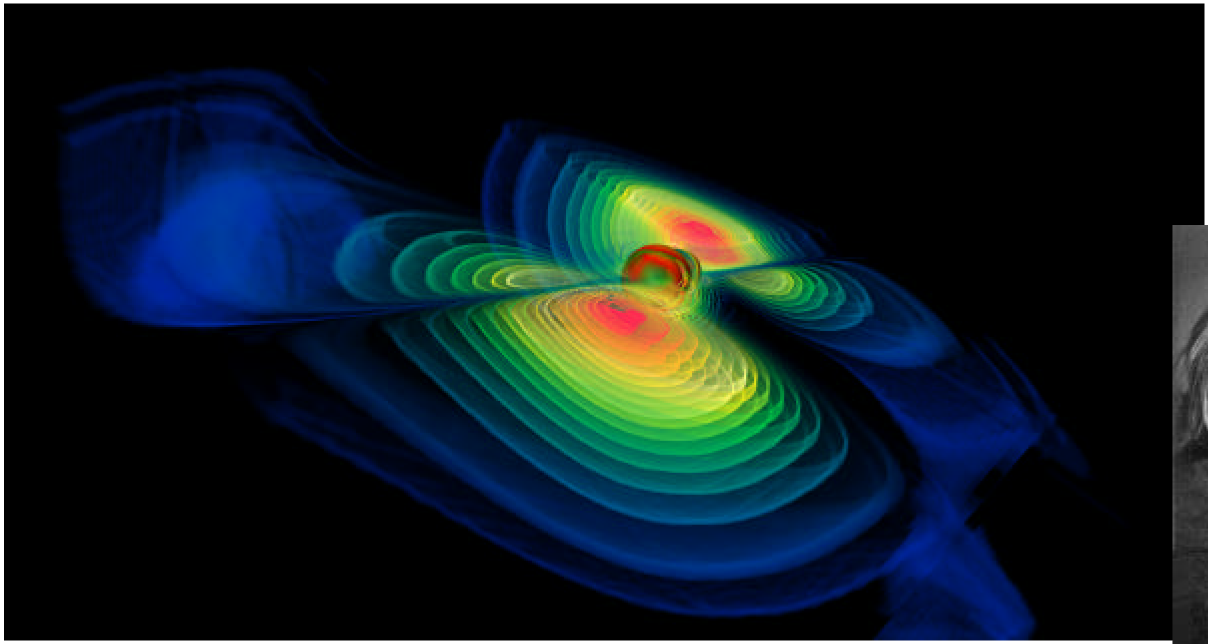
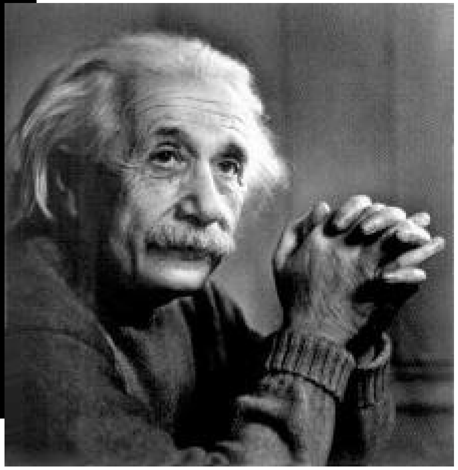
The Laser Interferometer Gravitational-Wave Observatory



"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)

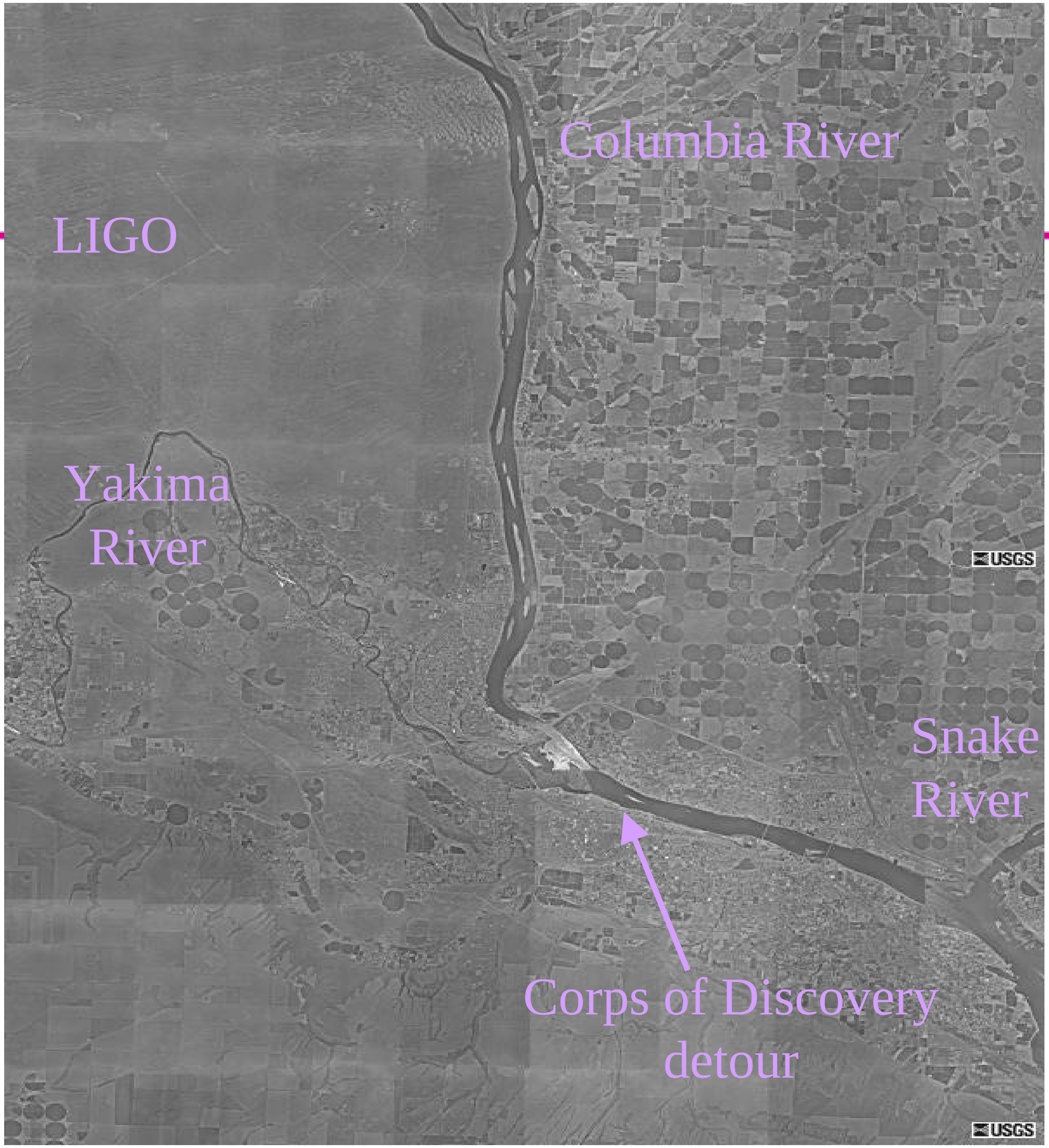


Reported on behalf of LIGO colleagues by

Fred Raab,

LIGO Hanford Observatory

The spirit of exploration did not end 200 years ago. A new age of discovery is beginning with LIGO…



LIGO’s Mission is to Open a New Portal on the Universe

- In 1609 Galileo viewed the sky through a 20X telescope and gave birth to modern astronomy
  - » The boost from “naked-eye” astronomy revolutionized humanity’s view of the cosmos
  - » Ever since, astronomers have “looked” into space to uncover the natural history of our universe
- LIGO’s quest is to create a radically new way to perceive the universe, by directly listening to the vibrations of space itself
- LIGO consists of large, earth-based, detectors that will act like huge microphones, listening for the most violent events in the universe

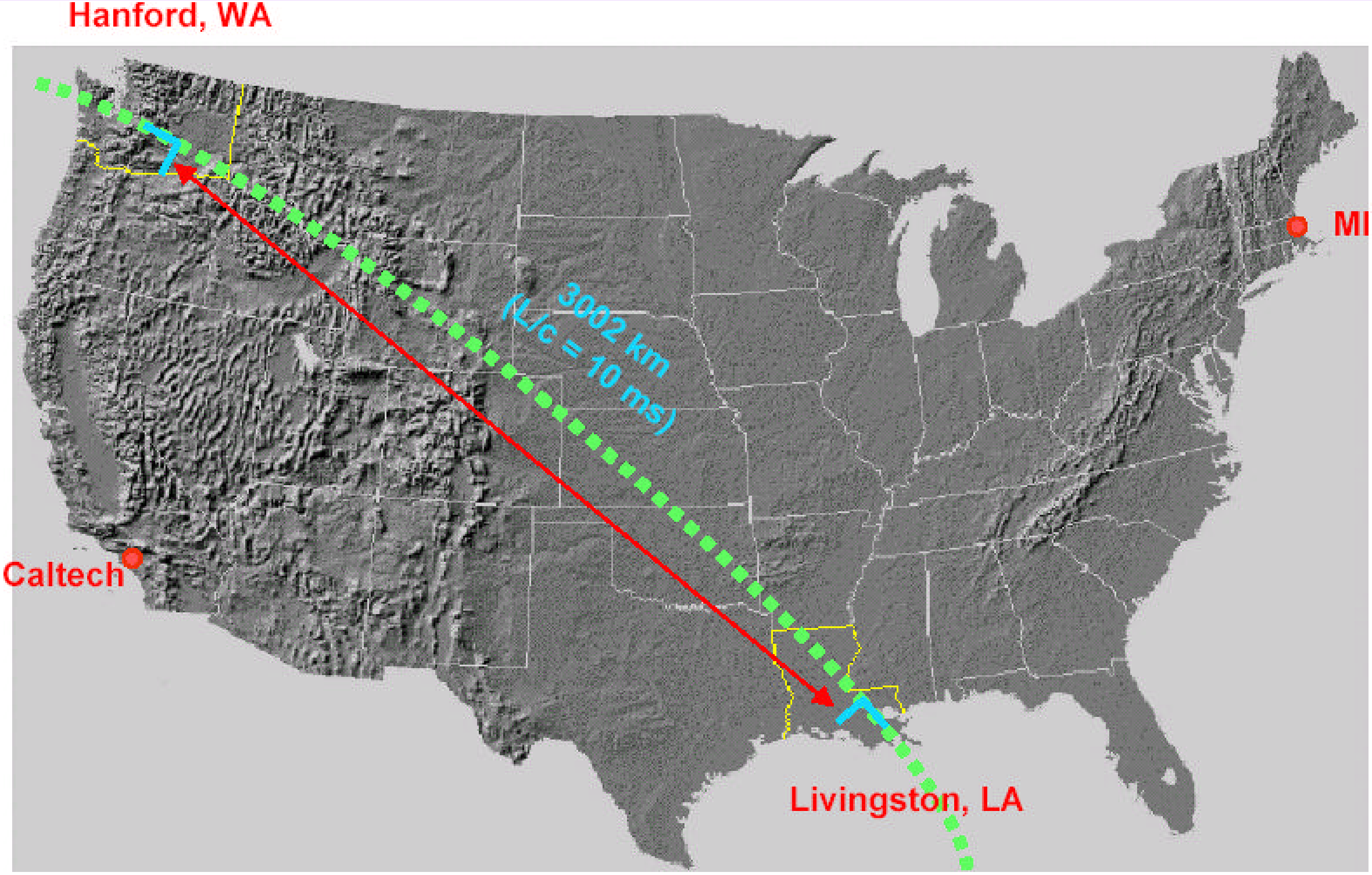
The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

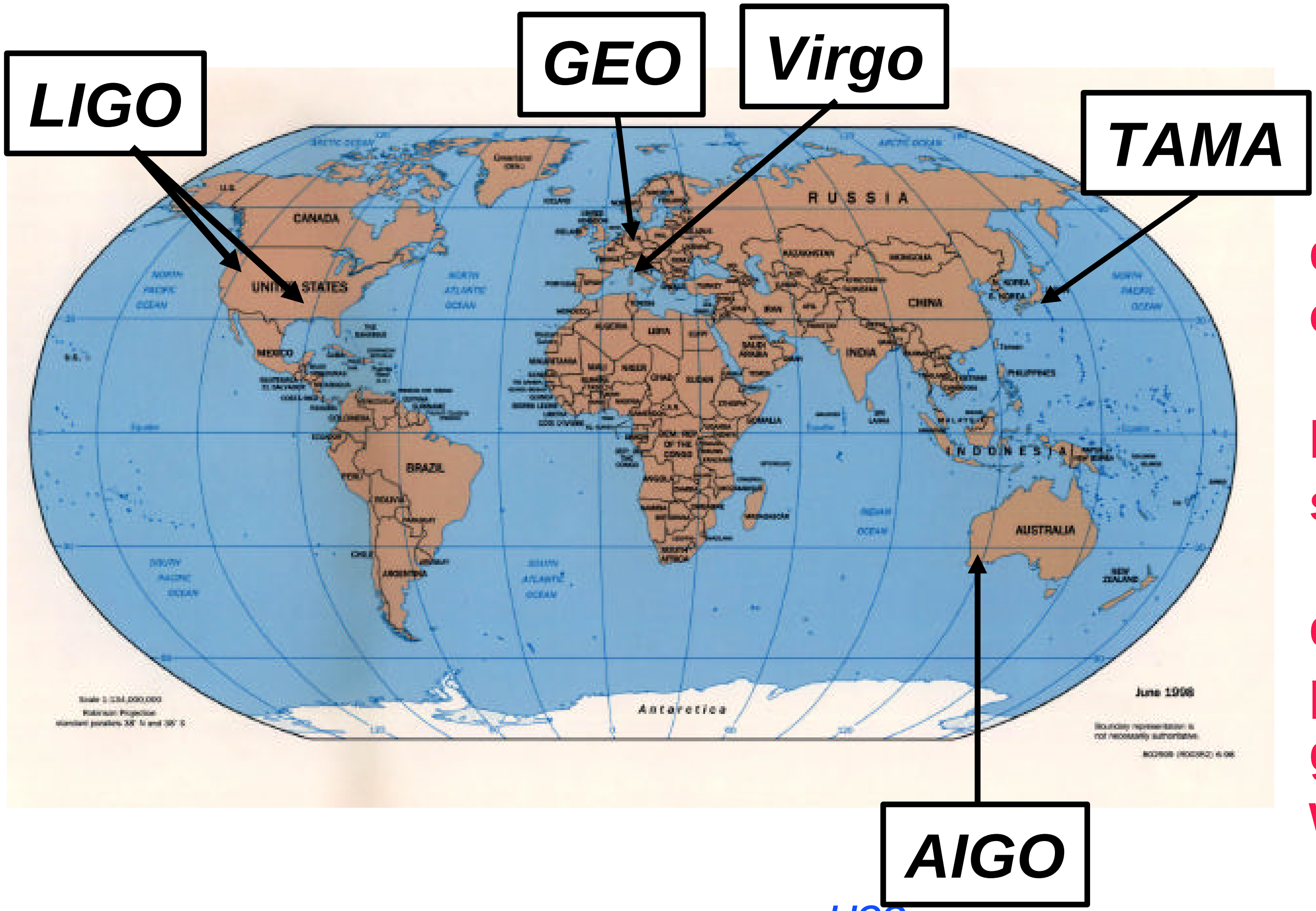
Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 400 LIGO Science Collaboration members worldwide.

LIGO Laboratories Are Operated as National Facilities in the US…



Part of Future International Detector Network

Simultaneously detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

Big Question: What is the universe like now and what is its future?

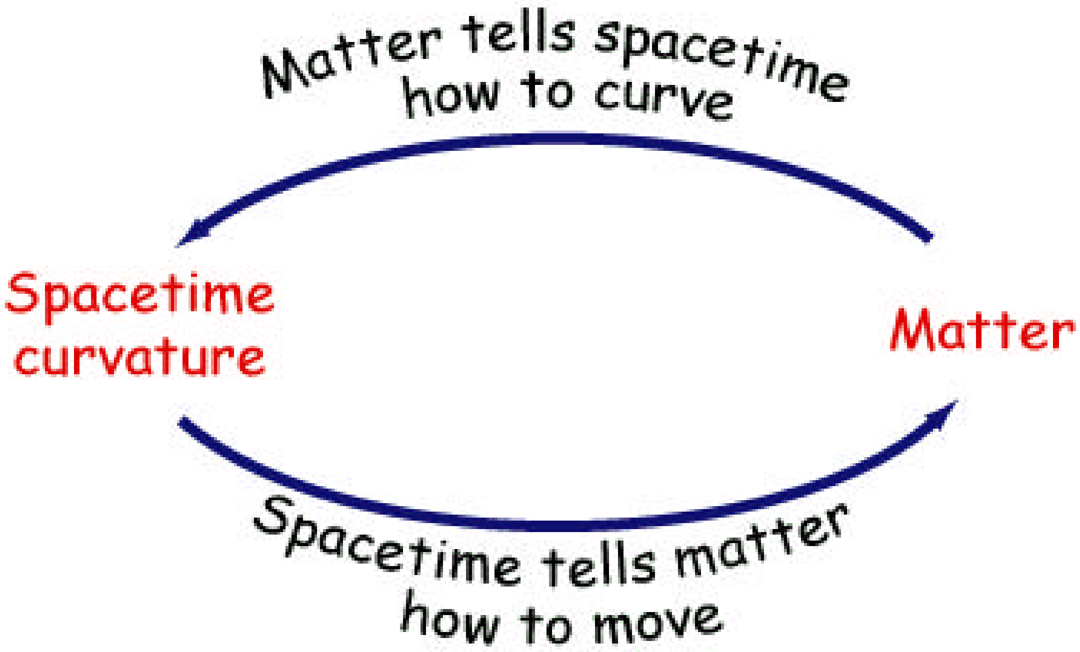
- New and profound questions exist after nearly 400 years of optical astronomy
  - » 1850's → Olber's Paradox: "Why is the night sky dark?"
  - » 1920's → Milky Way discovered to be just another galaxy
  - » 1930's → Hubble discovers expansion of the universe
  - » mid 20th century → "Big Bang" hypothesis becomes a theory, predicting origin of the elements by nucleosynthesis and existence of relic light (cosmic microwave background) from era of atom formation
  - » 1960's → First detection of relic light from early universe
  - » 1990's → First images of early universe made with relic light
  - » 2003 → High-resolution images imply universe is 13.7 billion years old and composed of 4% normal matter, 24% dark matter and 72% dark energy; 1st stars formed 200 million years after big bang.
- We hope to open a new channel to help study this and other mysteries

A Slight Problem

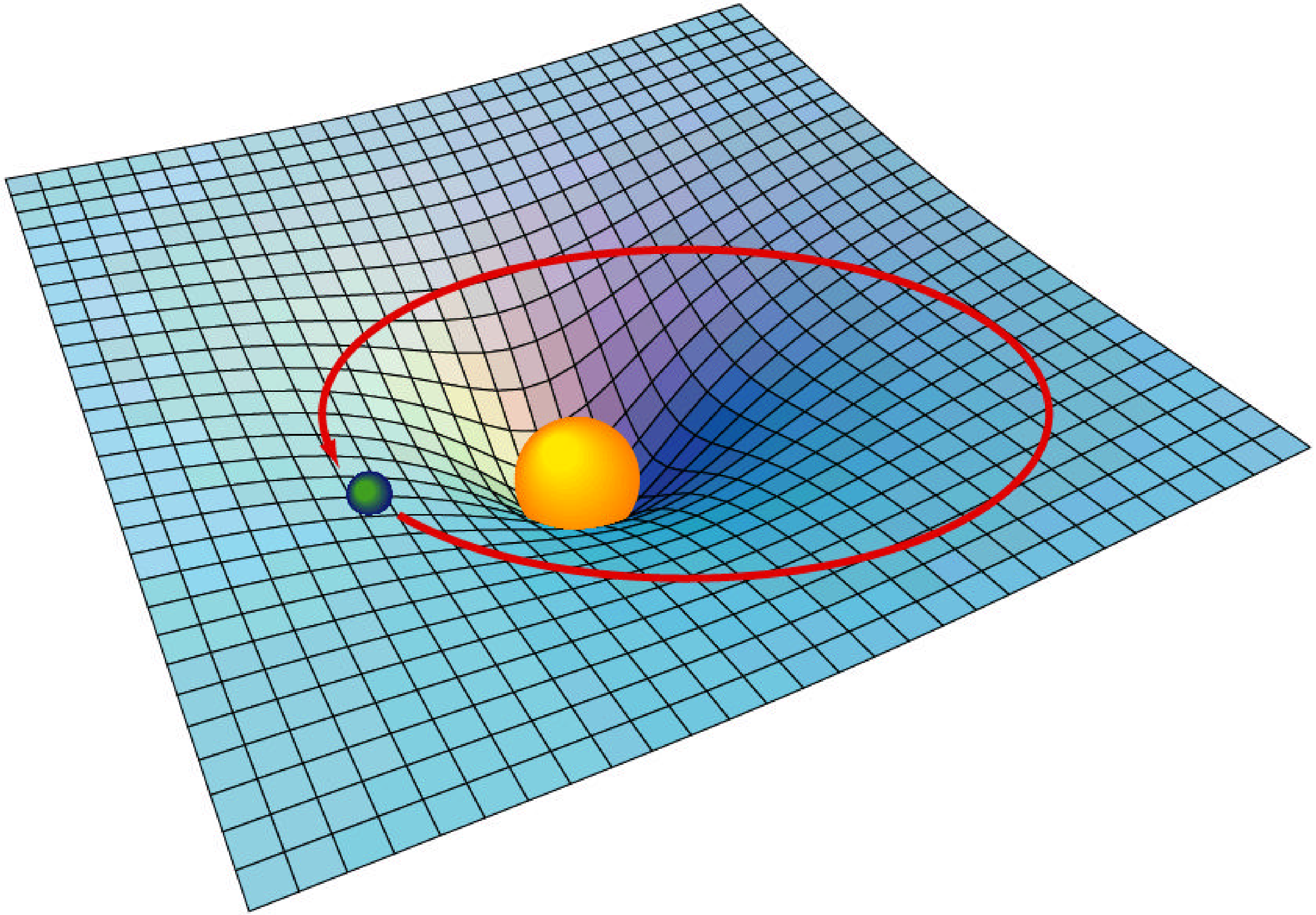
Regardless of what you see on Star Trek, the vacuum of interstellar space does not transmit conventional sound waves effectively.

Don’t worry, we’ll work around that!

John Wheeler’s Picture of General Relativity Theory



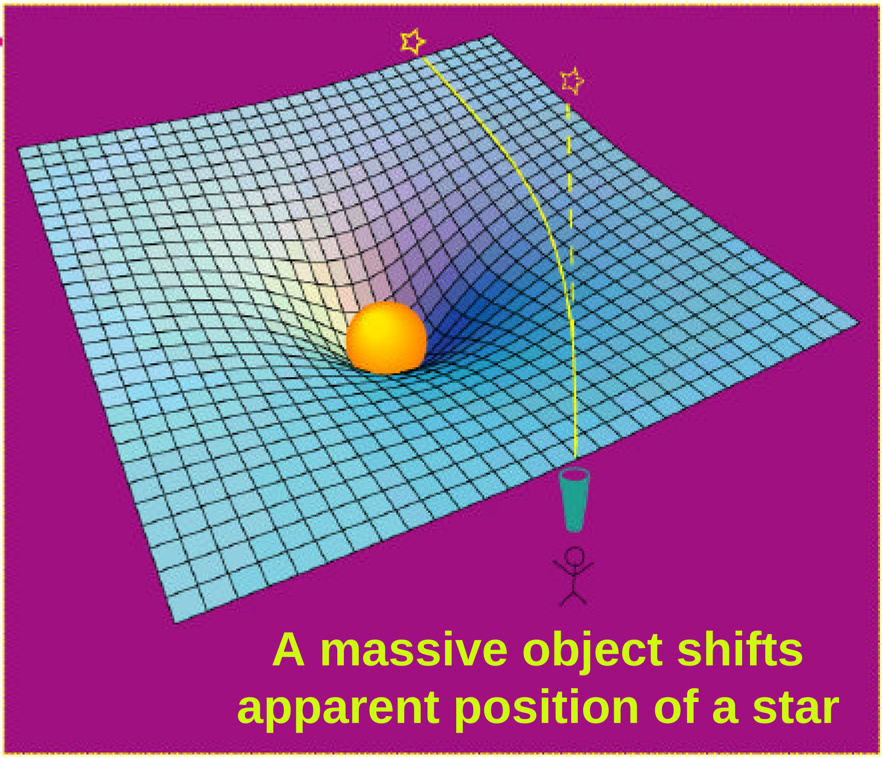
General Relativity: A Picture Worth a Thousand Words



New Wrinkle on Equivalence

bending of light

- Not only the path of matter, but even the path of light is affected by gravity from massive objects
- First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster
- Measurements showed that the light from these stars was bent as it grazed the Sun, by the exact amount of Einstein's predictions.



A massive object shifts apparent position of a star

The light never changes course, but merely follows the curvature of space. Astronomers now refer to this displacement of light as gravitational lensing.

Einstein's Theory of Gravitation
…at work

"Einstein Cross"
The bending of light rays
gravitational lensing

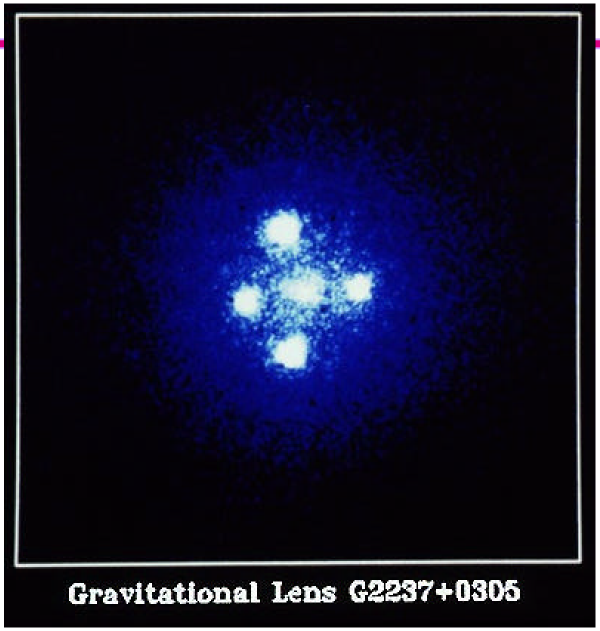


Photo credit: NASA and ESA

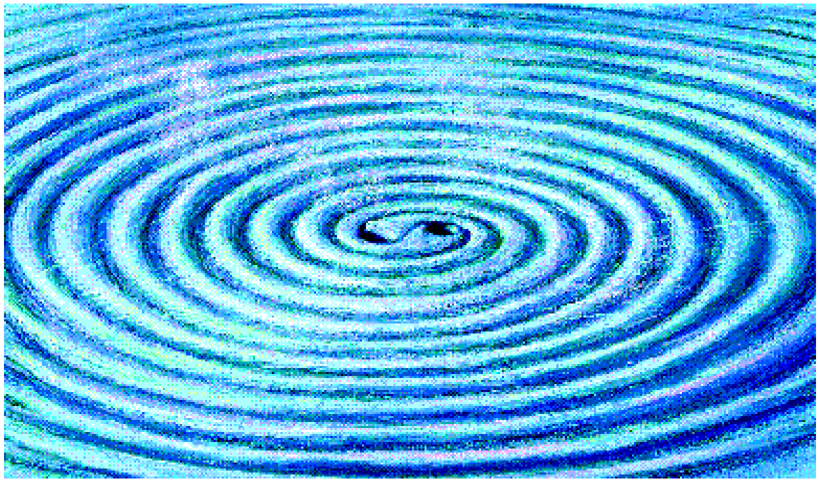
Quasar image appears around the central glow formed by nearby galaxy. The Einstein Cross is only visible in southern hemisphere.

In modern astronomy, such gravitational lensing images are used to detect a 'dark matter' body as the central object

Gravitational Waves

Gravitational waves are ripples in space when it is stirred up by rapid motions of large concentrations of matter or energy

Rendering of space stirred by two orbiting black holes:

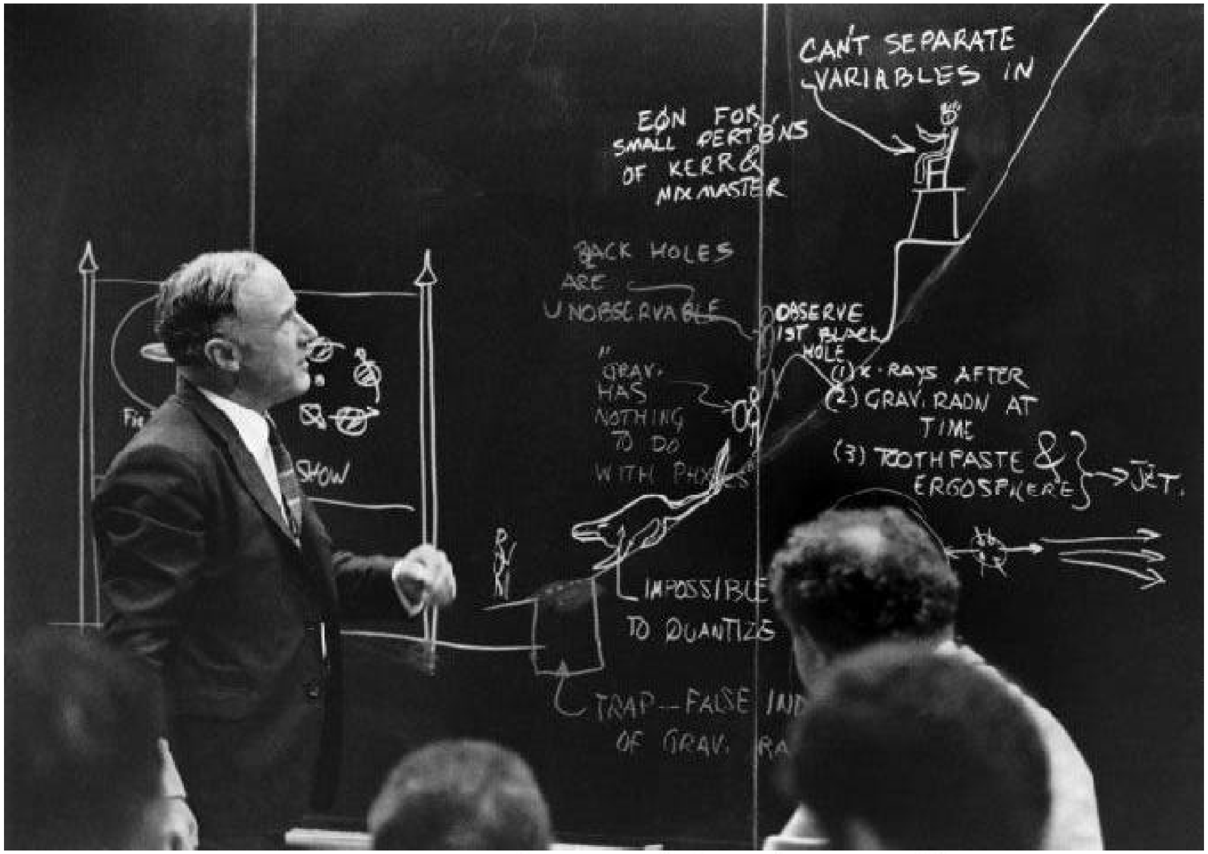


What Phenomena Do We Expect to Study With LIGO?

Gravitational Collapse and Its Outcomes Present LIGO Opportunities

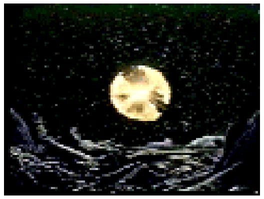
f_{GW} > few Hz accessible from earth

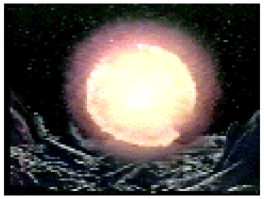
f_{GW} < several kHz interesting for compact objects



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

The Brilliant Deaths of Stars





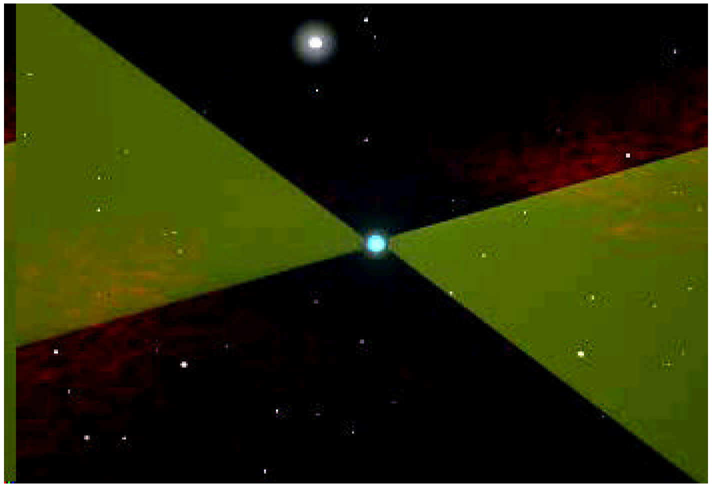
time evolution

Supernovae

Images from NASA High Energy Astrophysics Research Archive

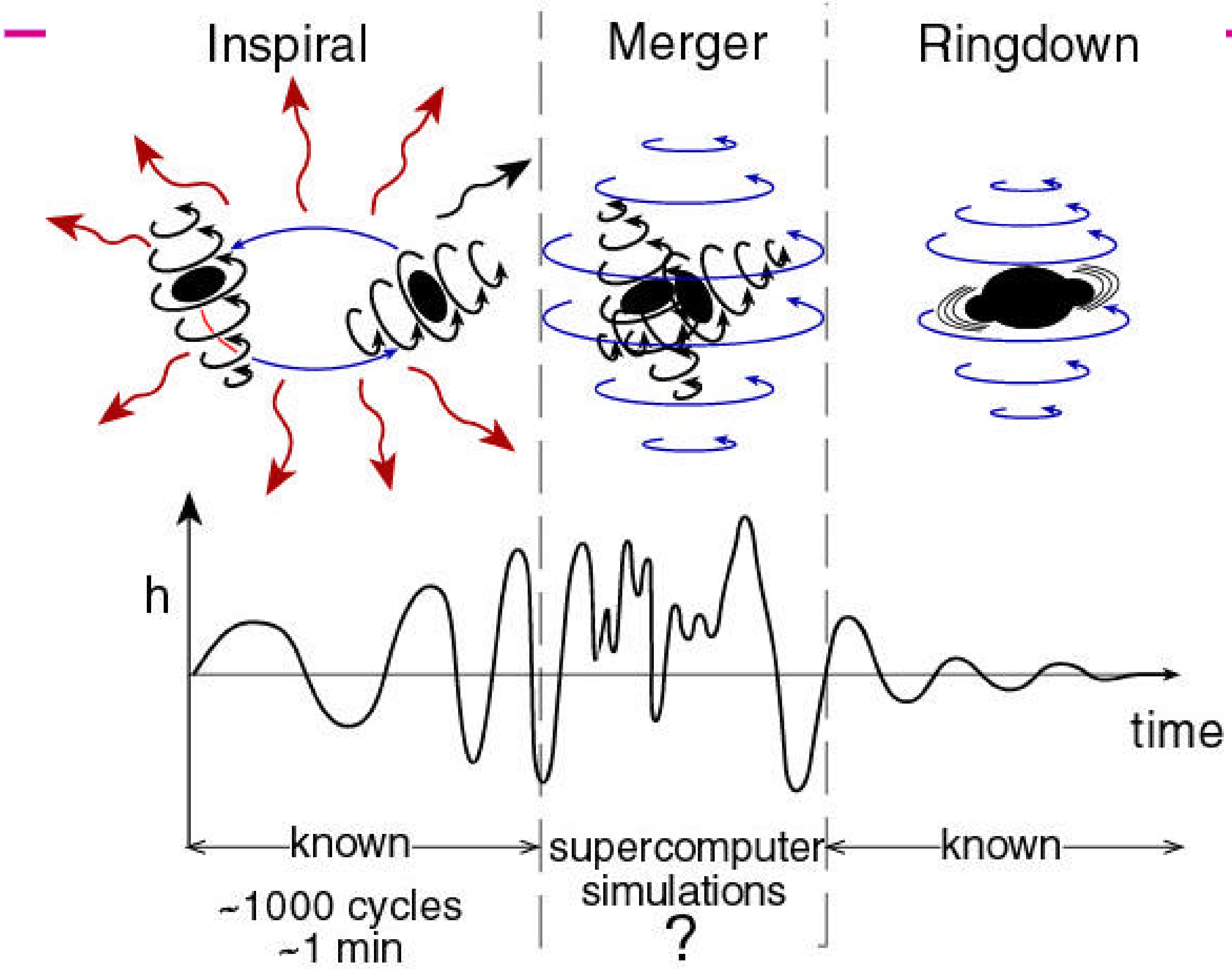
The "Undead" Corpses of Stars: Neutron Stars and Black Holes

- Neutron stars have a mass equivalent to 1.4 suns packed into a ball 10 miles in diameter, enormous magnetic fields and high spin rates
- Black holes are even more dense, the extreme edges of the space-time fabric



Artist: Walt Feimer, Space Telescope Science Institute

Catching Waves From Black Holes

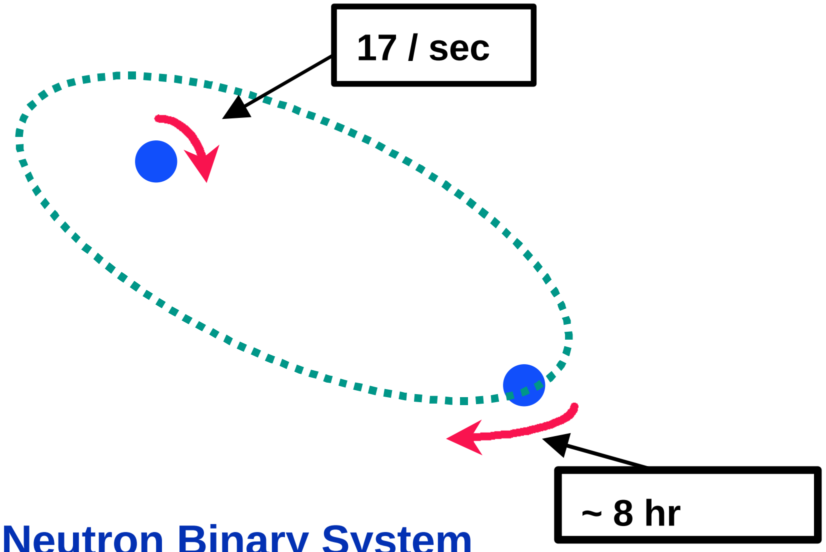


Sketches courtesy of Kip Thorne

Gravitational Waves
the evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

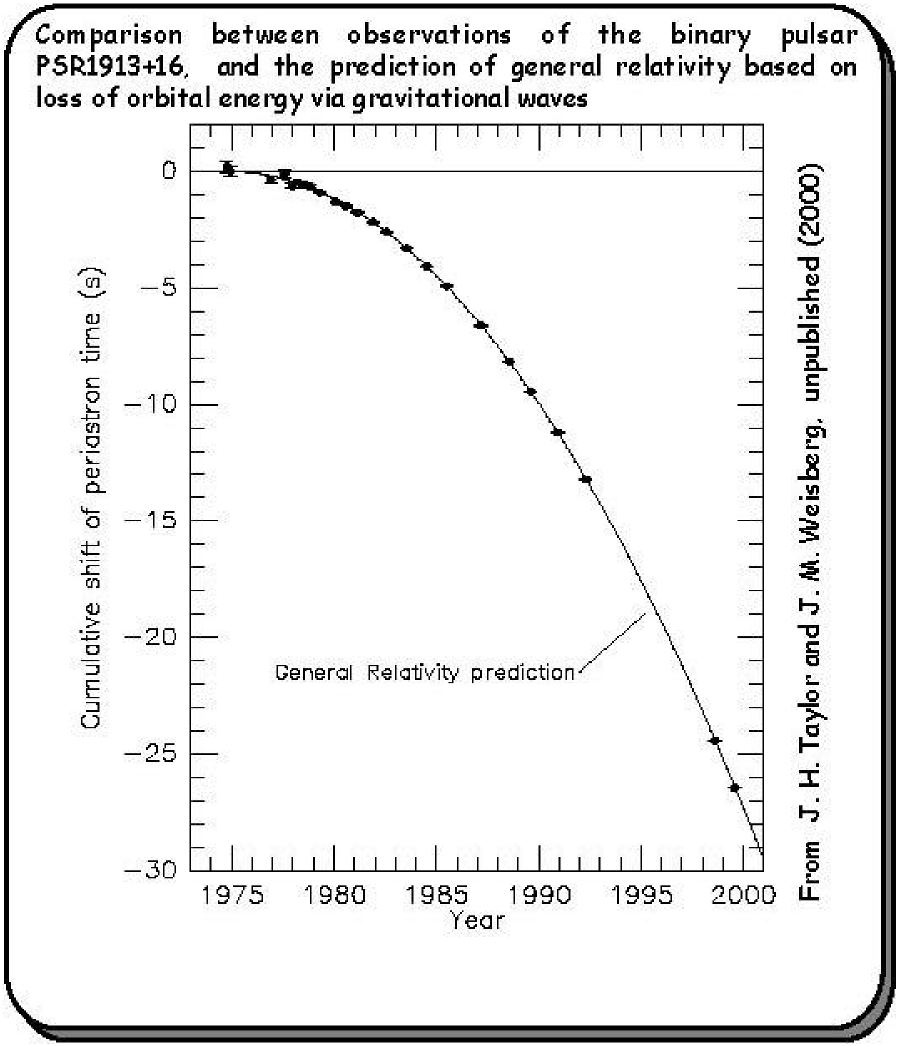

17 / sec

~ 8 hr

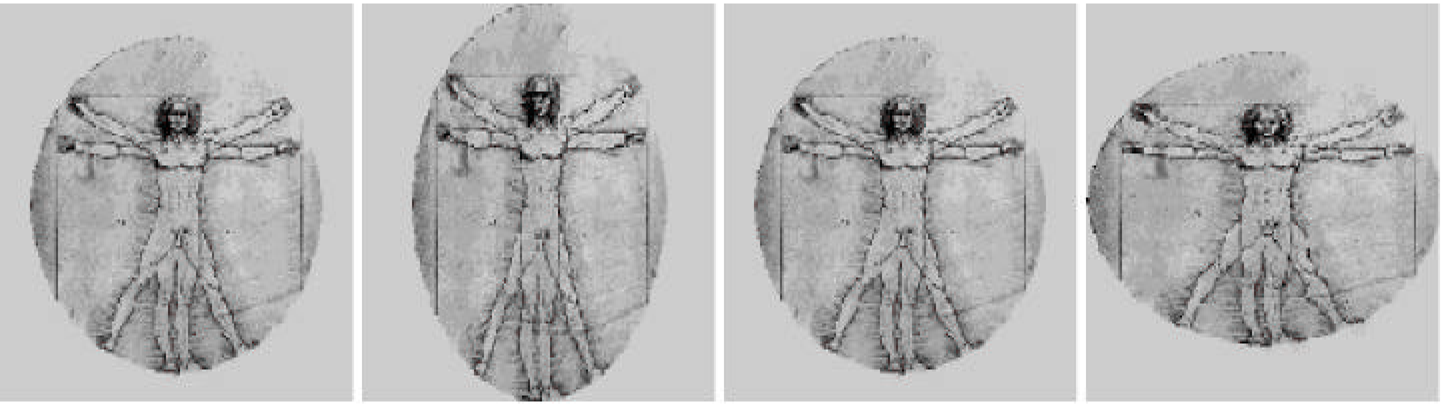
Neutron Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

Emission of gravitational waves

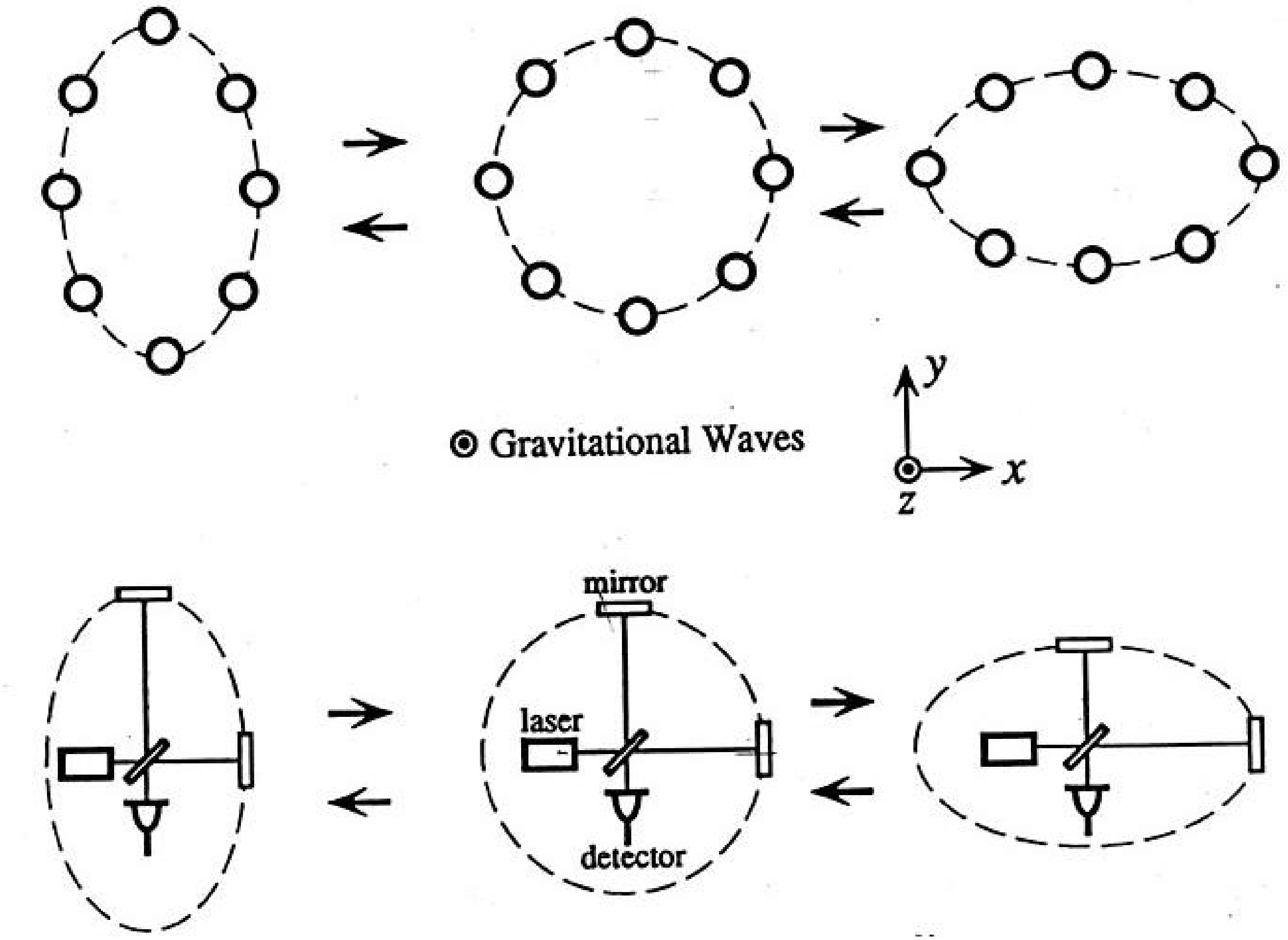

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

How does LIGO detect spacetime vibrations?

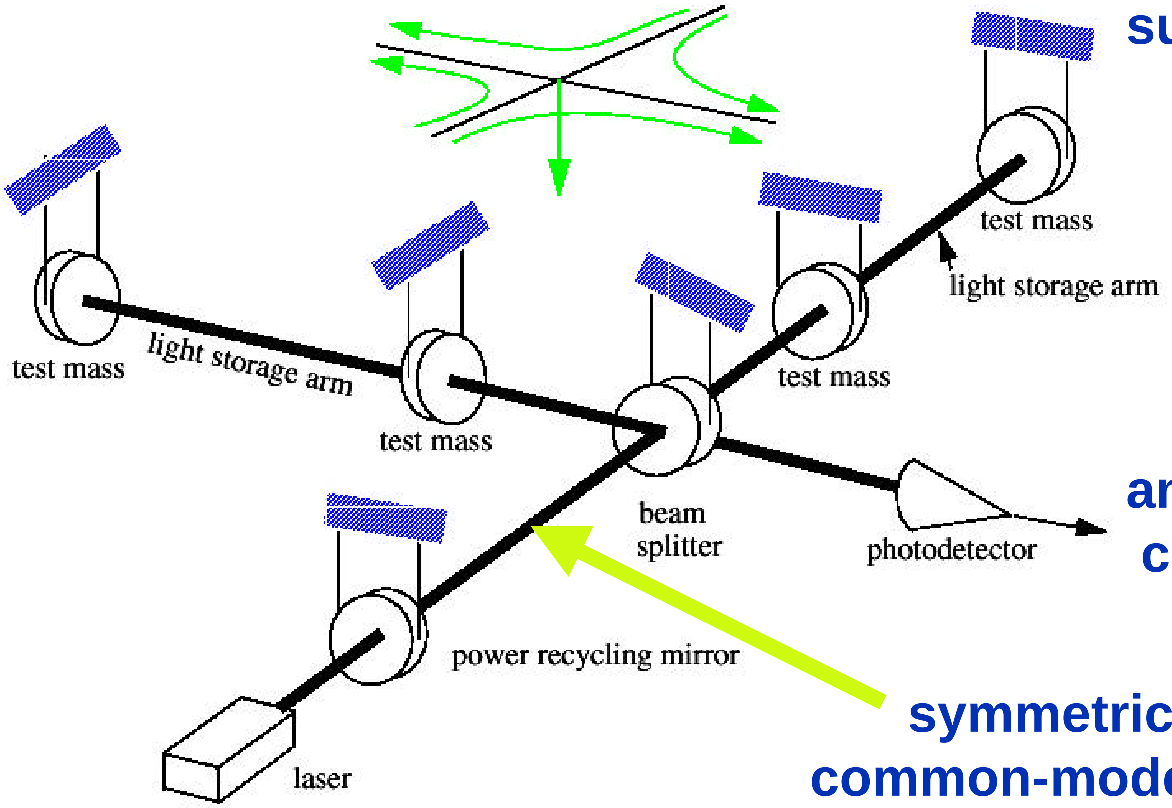


Leonardo da Vinci's Vitruvian man

Basic Signature of Gravitational Waves



Power-Recycled Fabry-Perot-Michelson Interferometer

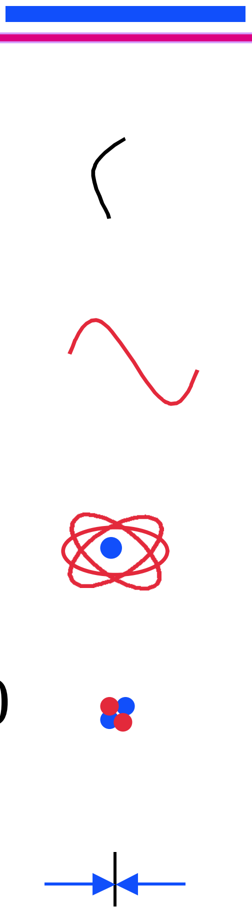


suspended mirrors mark inertial frames

antisymmetric port carries GW signal

symmetric port carries common-mode info, like shifts in laser frequency, intensity

How Small is 10^{-18} Meter?



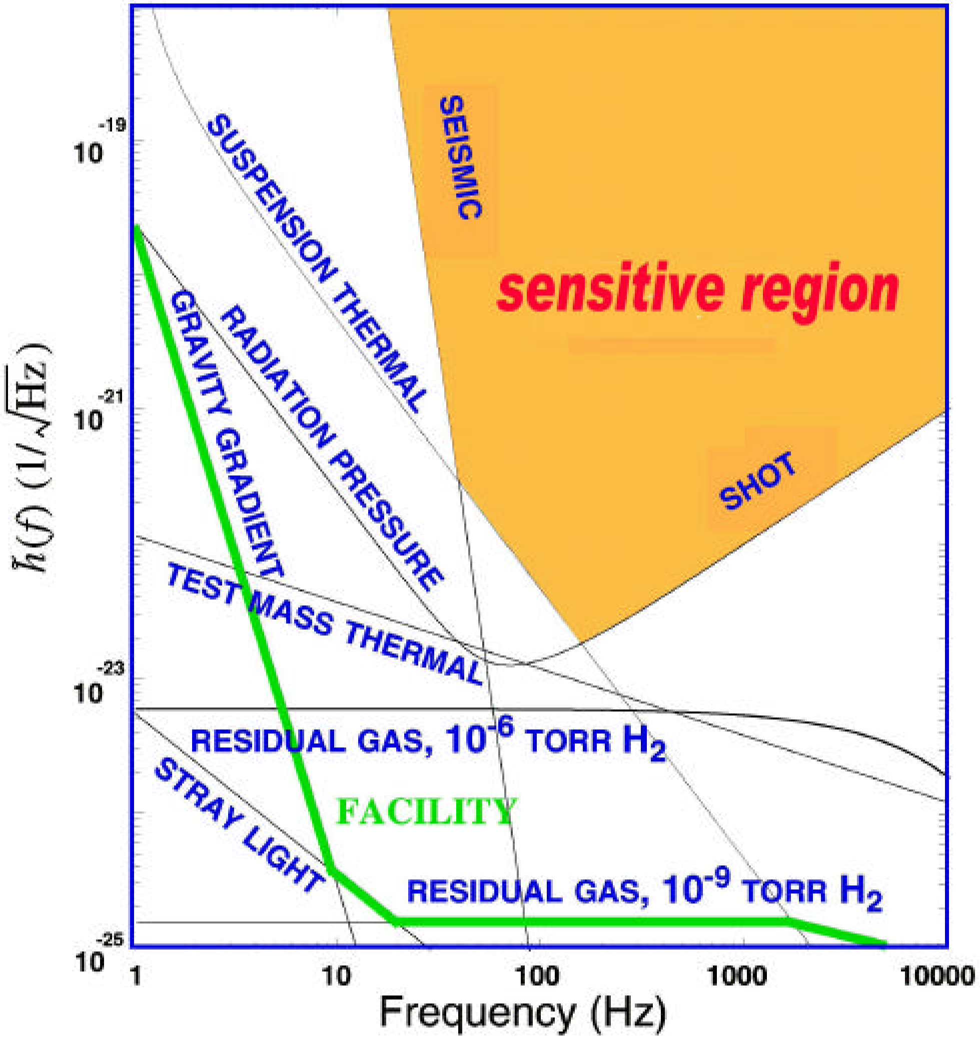
	One meter, about a yard
÷10,000	*Human hair, about 100 microns*
÷100	*Wavelength of light, about 1 micron*
÷10,000	*Atomic diameter, 10^{-10} meter*
÷100,000	*Nuclear diameter, 10^{-15} meter*
÷1,000	*LIGO sensitivity, 10^{-18} meter*

Some of the Technical Challenges

- Typical Strains < 10^{-21} at Earth ~ 1 hair's width at 4 light years
- Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000th of a proton diameter)
- Control arm lengths to 10^{-13} meters RMS
- Detect optical phase changes of ~ 10^{-10} radians
- Hold mirror alignments to 10^{-8} radians
- Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors

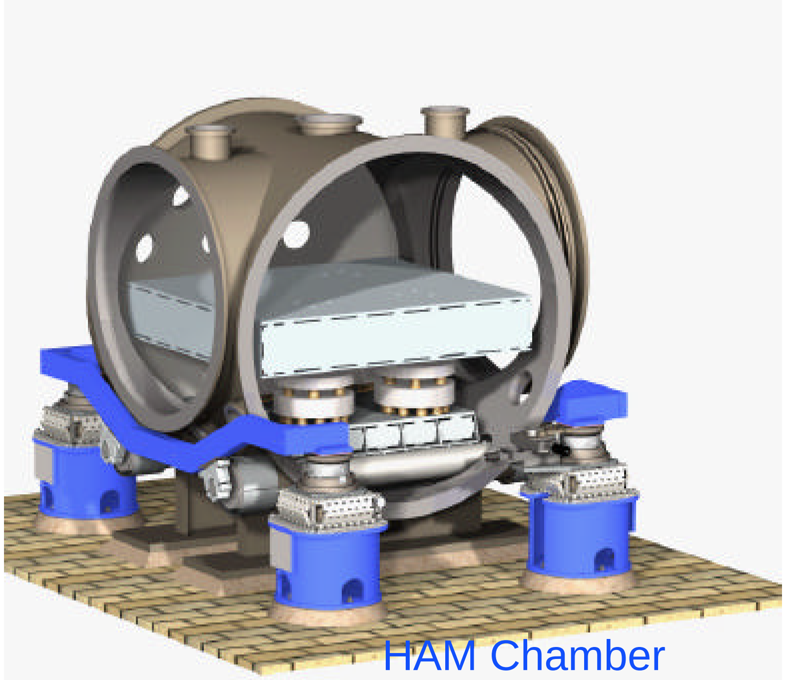
What Limits Sensitivity of Interferometers?

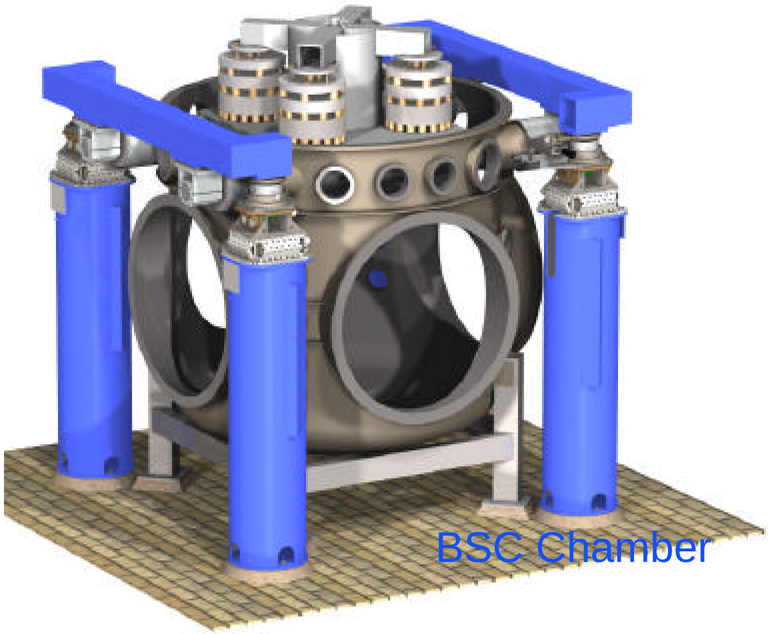
- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



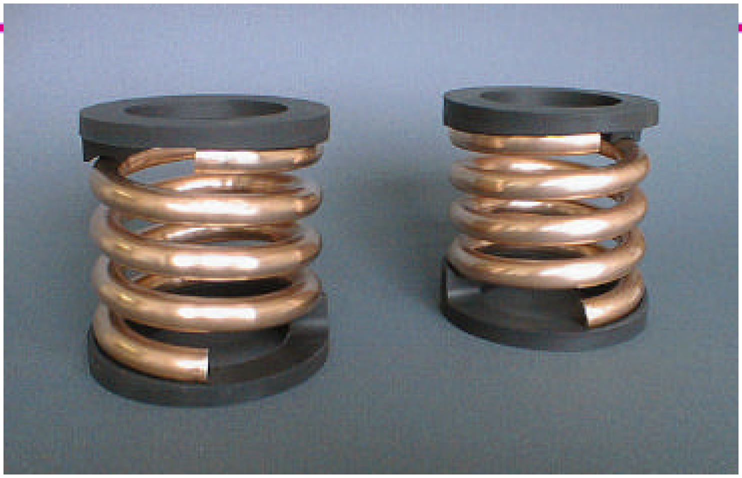
Vibration Isolation Systems

- 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

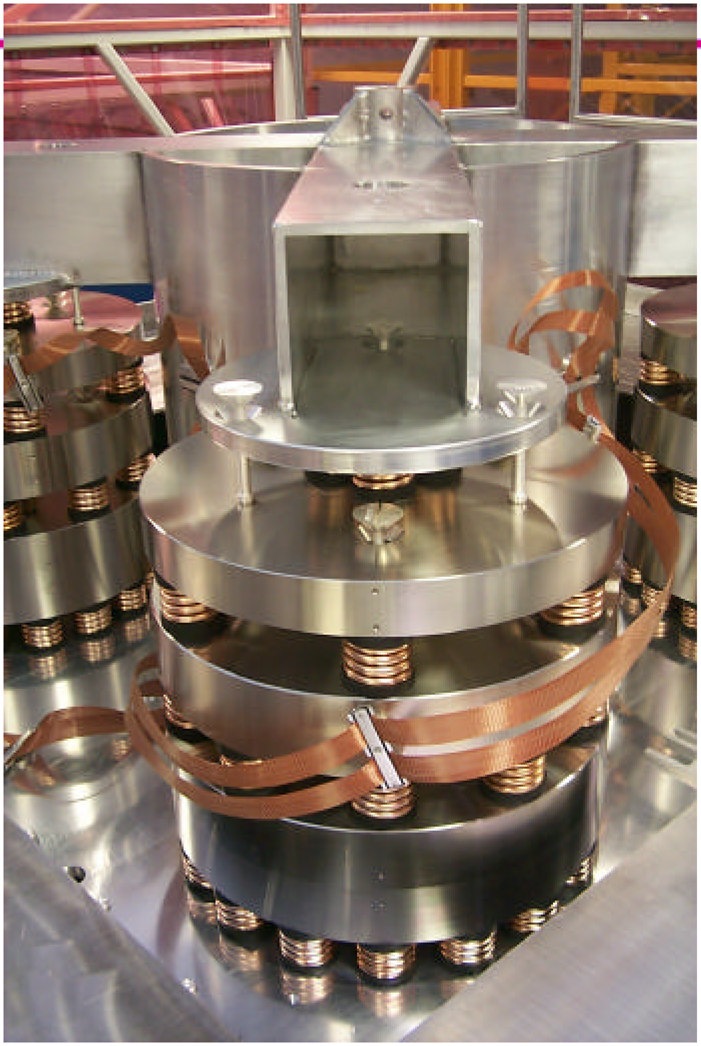

HAM Chamber


BSC Chamber

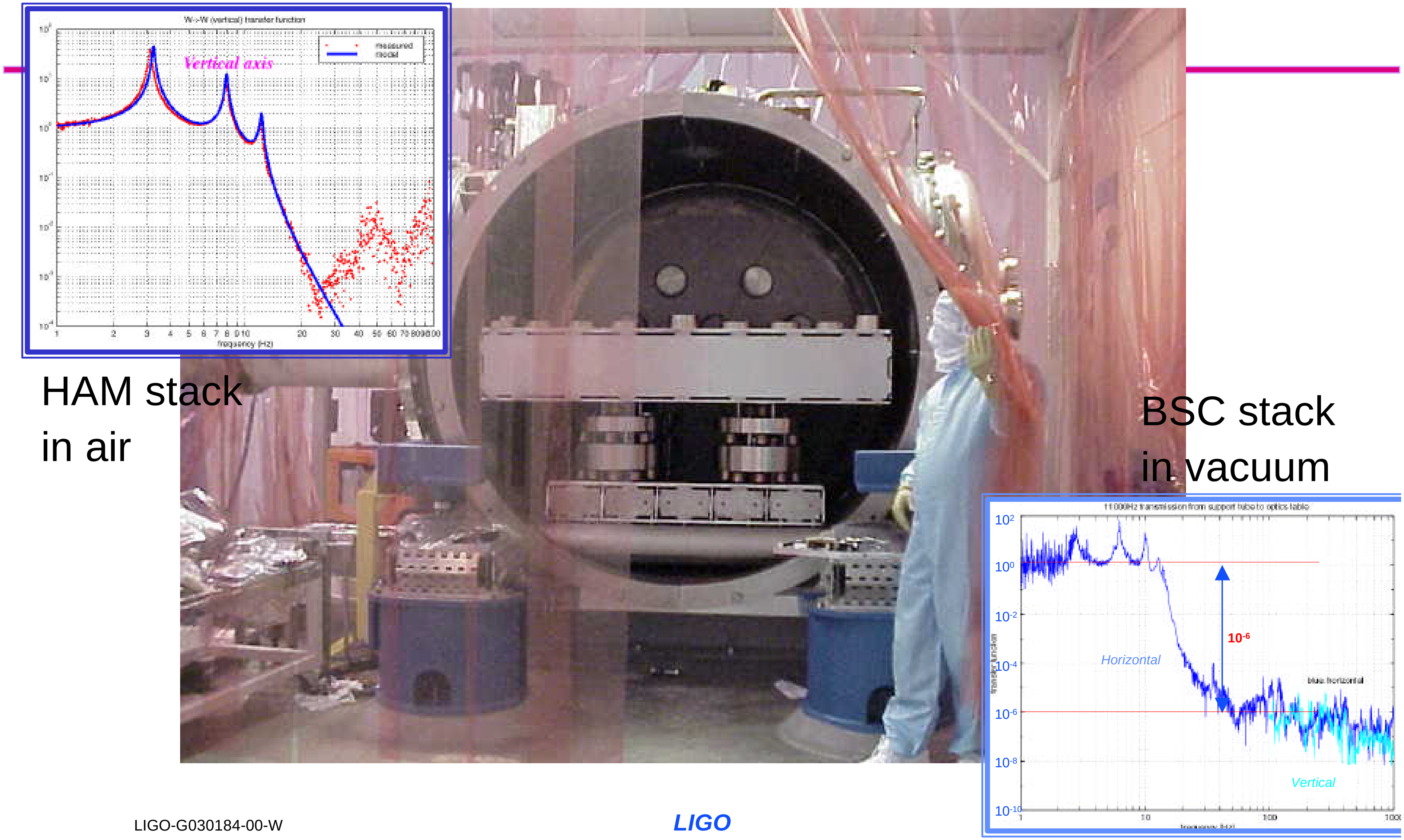
Seismic Isolation – Springs and Masses



damped spring
cross section



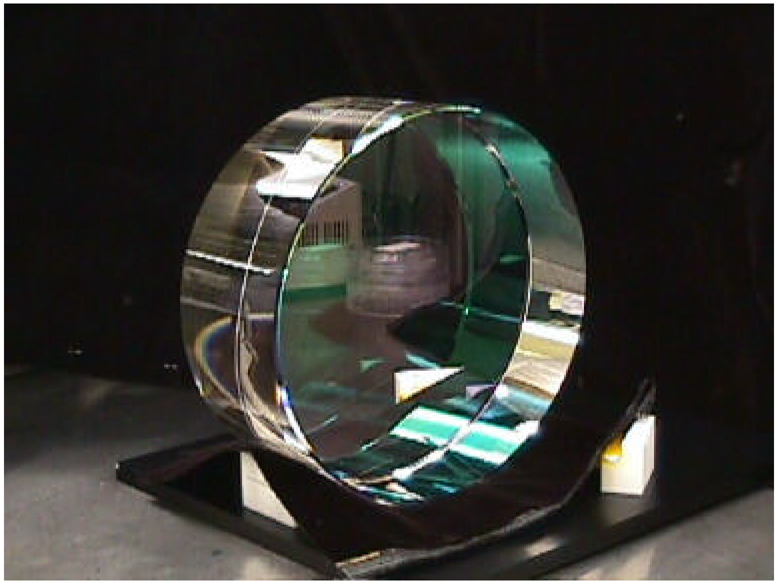
Seismic System Performance



HAM stack
in air

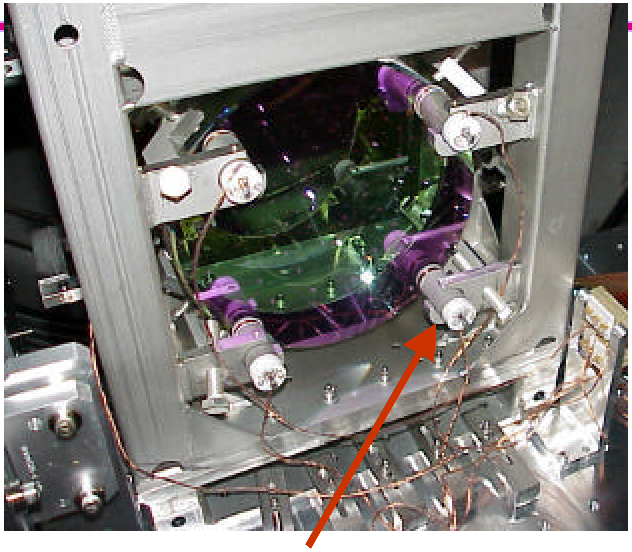
BSC stack
in vacuum

Core Optics

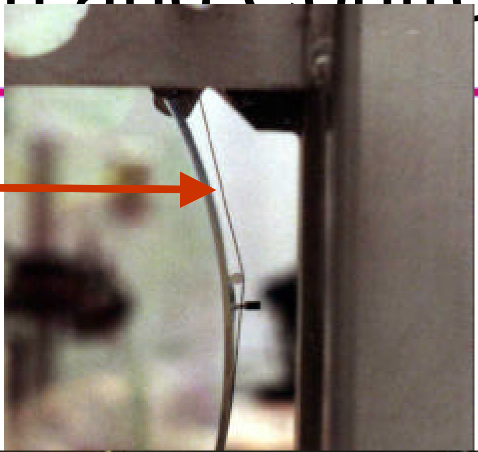


- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5×10^{-7}
  - » Internal mode Q's > 2×10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity $<10^{-3}$
- Production involved 6 companies, NIST, and LIGO

Core Optics Suspension and Control



Optics suspended as simple pendulums



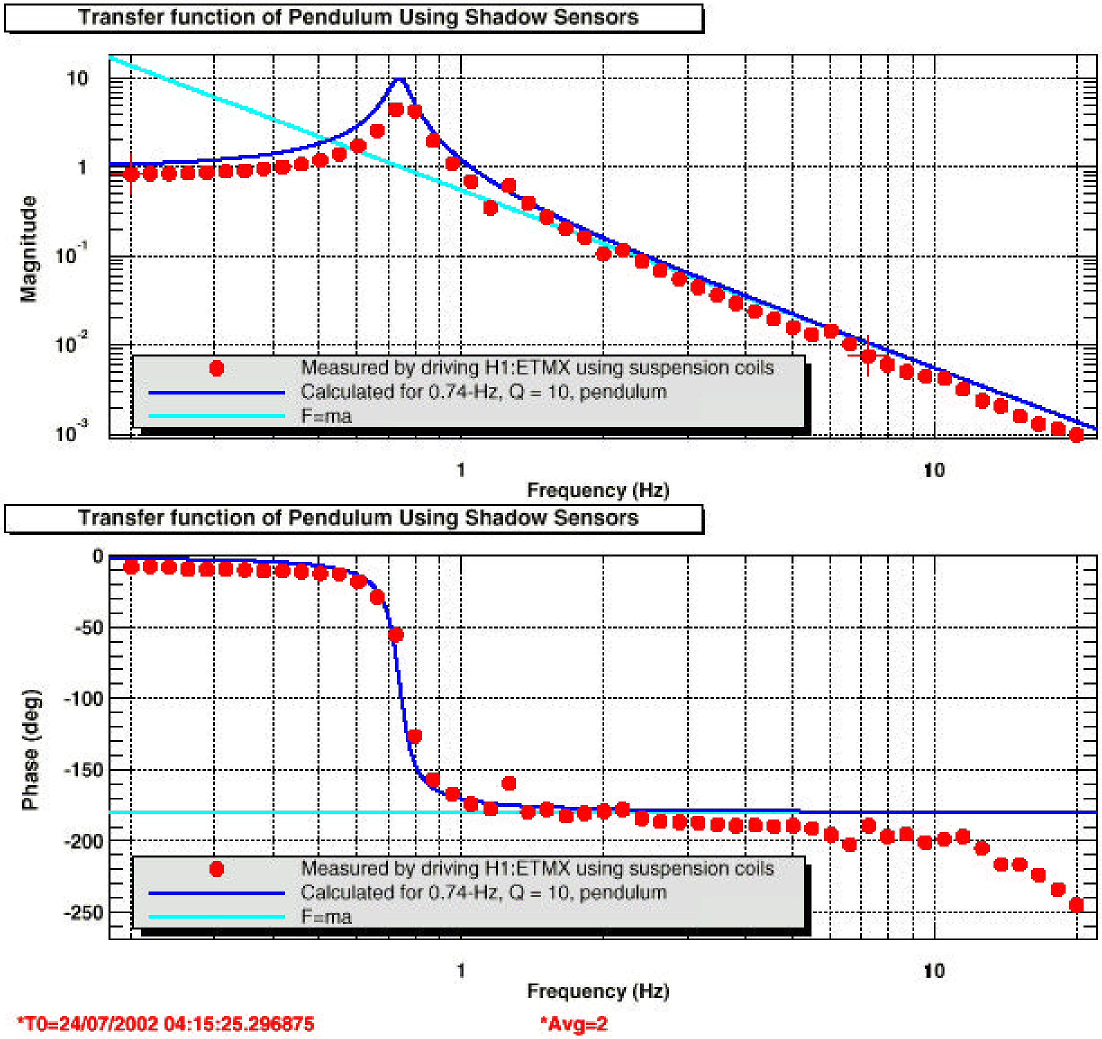
Shadow sensors & voice-coil actuators provide damping and control forces

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

Feedback & Control for Mirrors and Light

- Damp suspended mirrors to vibration-isolated tables
  - » 14 mirrors × (pos, pit, yaw, side) = 56 loops
- Damp mirror angles to lab floor using optical levers
  - » 7 mirrors × (pit, yaw) = 14 loops
- Pre-stabilized laser
  - » (frequency, intensity, pre-mode-cleaner) = 3 loops
- Cavity length control
  - » (mode-cleaner, common-mode frequency, common-arm, differential arm, michelson, power-recycling) = 6 loops
- Wave-front sensing/control
  - » 7 mirrors × (pit, yaw) = 14 loops
- Beam-centering control
  - » 2 arms × (pit, yaw) = 4 loops

Suspended Mirror Approximates a Free Mass Above Resonance



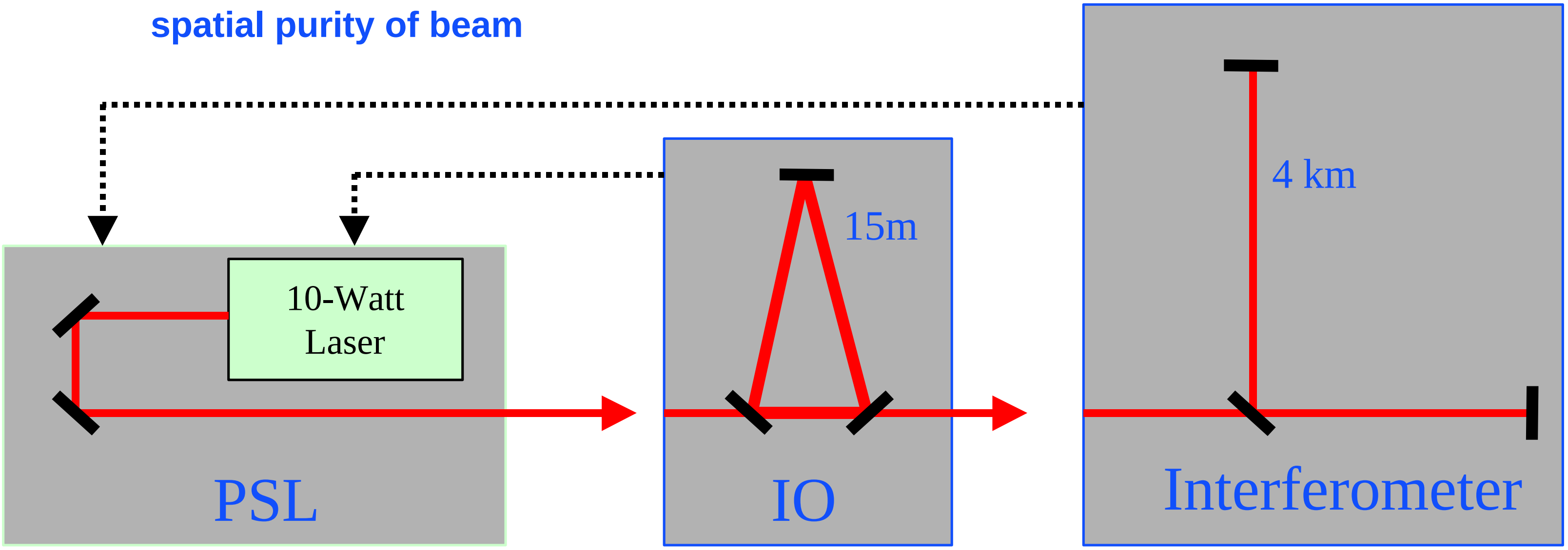
Blue: suspended mirror XF

Cyan: free mass XF

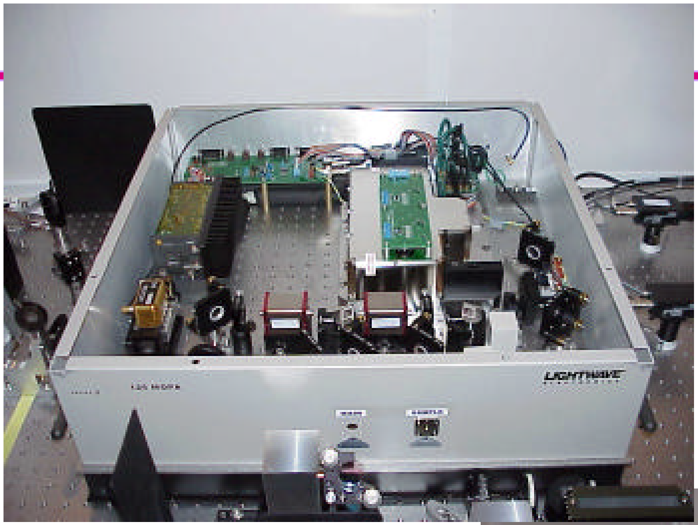
Data taken using shadow sensors & voice coil actuators

Frequency Stabilization of the Light Employs Three Stages

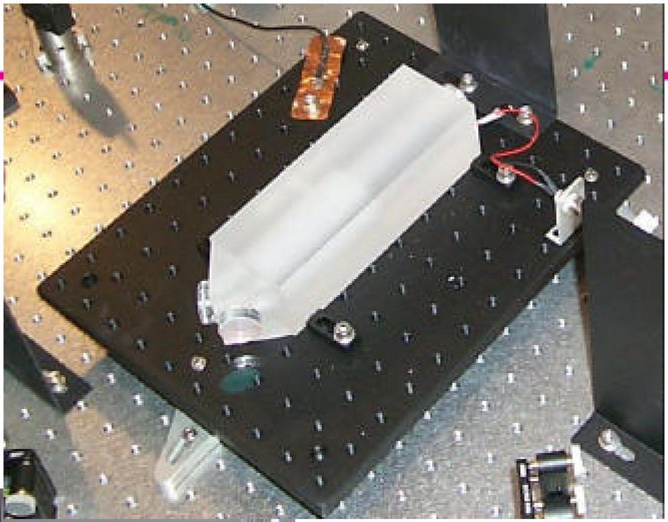
- Pre-stabilized laser delivers light to the long mode cleaner
  - **Start with high-quality, custom-built Nd:YAG laser**
  - **Improve frequency, amplitude and spatial purity of beam**
- Actuator inputs provide for further laser stabilization
  - **Wideband**
  - **Tidal**



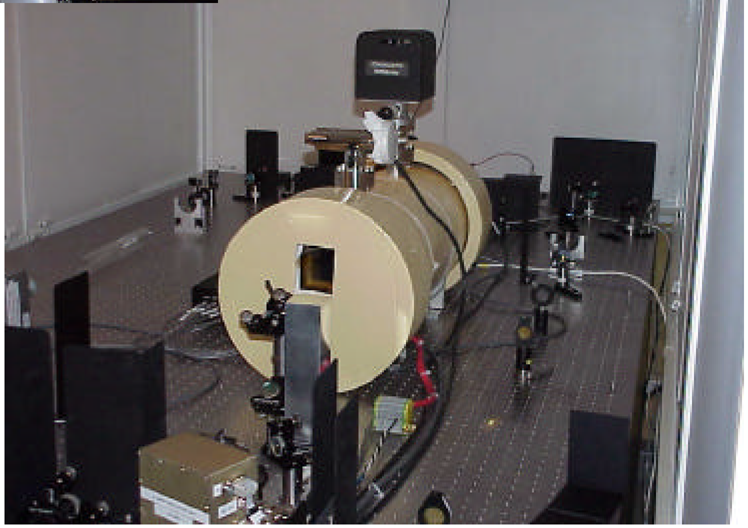
Pre-stabilized Laser (PSL)



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

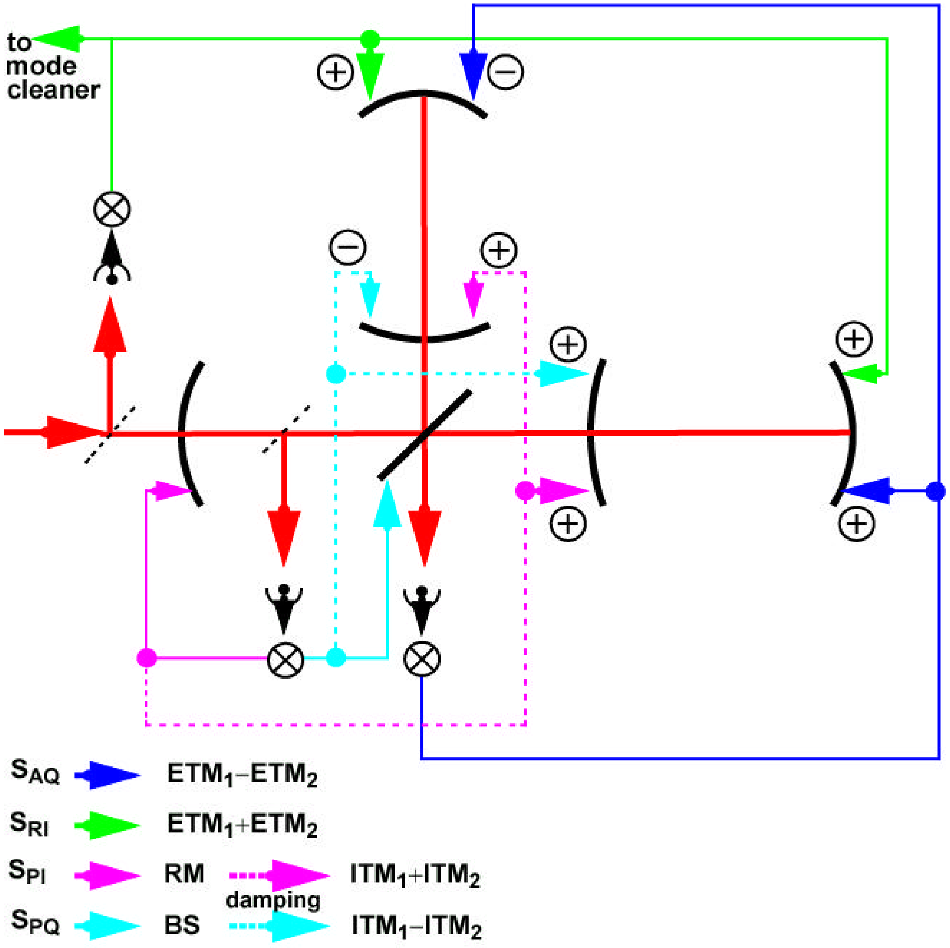


Cavity for
defining beam geometry,
joint development with
Stanford



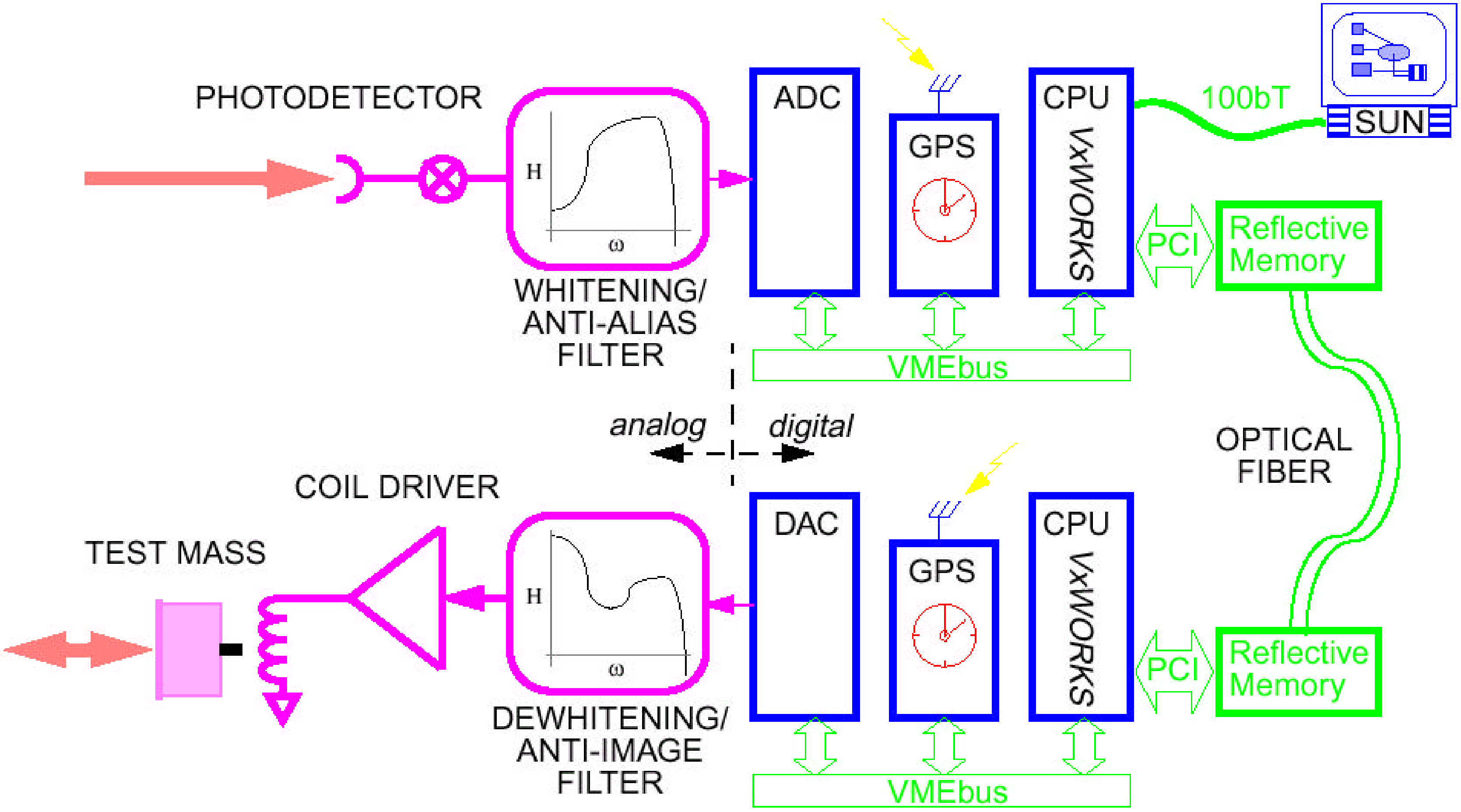
Frequency reference
cavity (inside oven)

Interferometer Length 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

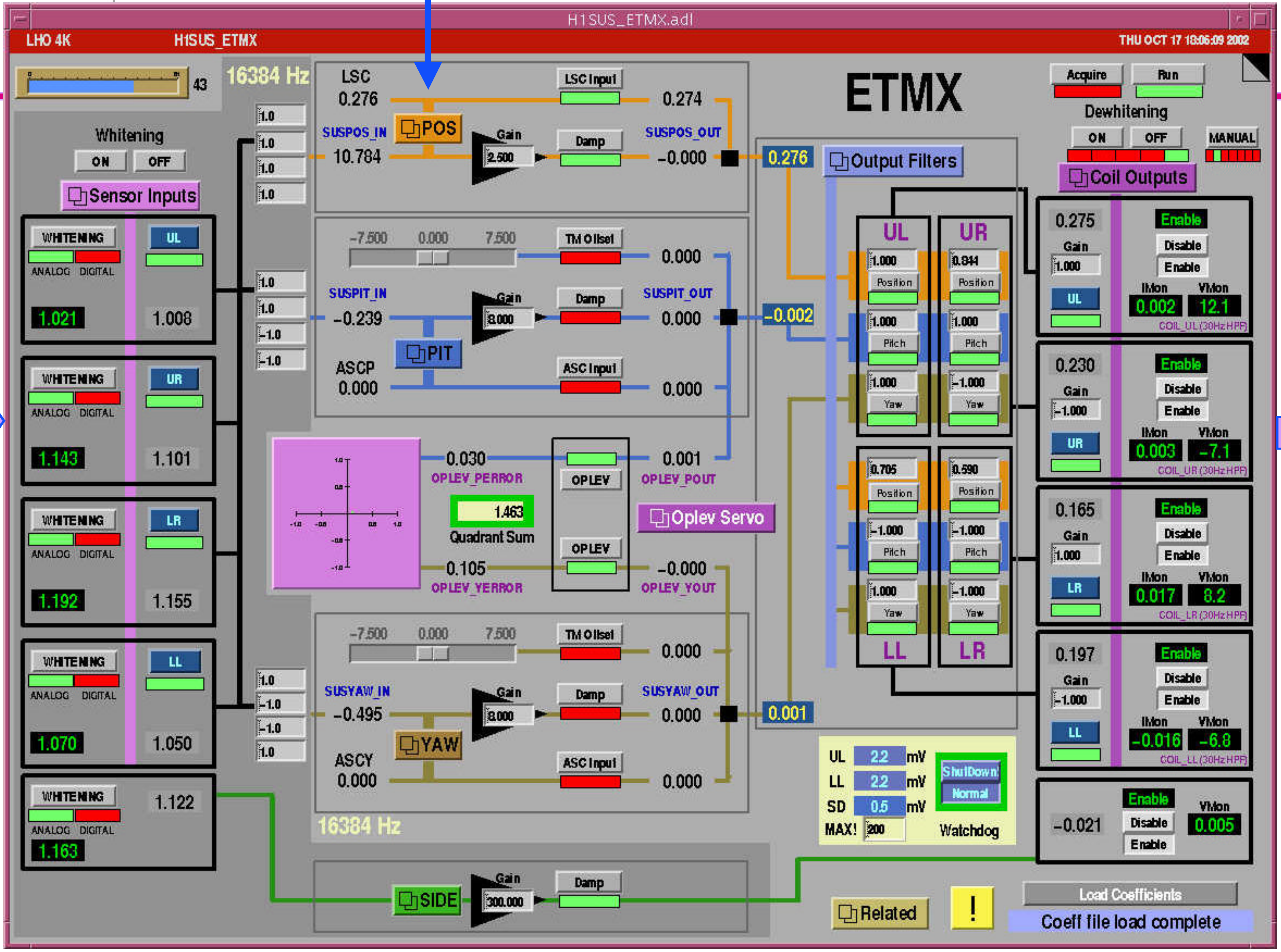
Digital Interferometer Sensing & Control System



Digital Controls screen example

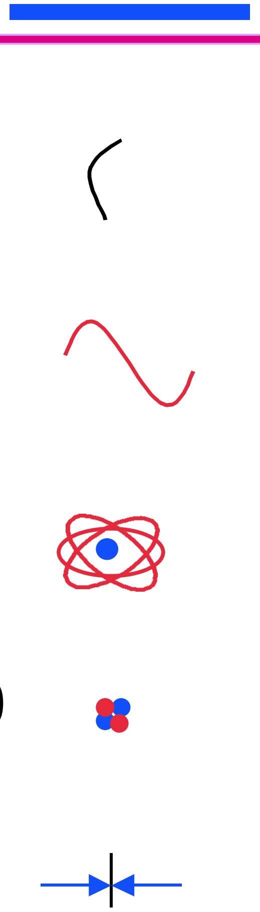
Digital calibration input

Analog In



Analog Out

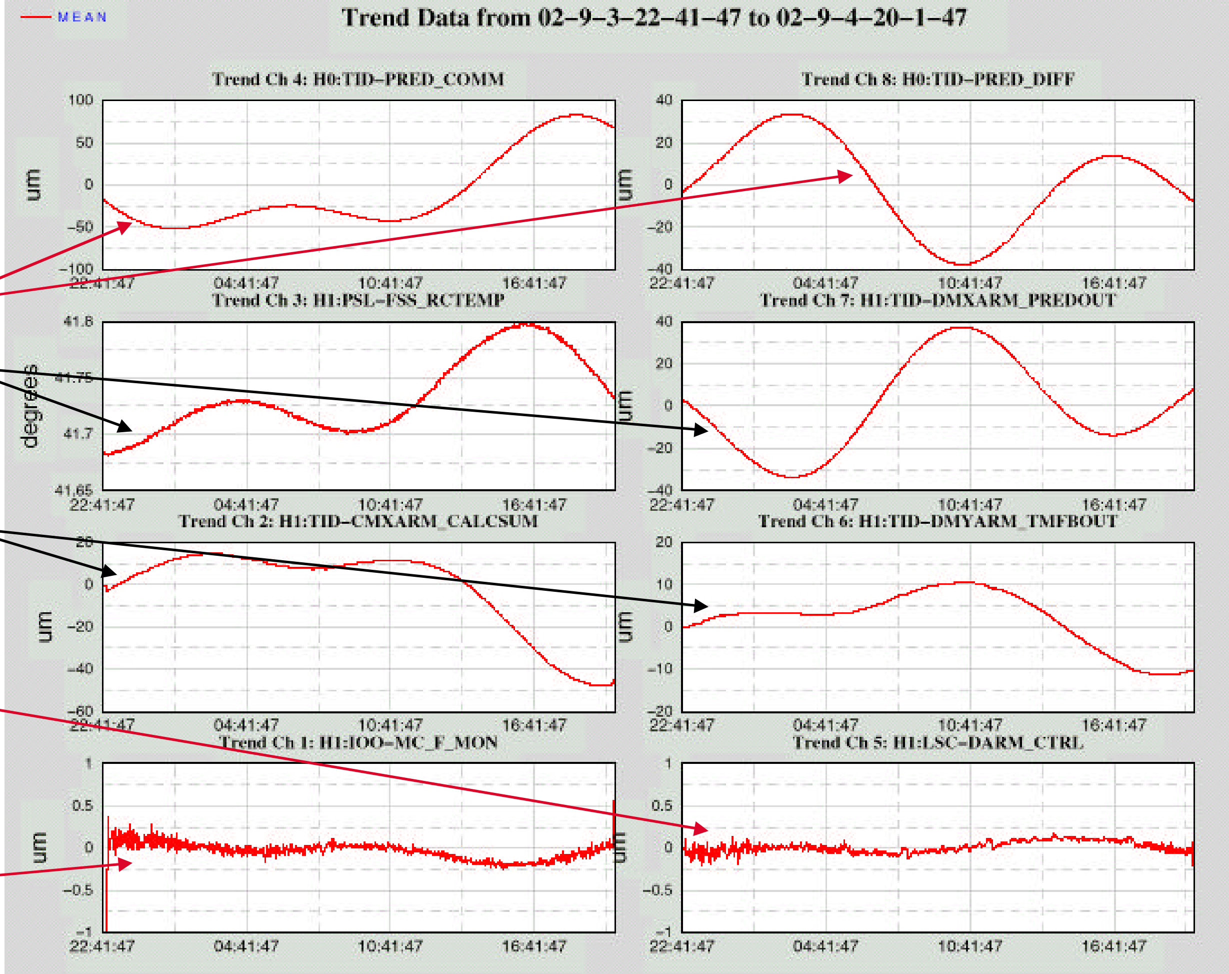
Why is Locking Difficult?



	One meter
÷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*

Tidal Compensation Data

Tidal evaluation on 21-hour locked section of S1 data



Predicted tides

Feedforward

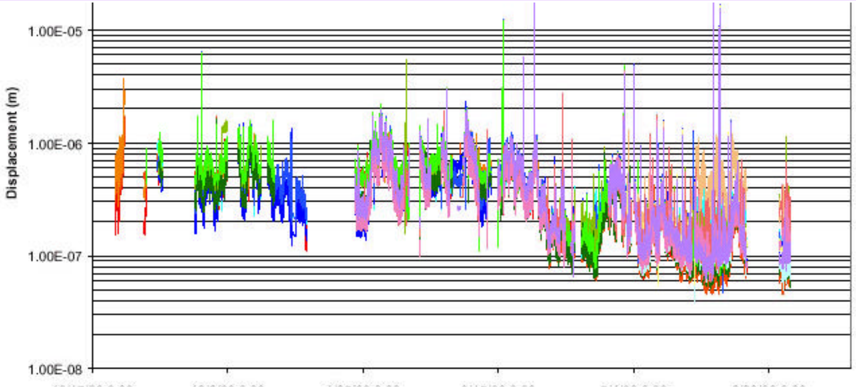
Feedback

Residual signal on voice coils

Residual signal on laser

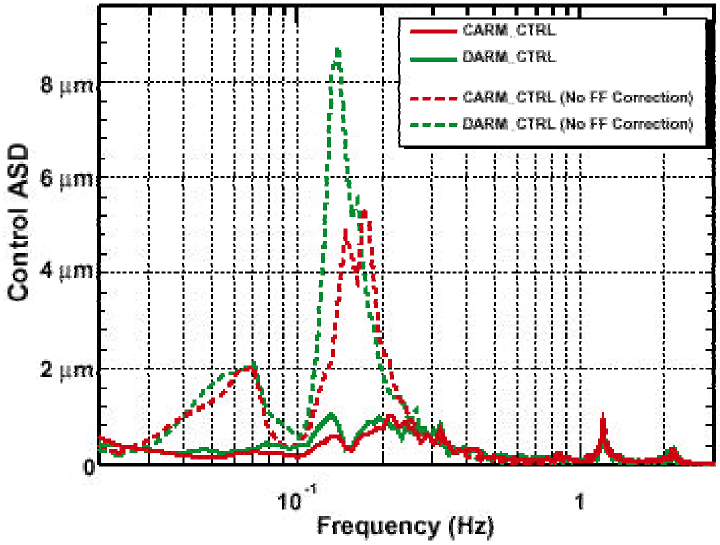
Microseism: Effect of Ocean Waves

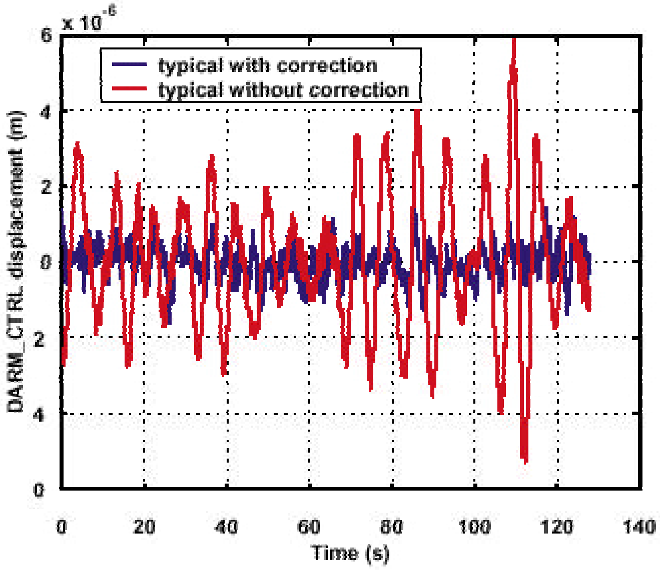
Microseism at 0.12 Hz dominates ground velocity



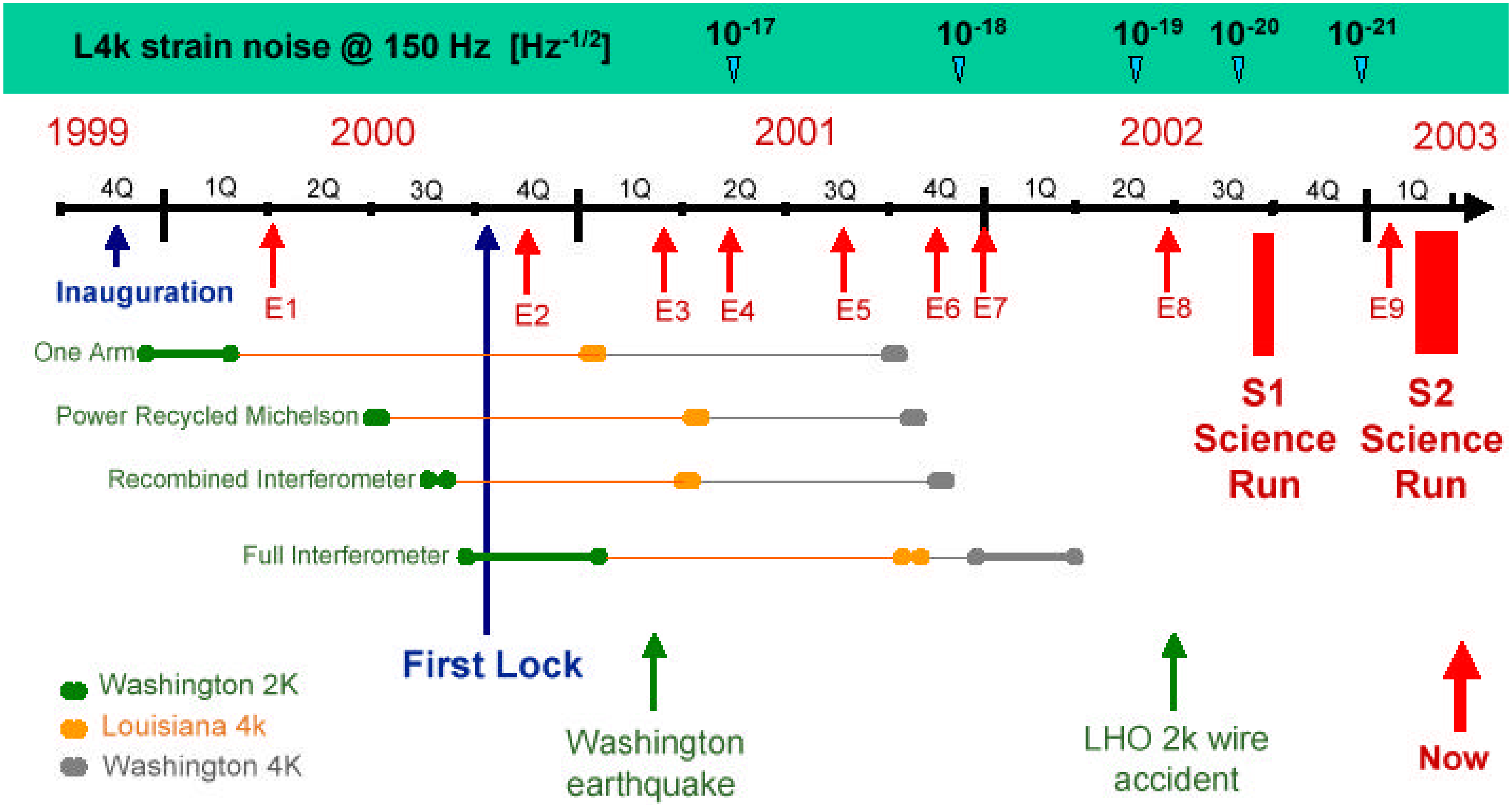
Trended data (courtesy of Gladstone High School) shows large variability of microseism, on several-day- and annual- cycles

Reduction by feed-forward derived from seismometers

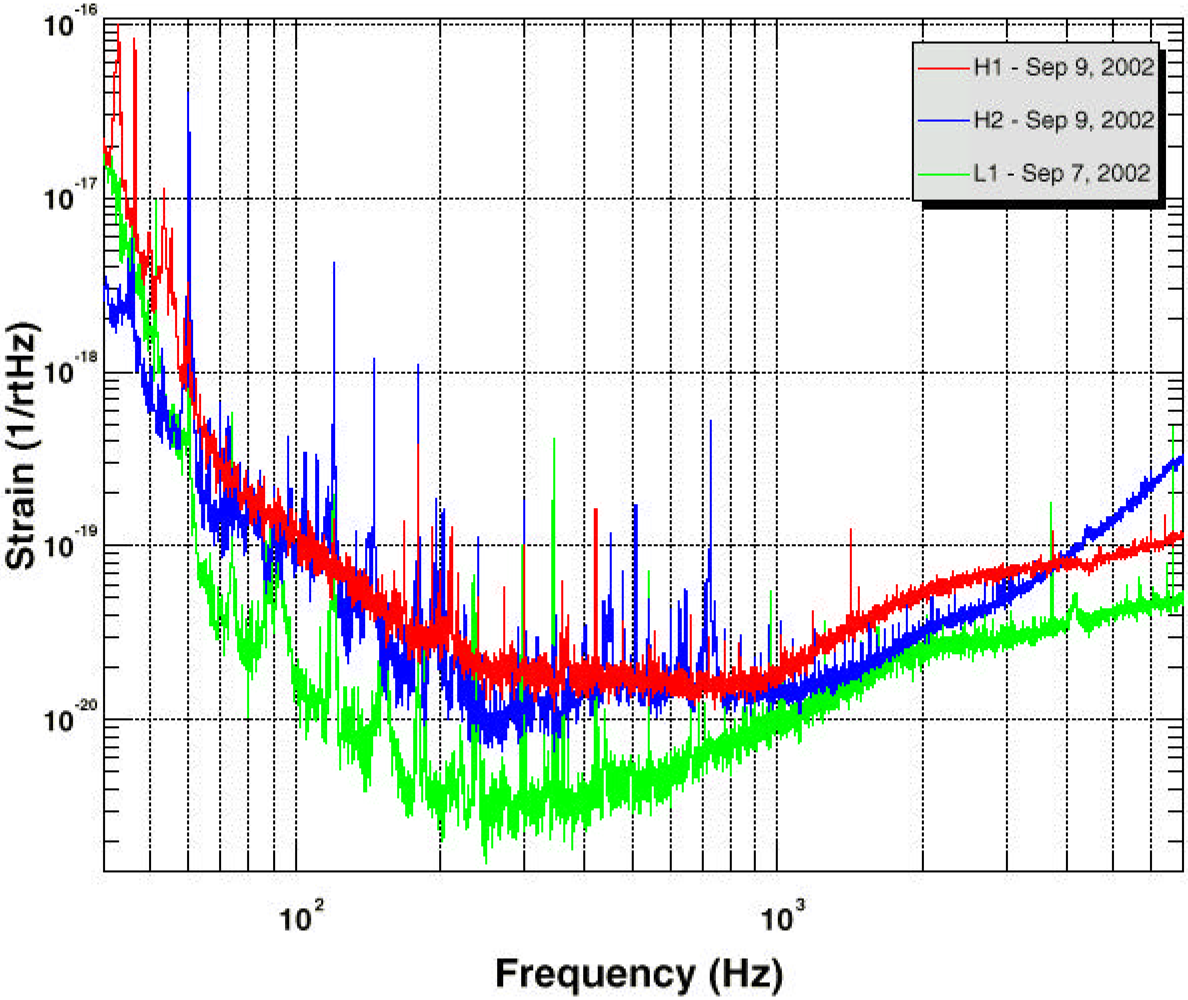




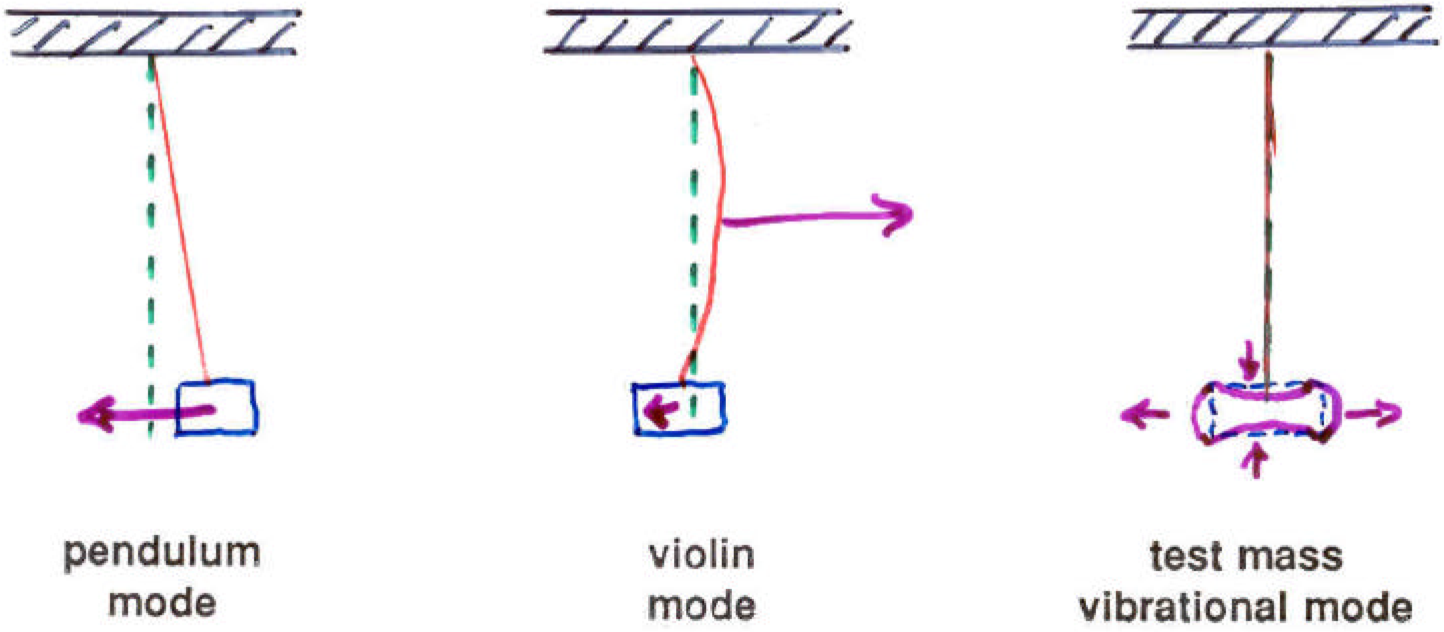
Commissioning Time Line



Noise Equivalent Strain Spectra for S1



Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



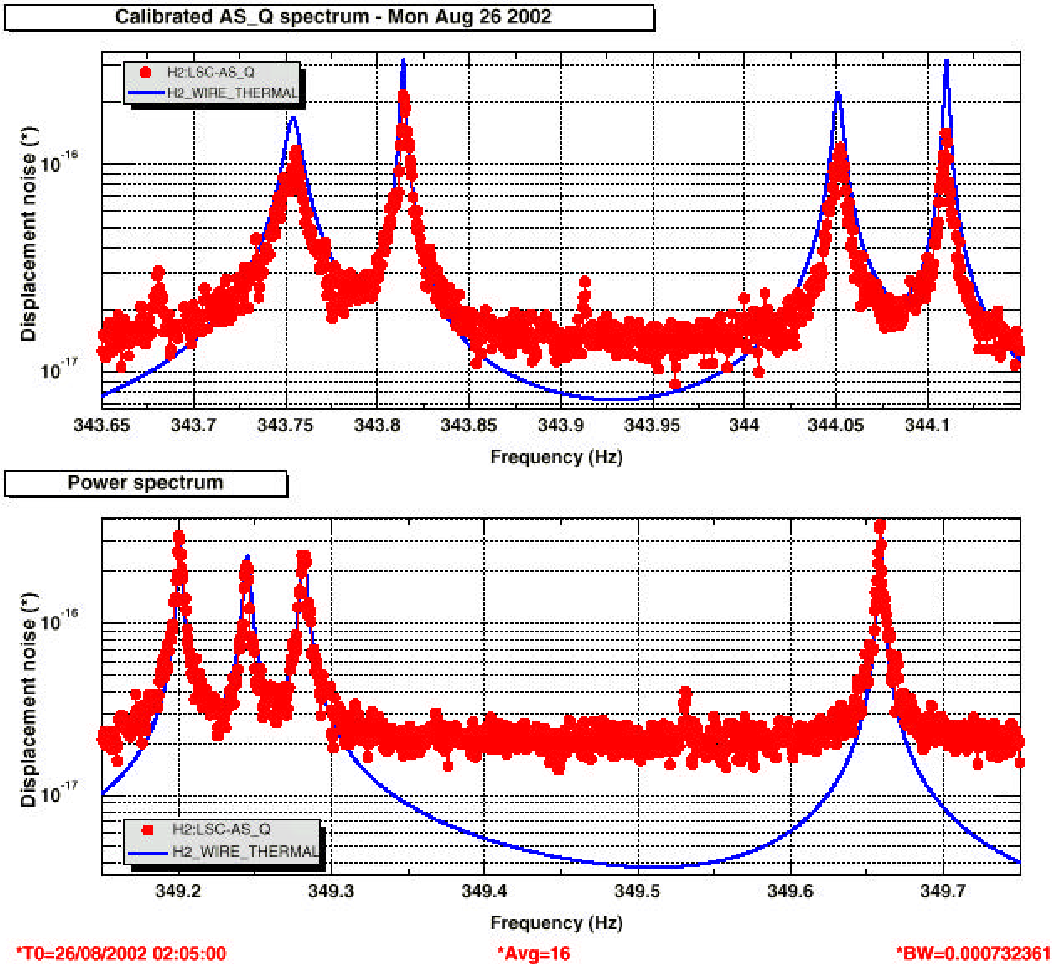
$x_{rms} \approx 10^{-11}$ m
f < 1 Hz

$x_{rms} \approx 2\times10^{-17}$ m
f ~ 350 Hz

$x_{rms} \approx 5\times10^{-16}$ m
f ≥ 10 kHz

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

Thermal Noise Observed in 1st Violins on H2, L1 During S1



~ 20 millifermi
RMS for each
free wire
segment

Binary Neutron Stars:
S1 Range

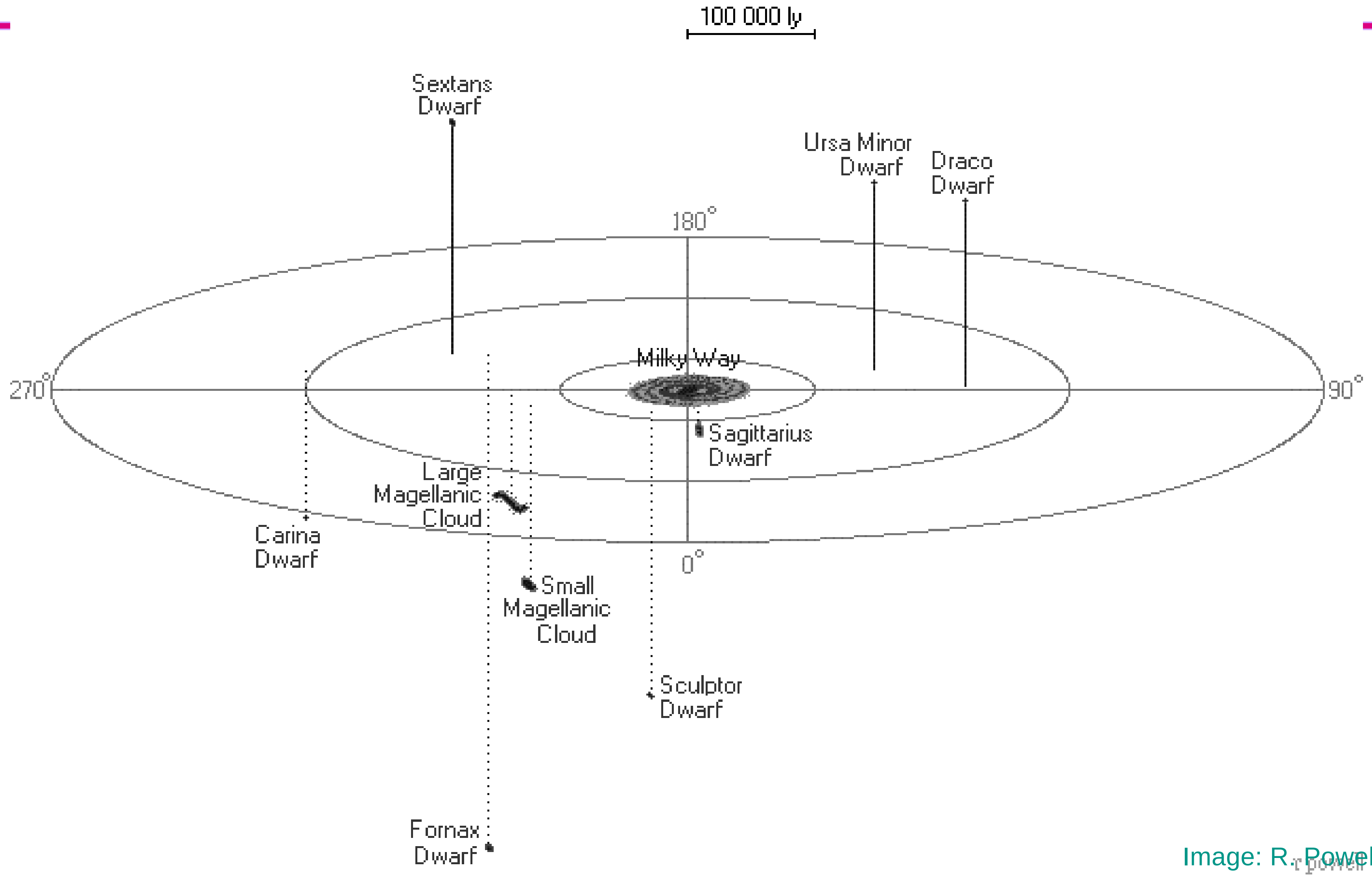
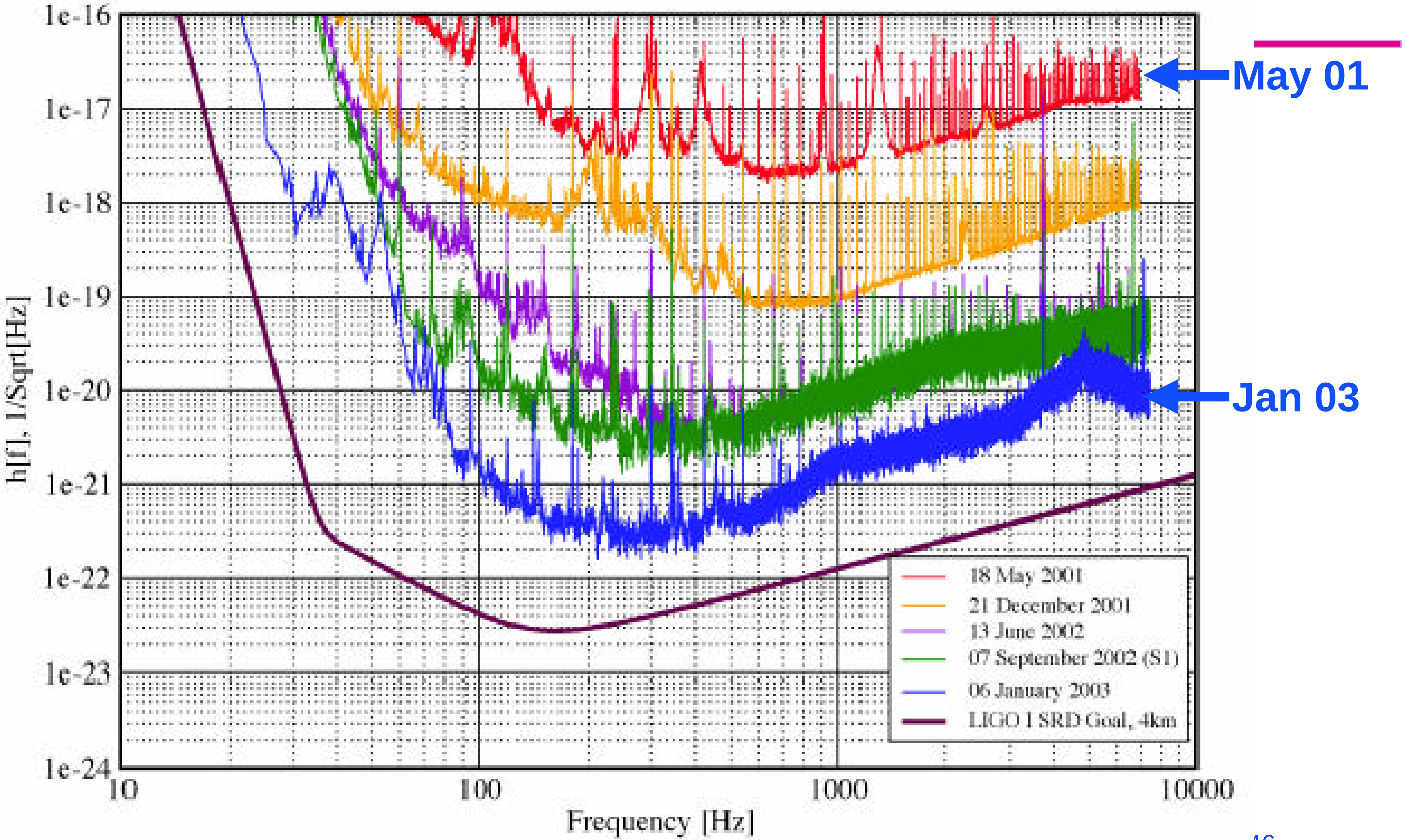


Image: R. Powell

LIGO Sensitivity Over Time

Livingston 4km Interferometer



May 01

Jan 03

Binary Neutron Stars: S2 Range

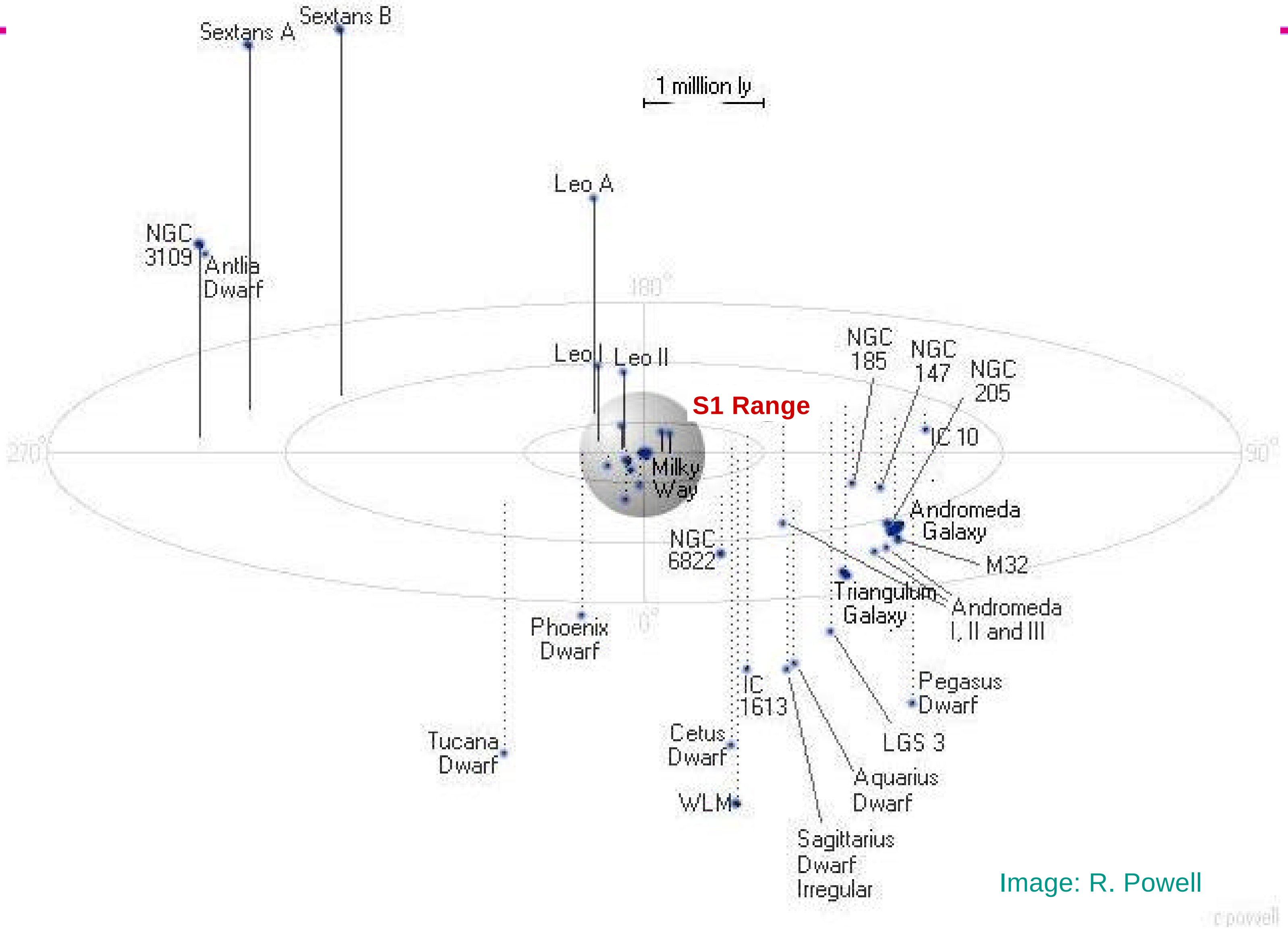


Image: R. Powell

Binary Neutron Stars: Initial LIGO Target Range

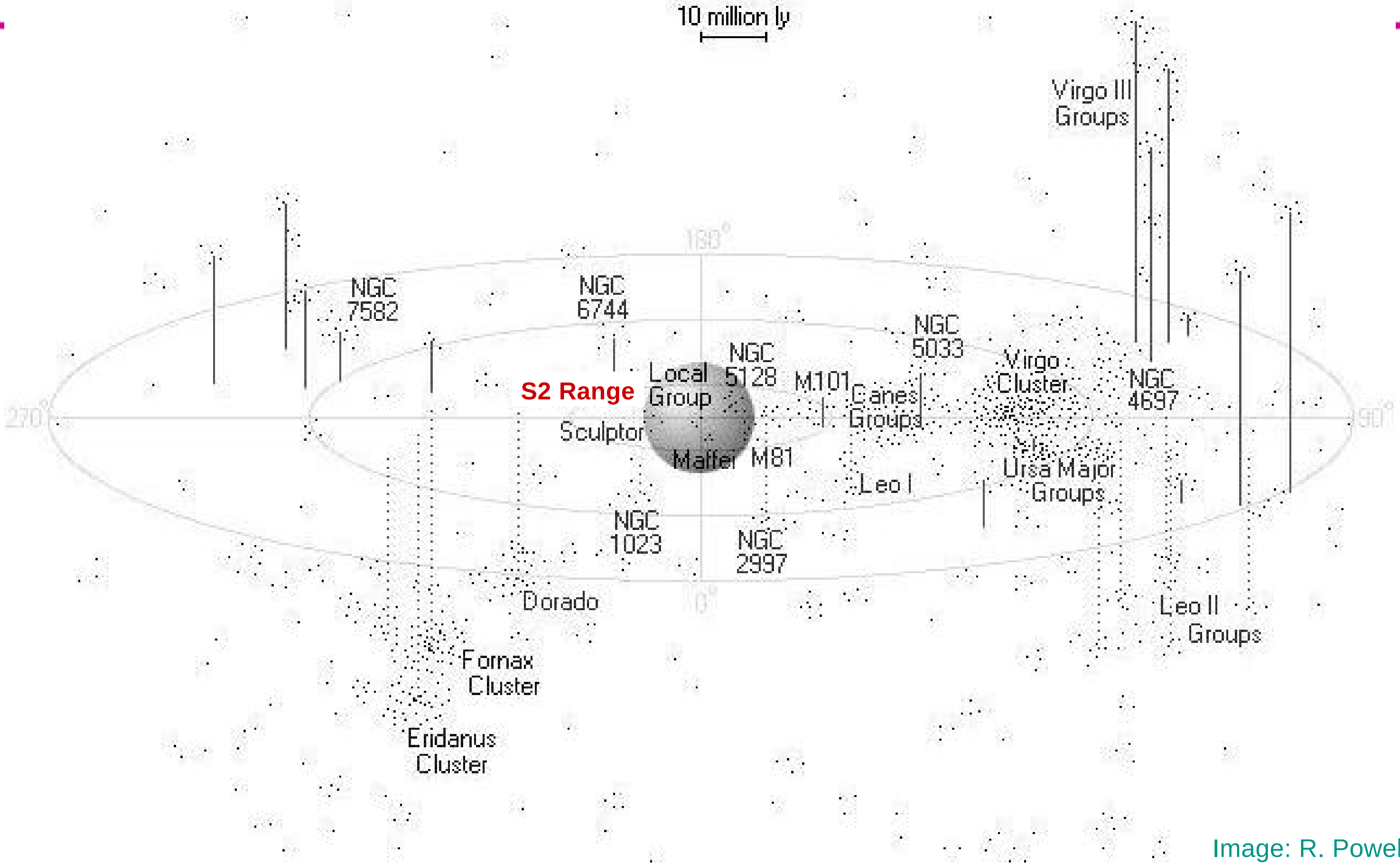
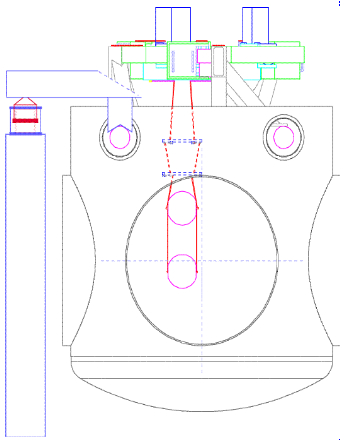


Image: R. Powell

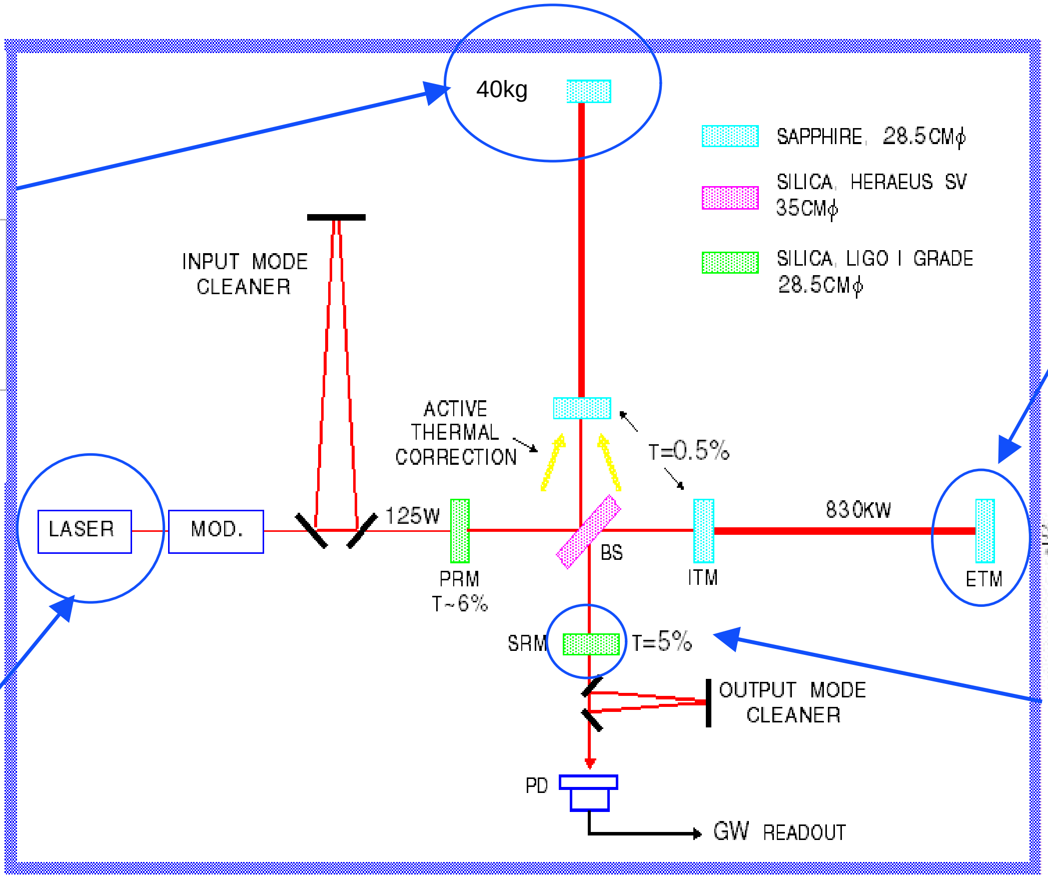
What’s next? Advanced LIGO…

Major technological differences between LIGO and Advanced LIGO

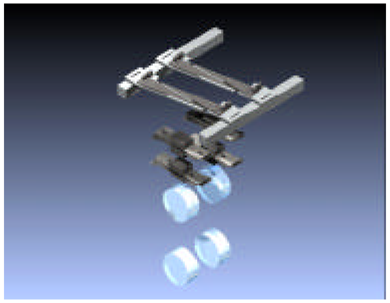


Active vibration isolation systems

High power laser (180W)



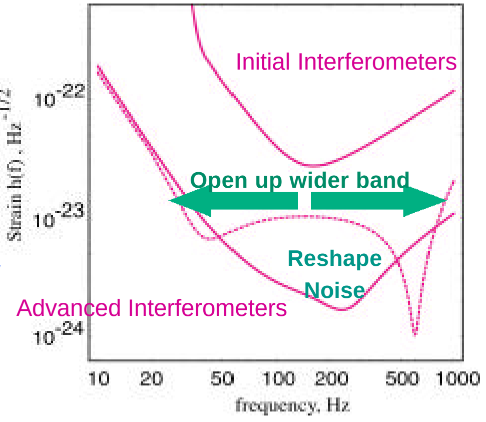
LIGO



Quadruple pendulum

Sapphire optics

Silica suspension fibers



Advanced interferometry

Signal recycling

Binary Neutron Stars: AdLIGO Range

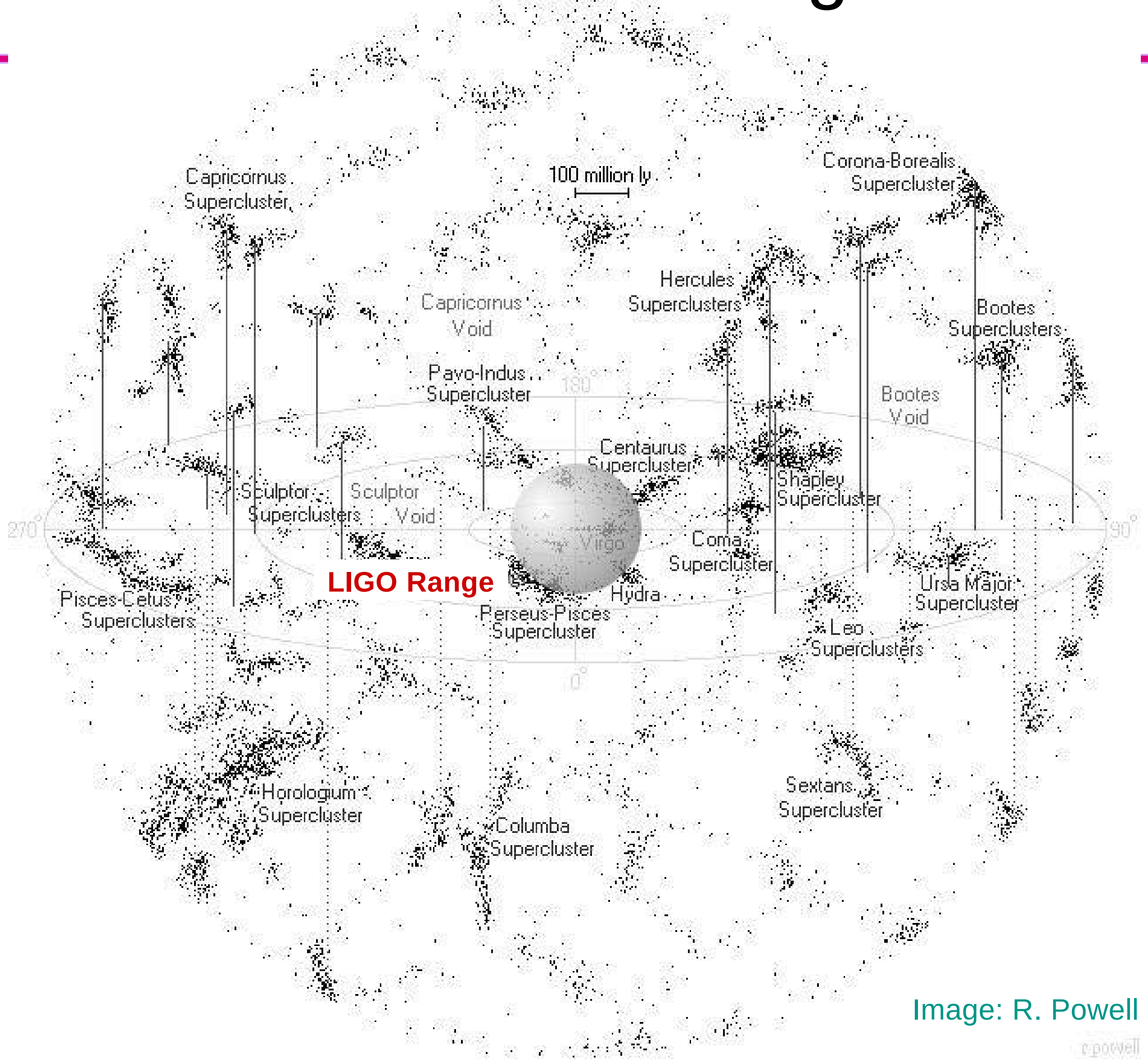
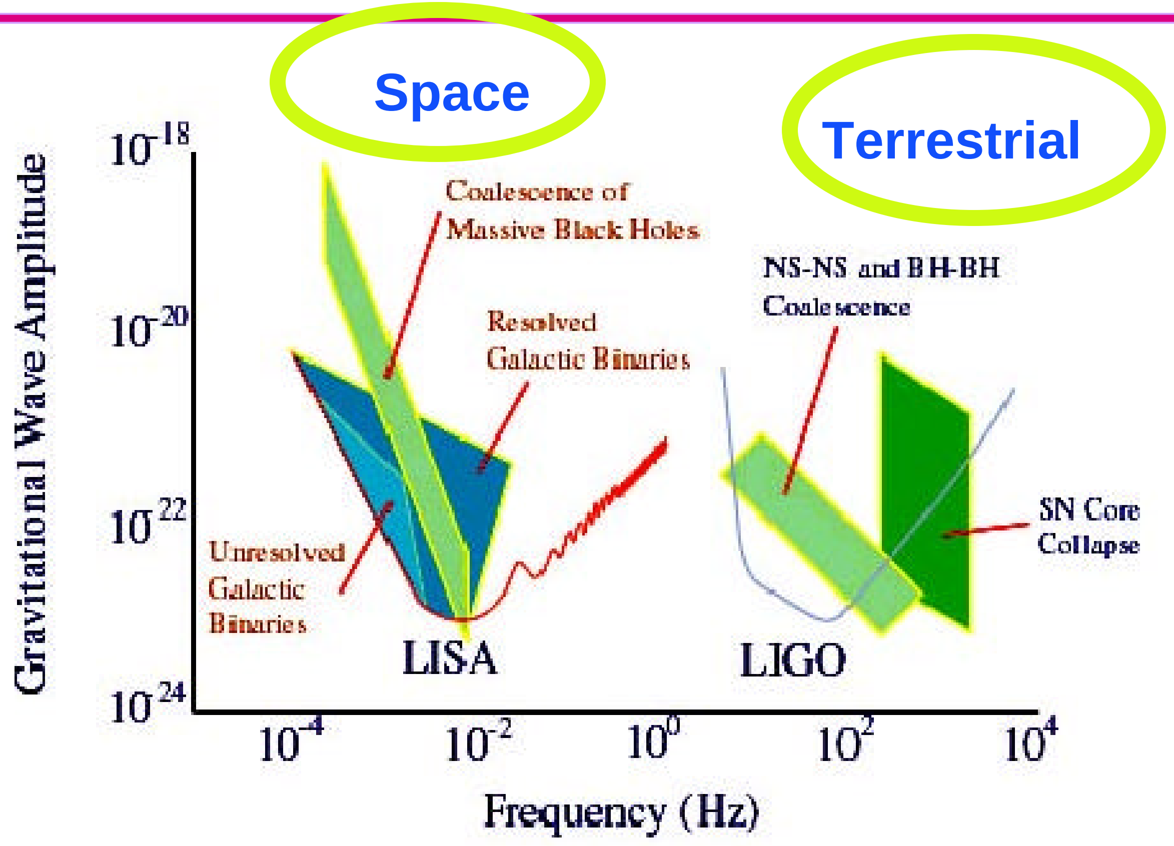


Image: R. Powell

…and opening a new channel with a detector in space.



Planning underway for space-based detector, LISA, to open up a lower frequency band ~ 2015

Despite a few difficulties, science runs started in 2002.