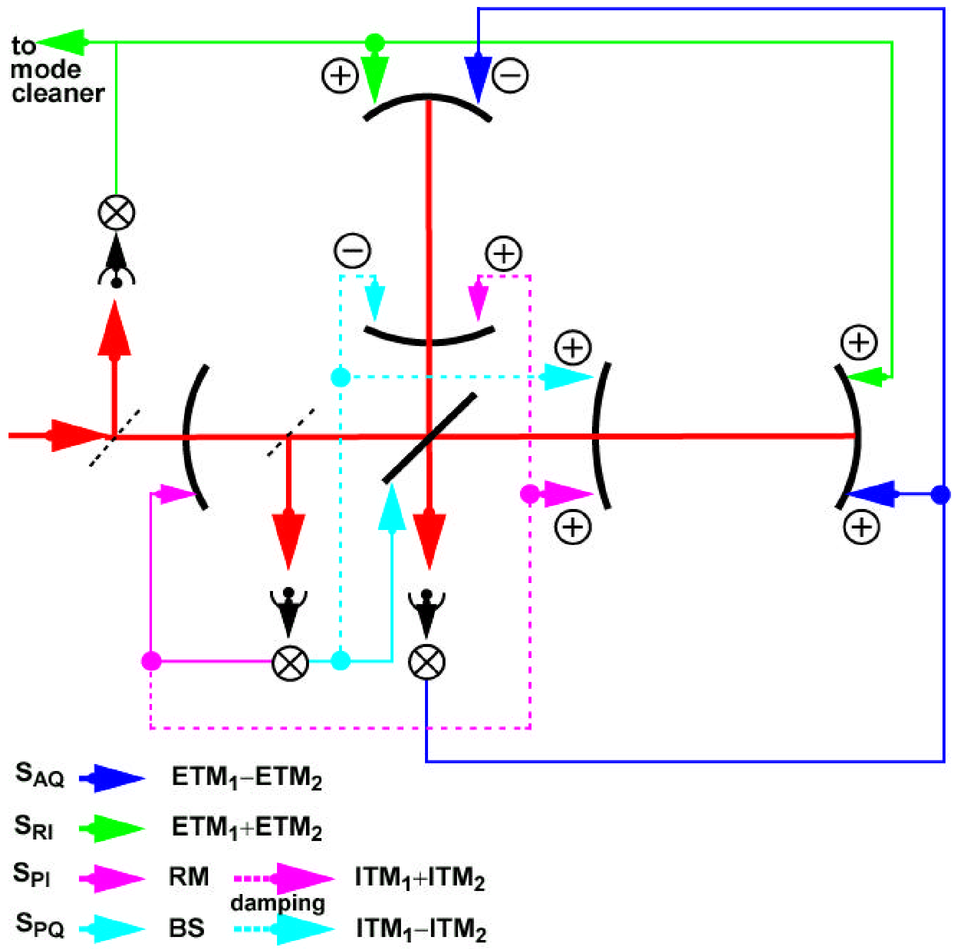
Frequency reference
cavity (inside oven)

Continued improvement in PSL Frequency Noise

- Simplification of beam path external to vacuum system eliminated peaks due to vibrations
- Broadband noise better than spec in 40-200 Hz region

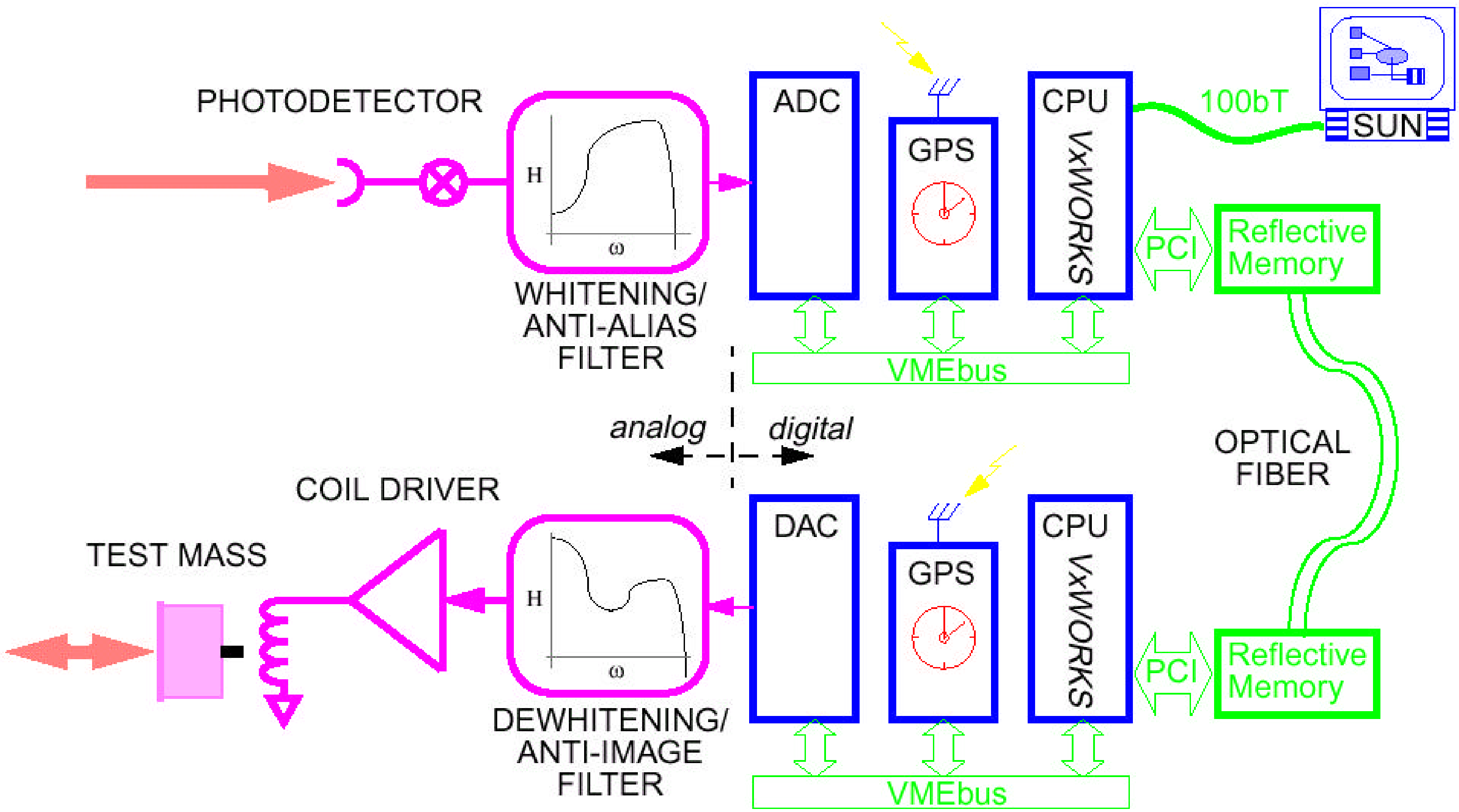


Interferometer Control System



- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition
- But it works!

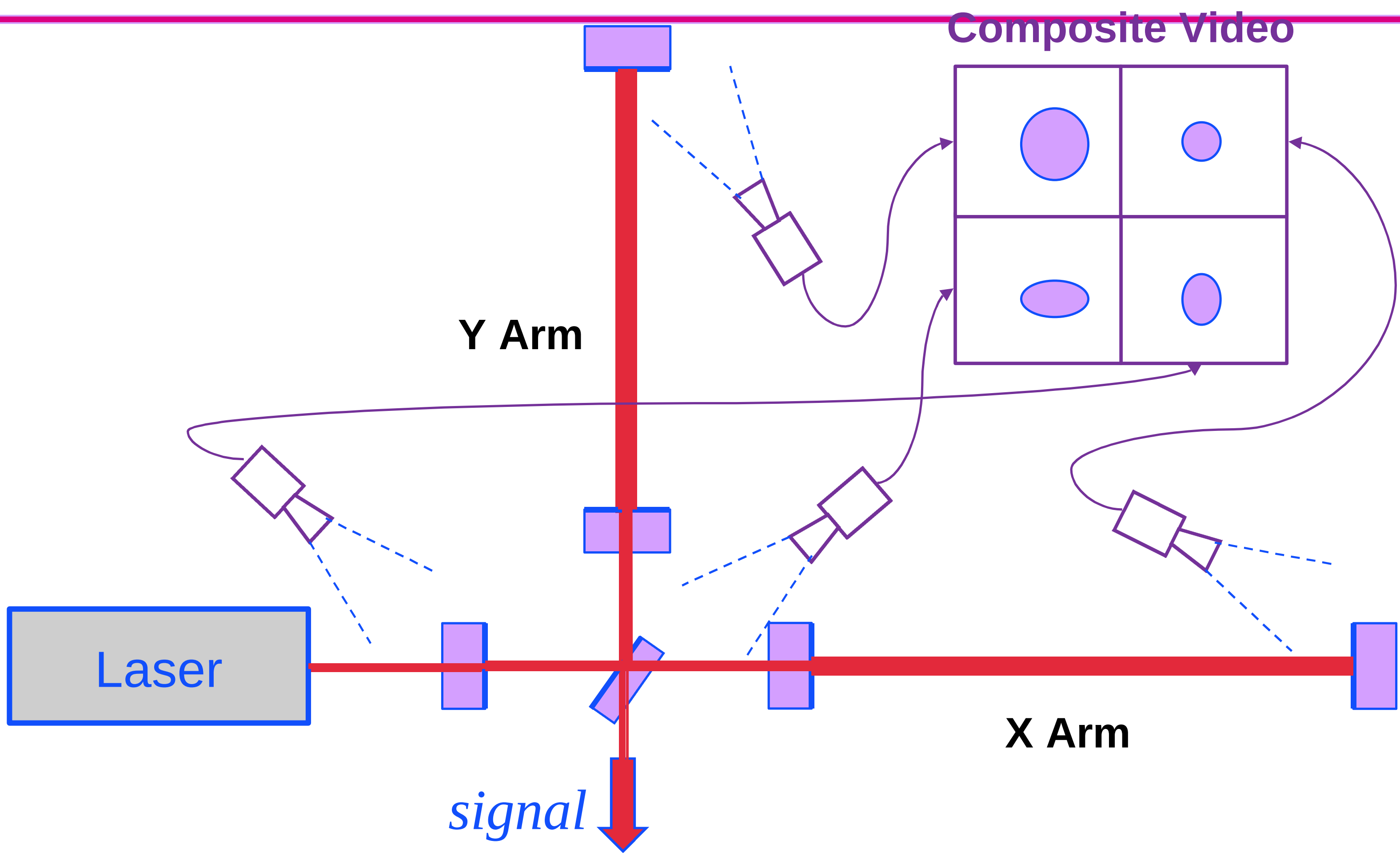
Digital Interferometer Sensing & Control System



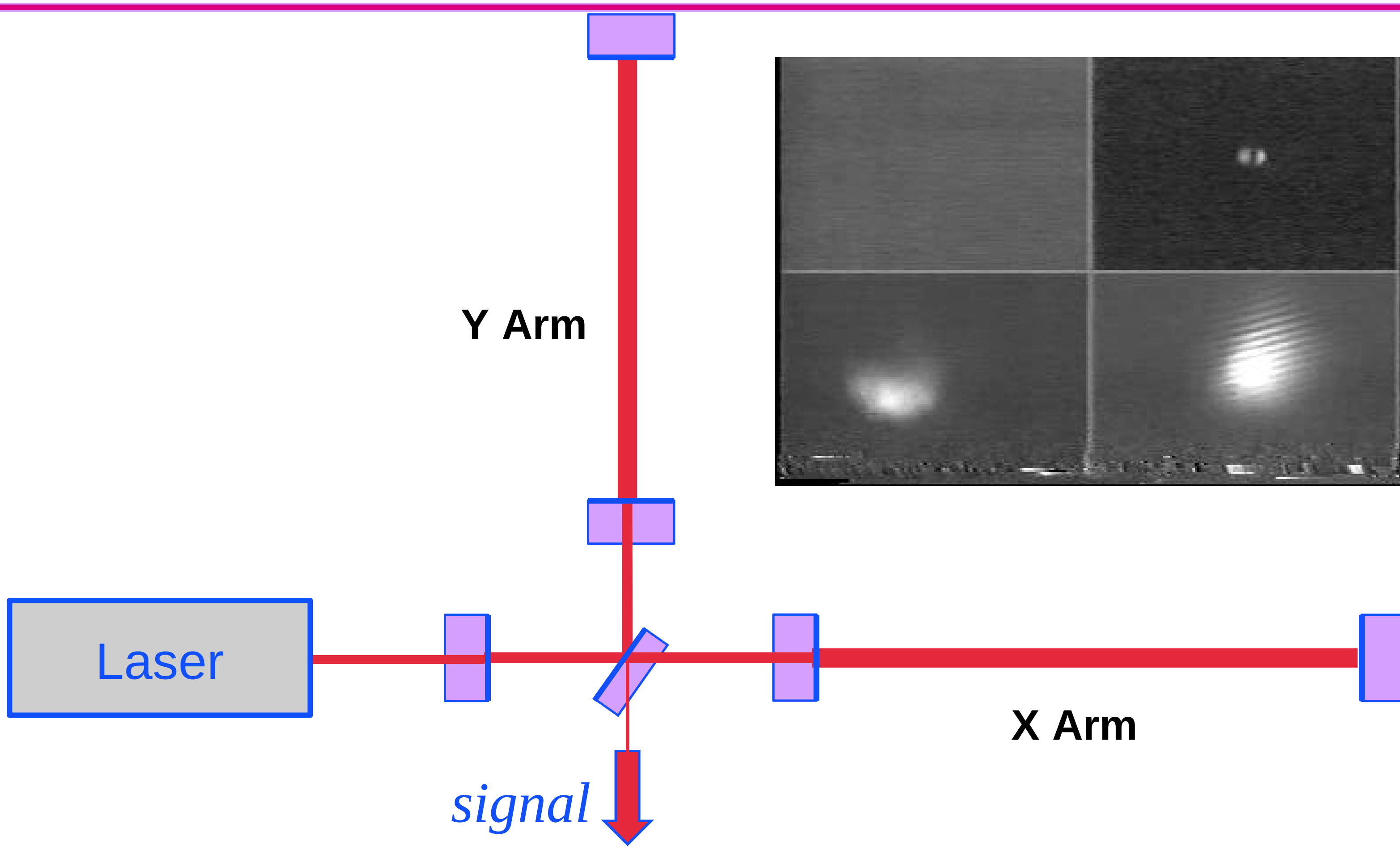
Chronology of Detector Installation & Commissioning

- 7/98 Begin LHO detector installation
- 2/99 Begin LLO detector installation
- 6/99 Lock first mode cleaner
- 11/99 Laser spot on first end mirror
- 12/99 First lock of a 2-km Fabry-Perot arm
- 4/00 Engineering Run 1 (E1)
- 6/00 Brush Fire burns 500 km^2 of land surrounding LHO
- 10/00 Recombined LHO-2km interferometer in E2 run
- 10/00 First lock of LHO-2km power-recycled interferometer
- 2/01 Nisqually earthquake damages LHO interferometers
- 4/01 Recombined 4-km interferometer at LLO
- 5/01 Earthquake repairs completed at LHO
- 6/01 Last LIGO-1 mirror installed
- 12/01 Power recycling achieved for LLO-4km
- 1/2002 E7: First triple coincidence test; first on-site data analysis
- 1/2002 Power recycling achieved for LHO-4km

Steps to Locking an Interferometer



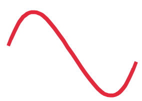
Watching the Interferometer Lock

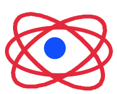


Why is Locking Difficult?

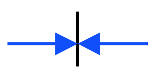
One meter, about 40 inches

÷10,000  Earthtides, about 100 microns

÷100  Microseismic motion, about 1 micron

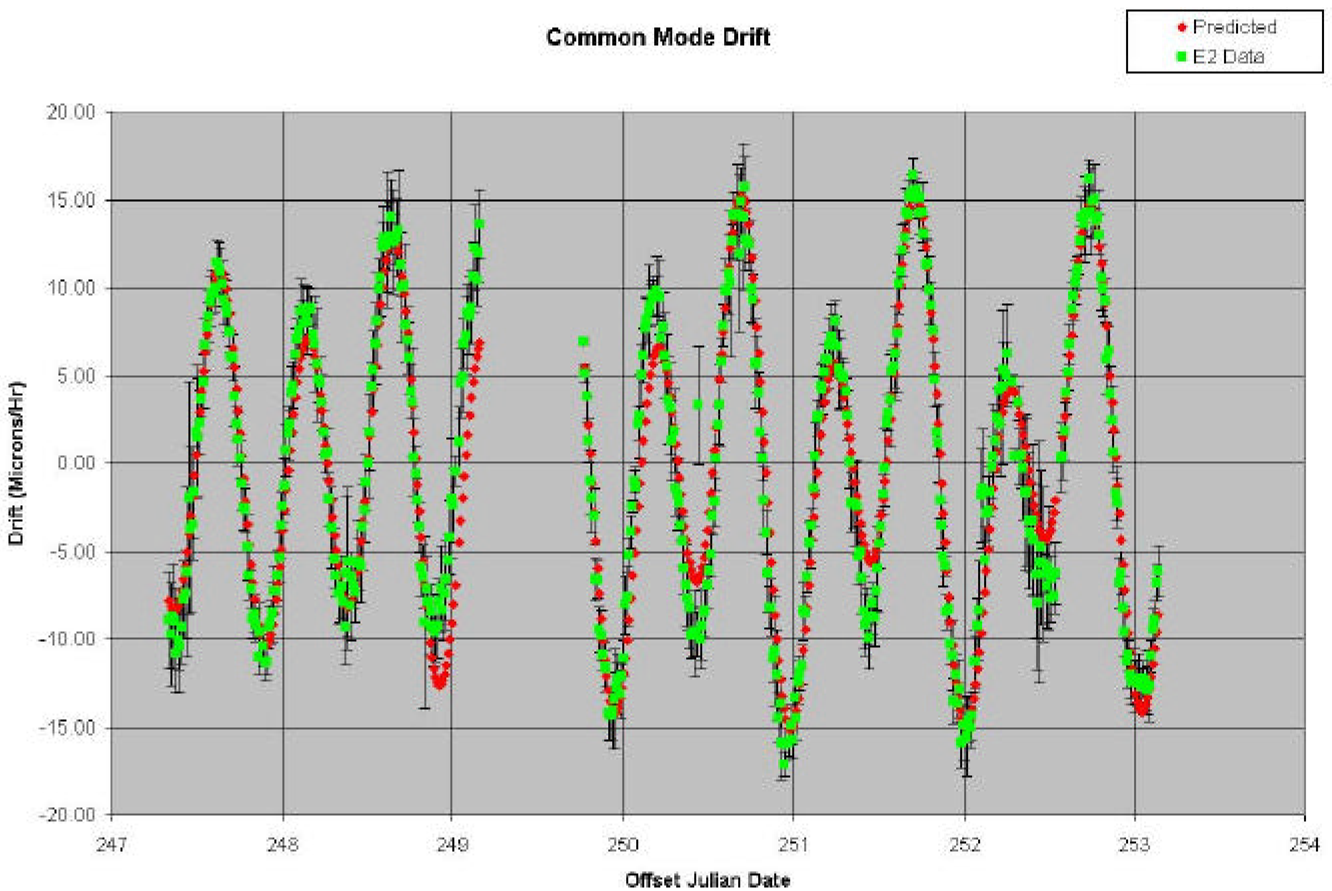
÷10,000  Precision required to lock, about 10^{-10} meter

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

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

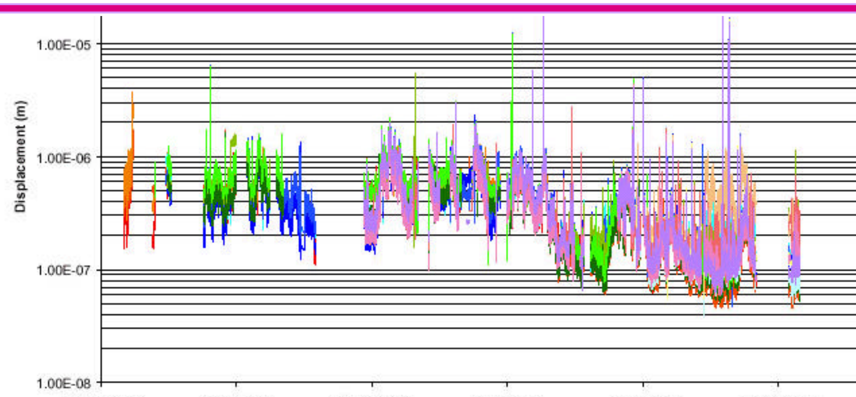
Earth Tide: Largest Source of Interferometer Drift

- Actuation in end/mid- stations and on laser reference cavity
- Simple model in feed-forward removes ~80%
- Feed-back removes ~20%
- Analysis of feed-back gives non-modeled tidal and temperature effects



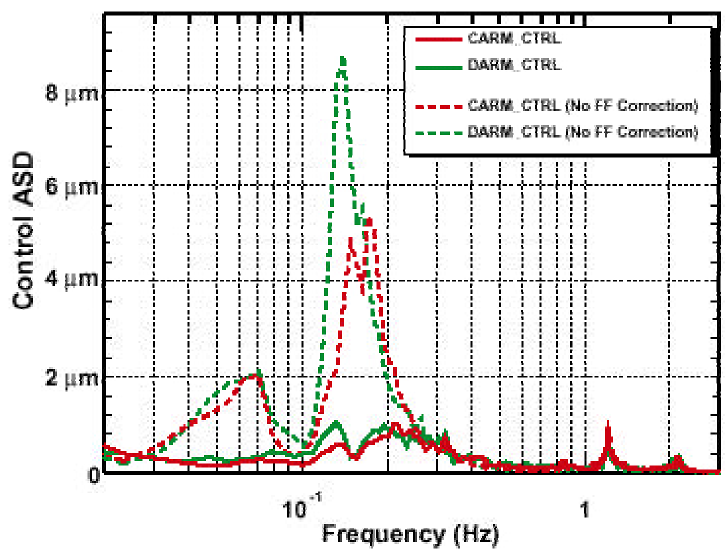
Microseism

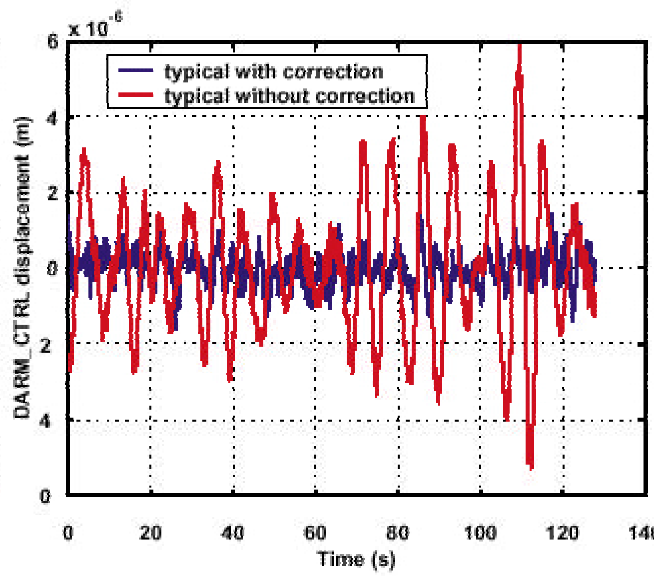
Microseism at 0.12 Hz dominates ground velocity



Trended data (courtesy of Gladstone High School) shows large variability of microseism

Reduction by feed-forward derived from seismometers





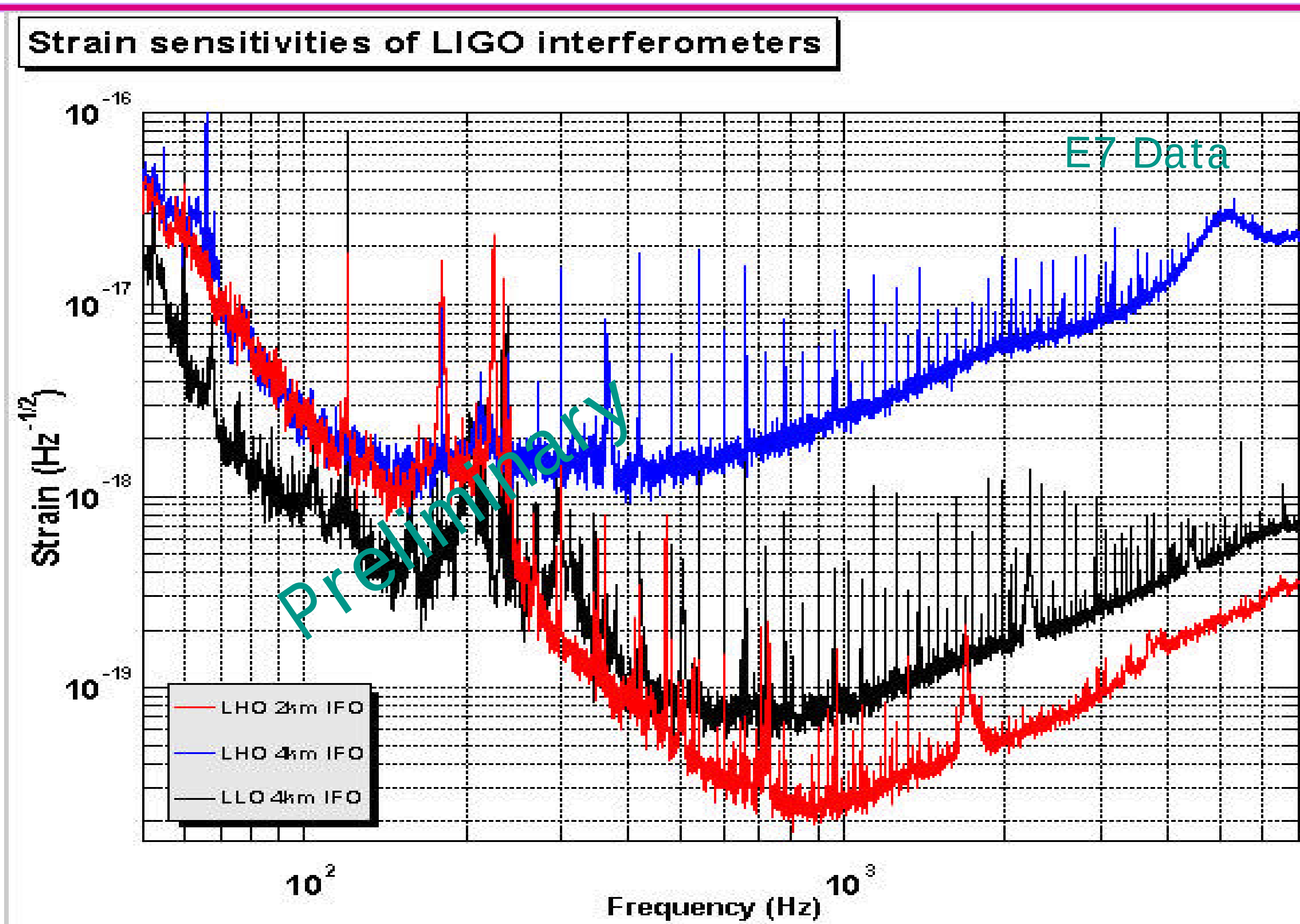
Engineering Run 7 (E7) 28Dec01 – 14Jan02

- Engineering runs test partially integrated and commissioned machines under “operational” conditions to identify needed improvements
- E7 was first engineering run to include all 3 interferometers in coincidence and tested on-line data analysis at Hanford and Livingston
- E7 data sets will be analyzed jointly with data sets from GEO600 and Allegro
- E7 analysis will exercise full range of astrophysical data-analysis software

E7 Interferometer Configurations

- H1: 4-km interferometer at Hanford; recombined configuration; digital suspension controllers; tidal compensation; 1-W laser power
- H2: 2-km interferometer at Hanford; full power-recycling configuration; differential-mode wave-front control; analog suspension controllers; tidal compensation ; 1-W laser power
- L1: 4-km interferometer at Livingston; recombined configuration; analog suspension controllers; microseism compensation ; 1-W laser power

Preliminary Noise Equivalent Strain Spectra for E7



E7 Analysis Working Groups

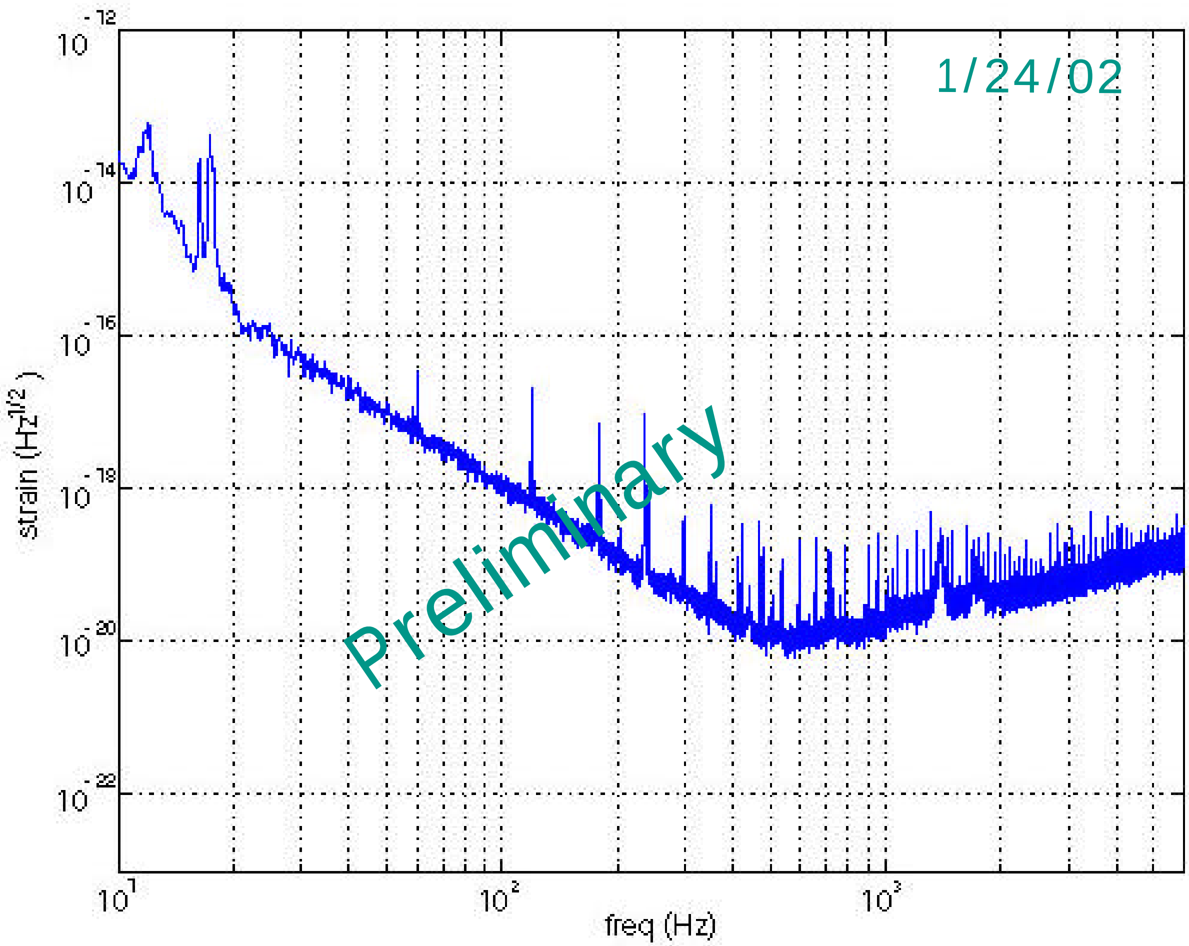
- Data from E7 is being analyzed by LSC working groups for:
  - » Detector Characterization
  - » Binary Inspirals
  - » Bursts
  - » Periodic Sources
  - » Stochastic Background
- This exercise will test analysis methodology for 1st Science Run S1 this summer and feed back results into detector commissioning and code-writing effort

Progress since 14Jan02

- Common-mode feedback from arms to laser frequency is now engaged on Hanford 2-km interferometer
  - » Improved control of laser frequency noise
  - » Establishes gain hierarchy to get better-conditioned control system
- Power-recycling works on Hanford 4-km interferometer
  - » Important validation of digital suspension controllers
- Laser power increased to 6 W for Hanford 2-km interferometer; AS photodiode kept at low power

Hanford 2km interferometer improvements after E7

- Closed feedback loop from arms to laser frequency
- Reallocation of gains within length control servo system
- laser power 6W in; AS port kept at low power



Summary

- Commissioning ongoing on 3 interferometers
- First triple-coincidence test run completed
- On-line analysis systems tested at LHO and LLO
- First end-to-end test of complete data analysis systems/algorithms ongoing
- Power-recycling demonstrated on all interferometers
- All interferometers still need some control loops to be closed and then tuned to enhance stability/sensitivity
- Working to increase immunity to high seismic noise periods (LLO will have seismic upgrade within a year) to improve duty cycle

Despite a few difficulties, science runs will start in 2002.