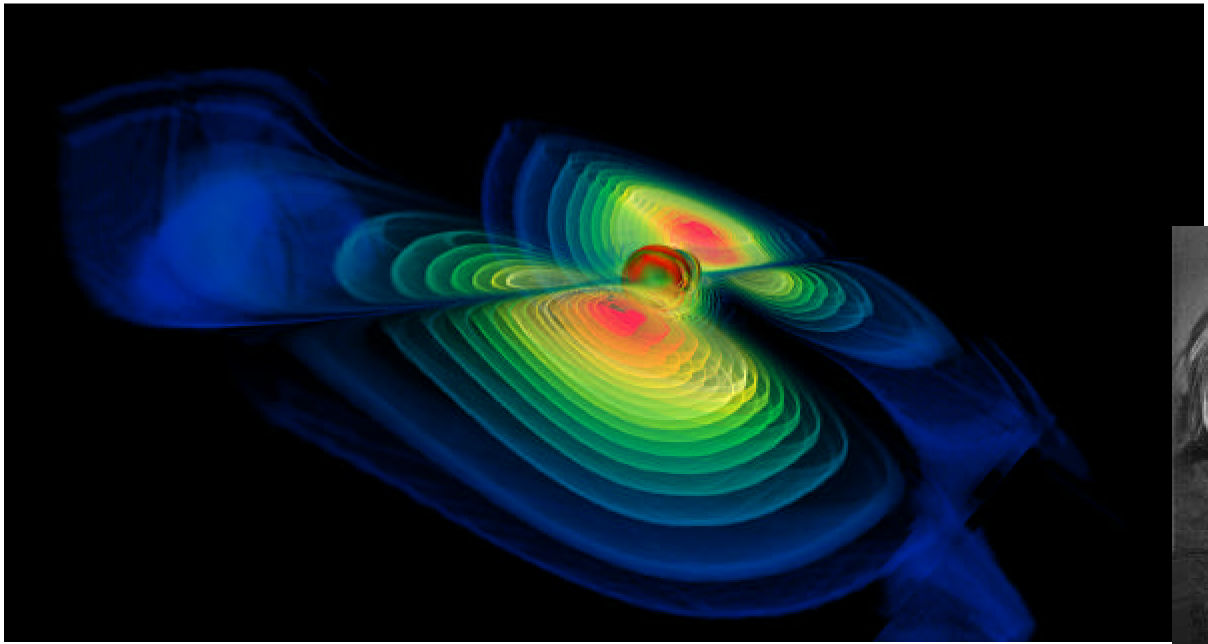
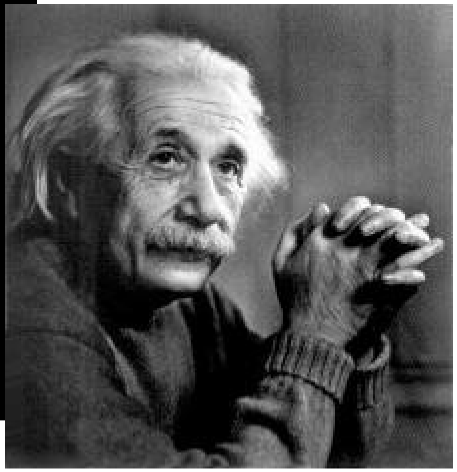
The Laser Interferometer Gravitational-Wave Observatory In Operation



"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)



Reported on behalf of LIGO colleagues by

Fred Raab,

LIGO Hanford Observatory

LIGO-G030515-00-W

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
- 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 "spacequakes" from the most violent events in the universe

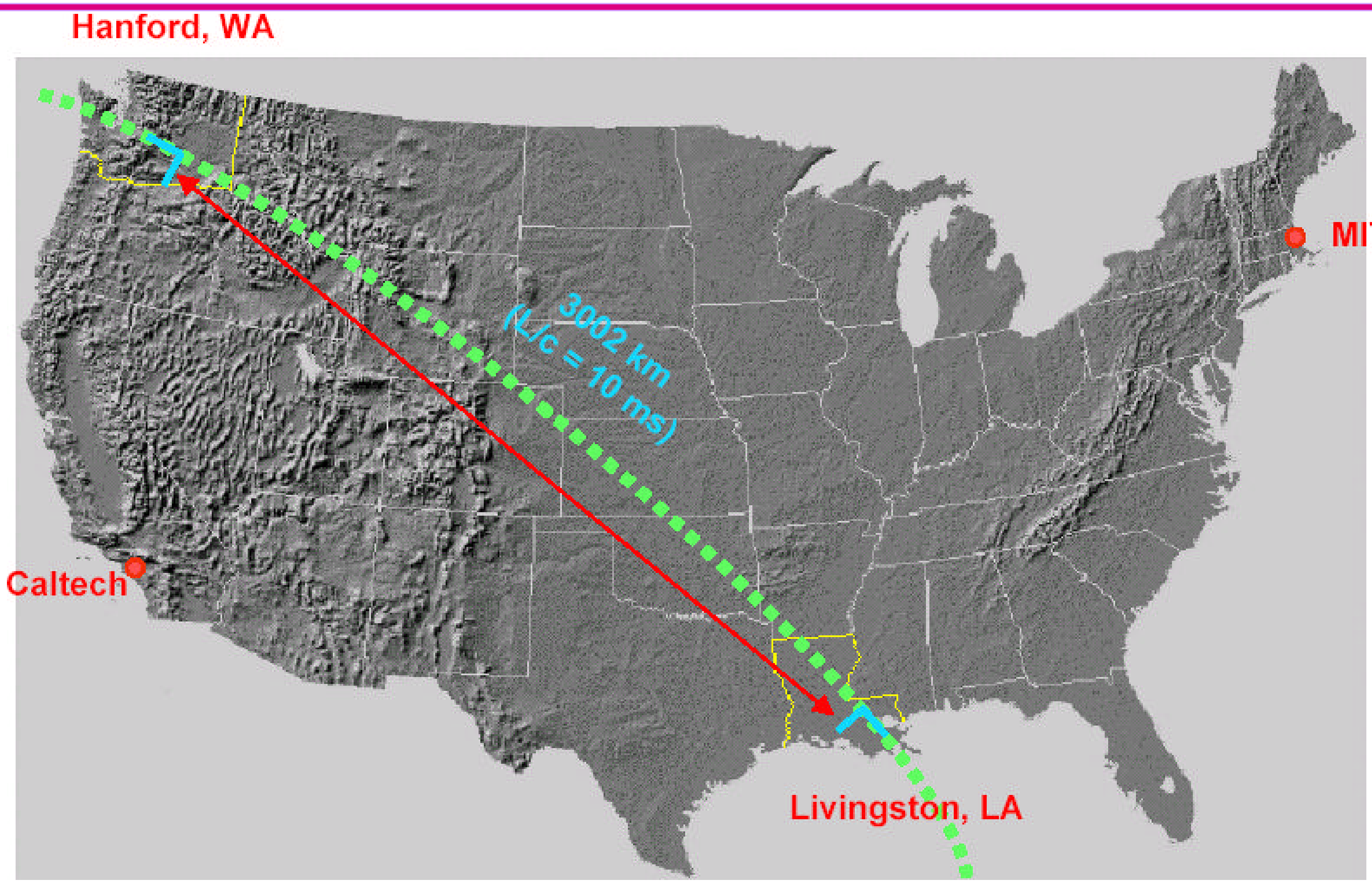
The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

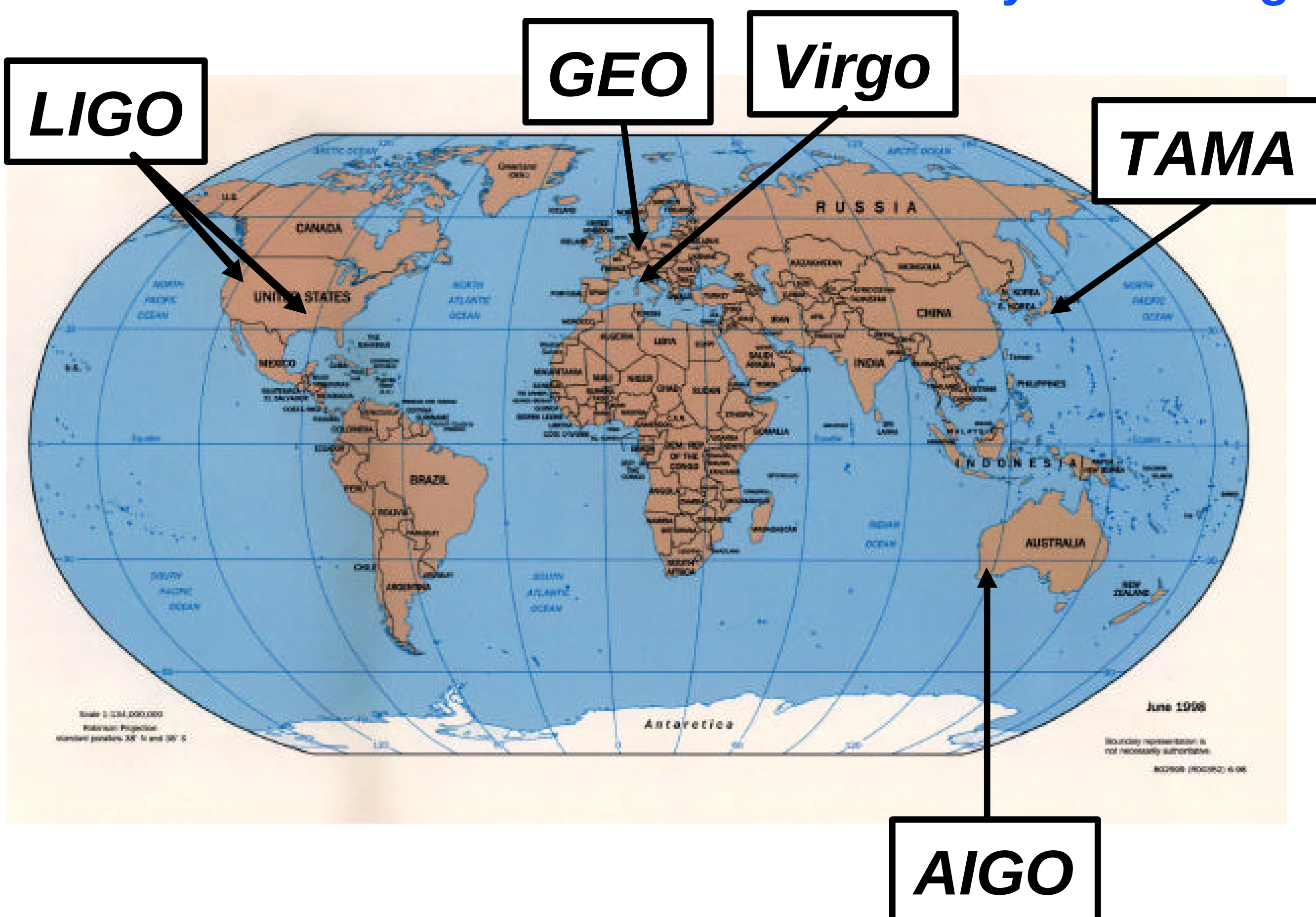
Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 400 LIGO Science Collaboration members worldwide.

LIGO Laboratories Are Operated as National Facilities in the US…



Part of Future International Detector Network

Simultaneously detect signal (within msec)

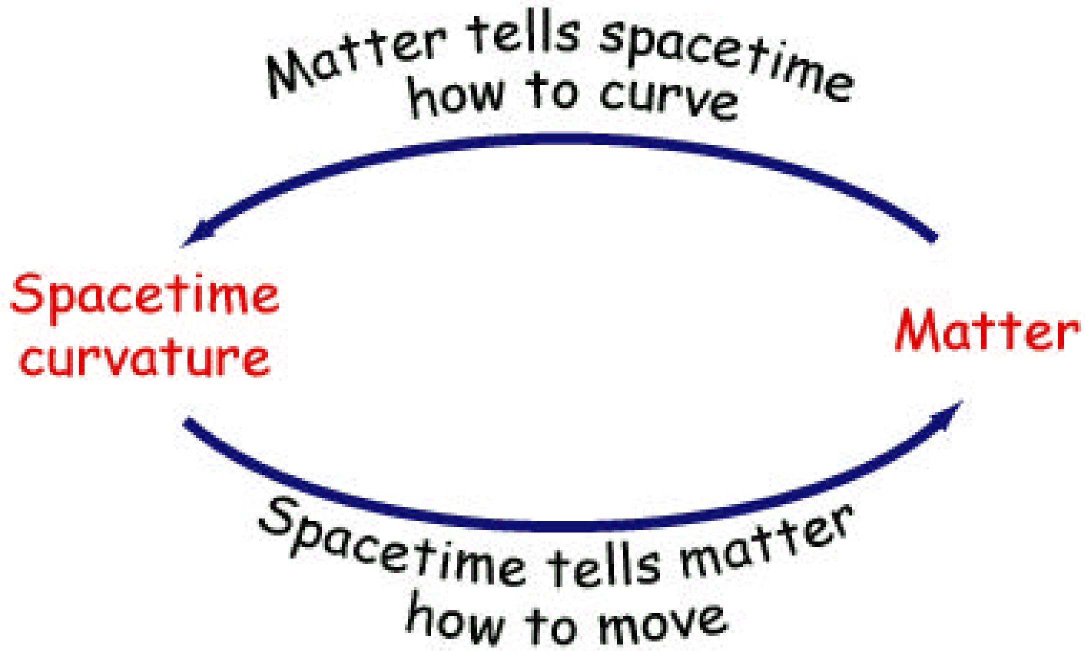


detection confidence

locate the sources

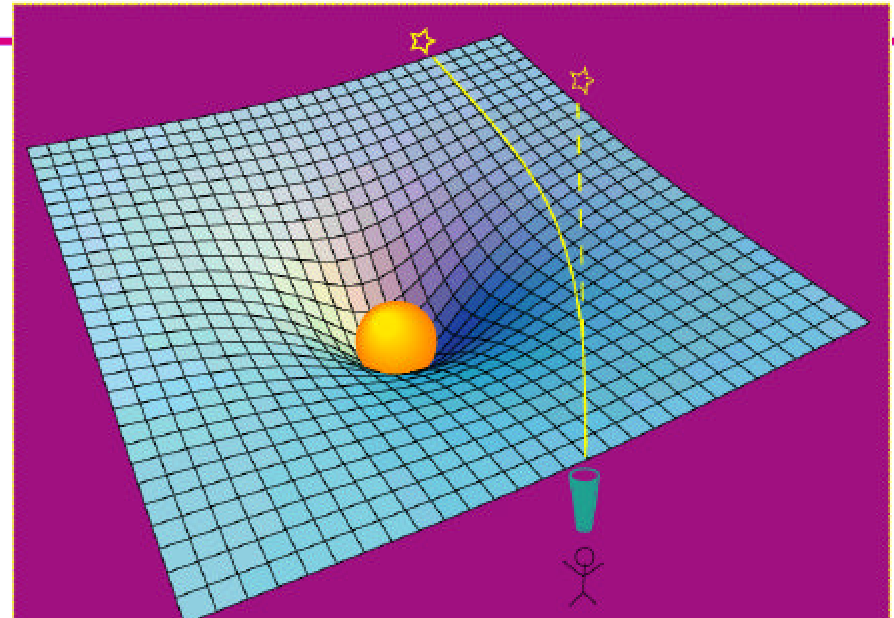
decompose the polarization of gravitational waves

John Wheeler's Picture of General Relativity Theory



Mass Distorts Space

- Presence of mass gives space the appearance of lumpy glass as evidenced by the bending of light
- First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster
- This effect now used to map out the distribution of dark matter

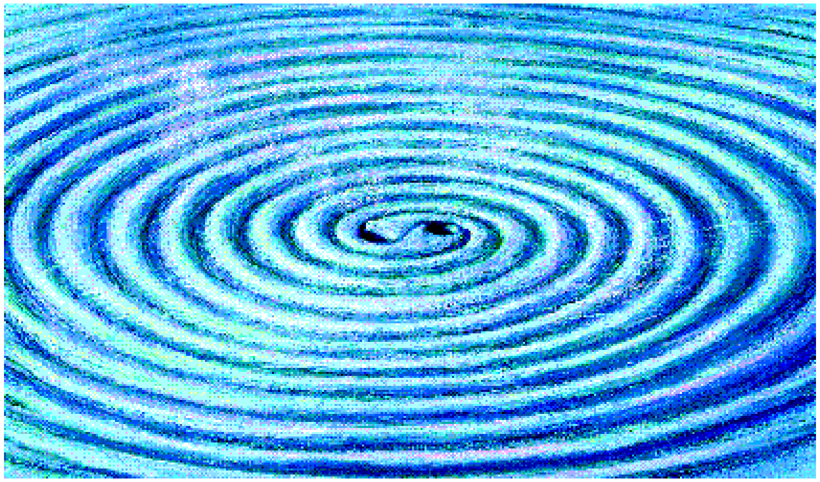


The light never changes course, but merely follows the curvature of space. Astronomers now refer to this displacement of light as gravitational lensing.

Gravitational Waves

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

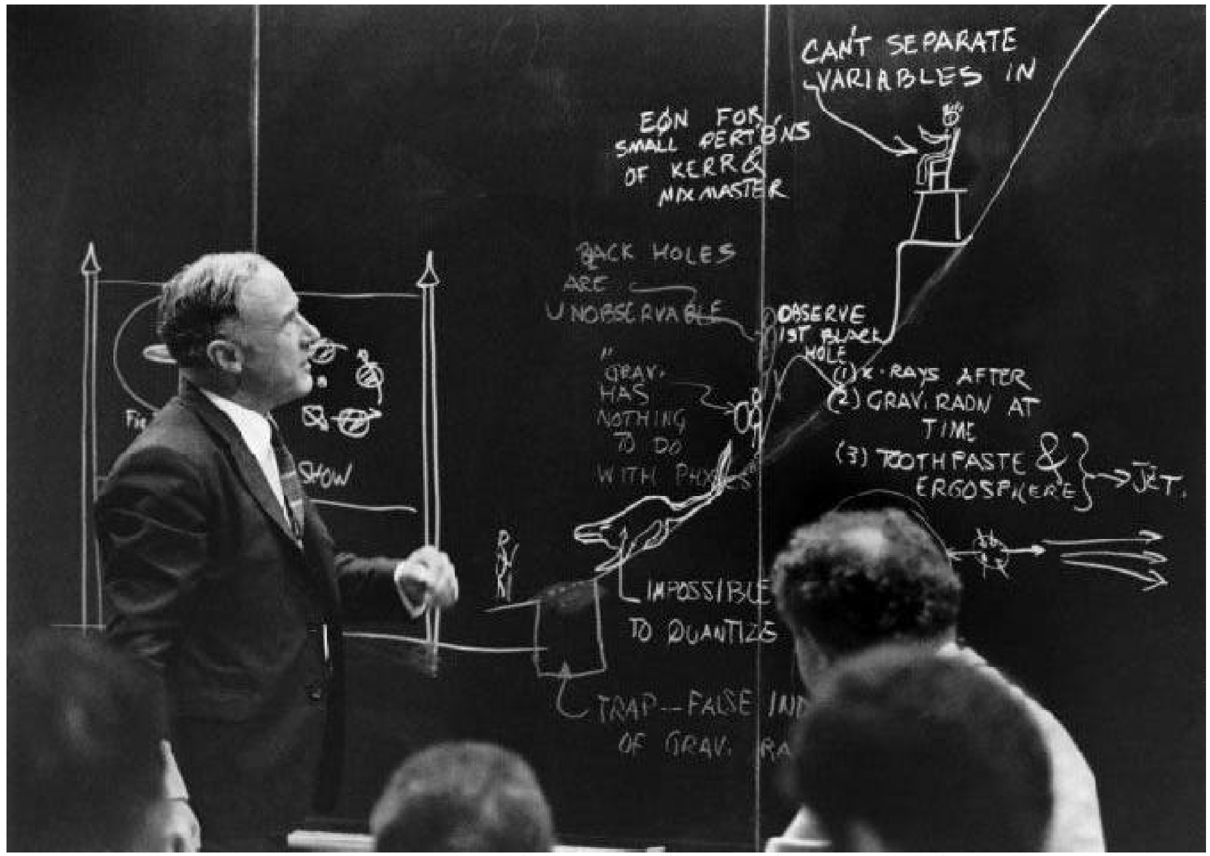
Rendering of space stirred by two orbiting black holes:



Gravitational Collapse and Its Outcomes Present LIGO Opportunities

f_{GW} > few Hz accessible from earth

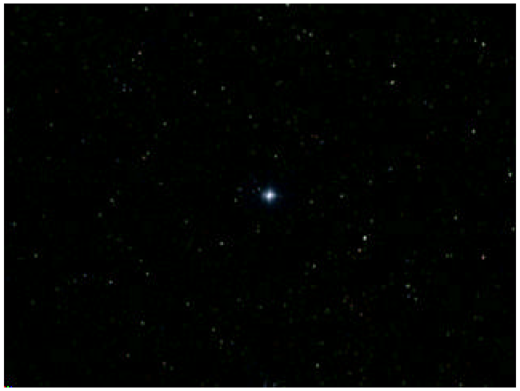
f_{GW} < several kHz interesting for compact objects



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

Supernova: Death of a Massive Star

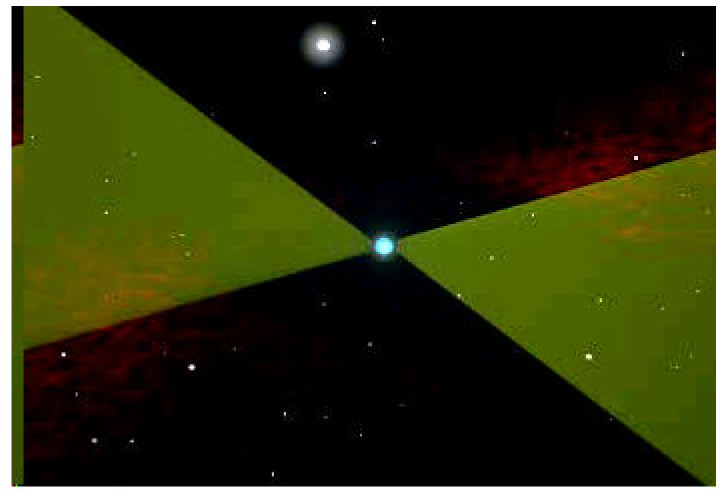
- Spacequake should preceed optical display by ½ day
- Leaves behind compact stellar core, e.g., neutron star, black hole
- Strength of waves depends on asymmetry in collapse
- Observed neutron star motions indicate some asymmetry present
- Simulations do not succeed from initiation to explosions



Credit: Dana Berry, NASA

The “Undead” Corpses of Stars: Neutron Stars and Black Holes

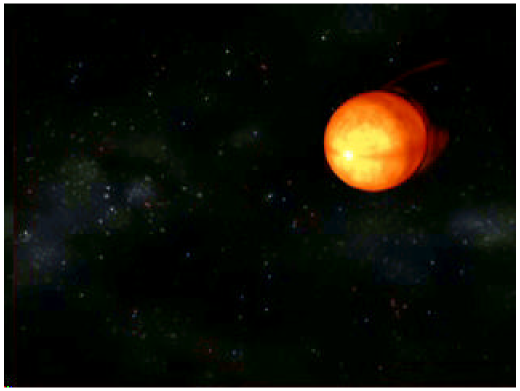
- Neutron stars have a mass equivalent to 1.4 suns packed into a ball 10 miles in diameter, enormous magnetic fields and high spin rates
- Black holes are even more dense, the extreme edges of the space-time fabric



Artist: Walt Feimer, Space Telescope Science Institute

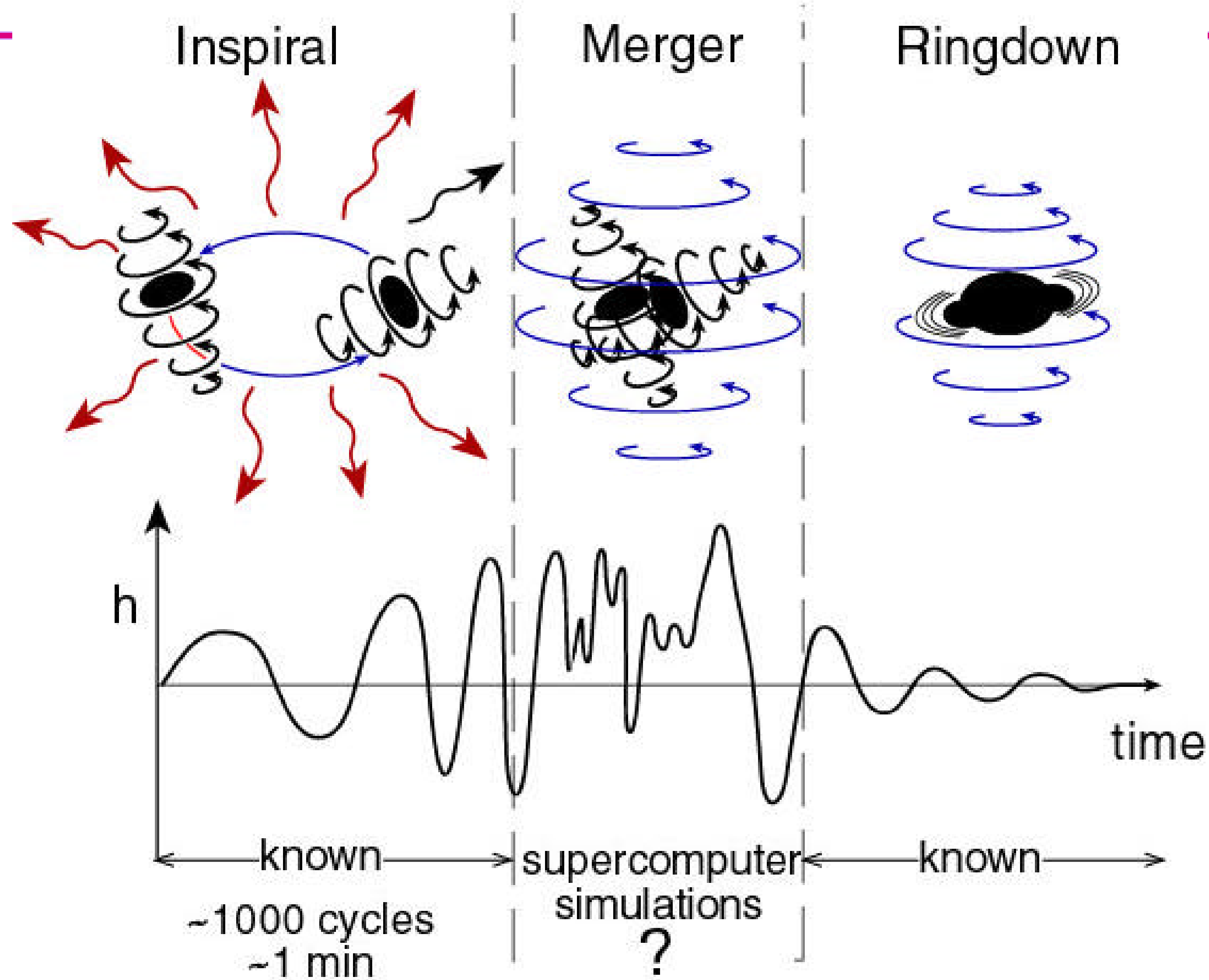
Gravitational-Wave Emission May be the "Regulator" for Accreting Neutron Stars

- Neutron stars spin up when they accrete matter from a companion
- Observed neutron star spins "max out" at ~700 Hz
- Gravitational waves are suspected to balance angular momentum from accreting matter



Credit: Dana Berry, NASA

Catching Waves From Black Holes

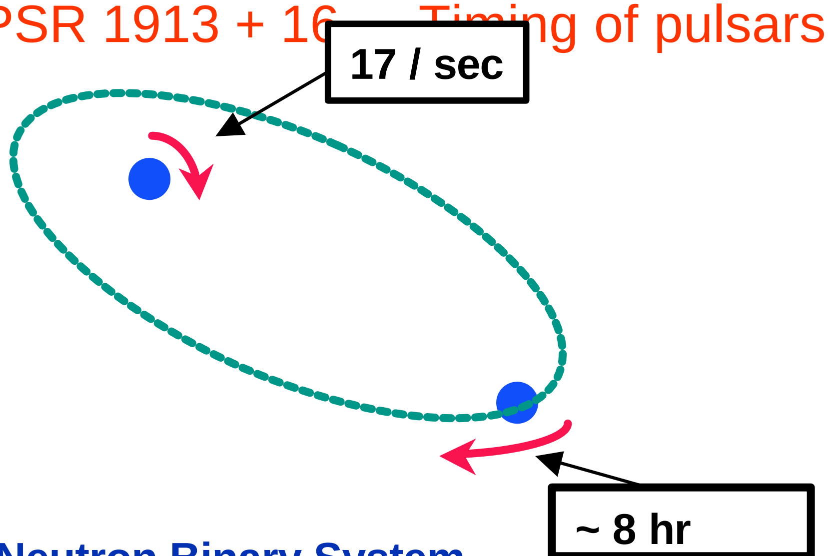


Sketches courtesy of Kip Thorne

Gravitational Waves
the evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

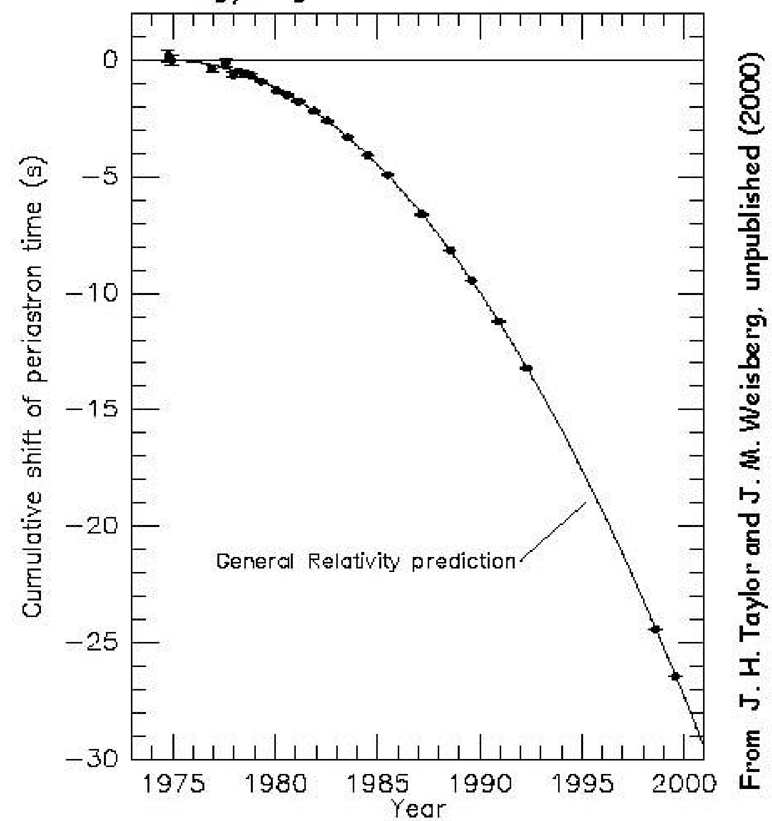


Neutron Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $e = 0.617$**

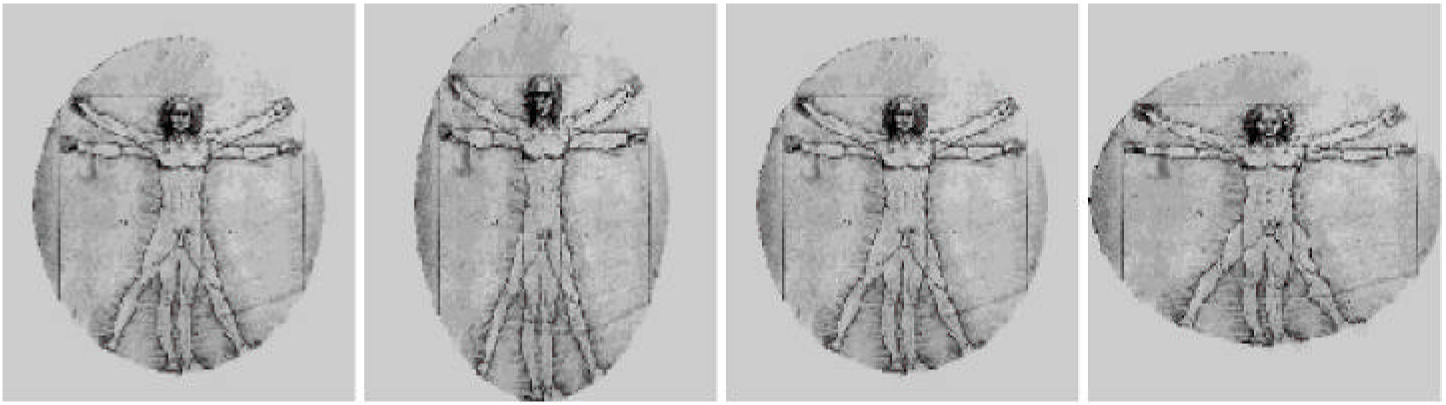
Prediction from general relativity
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

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

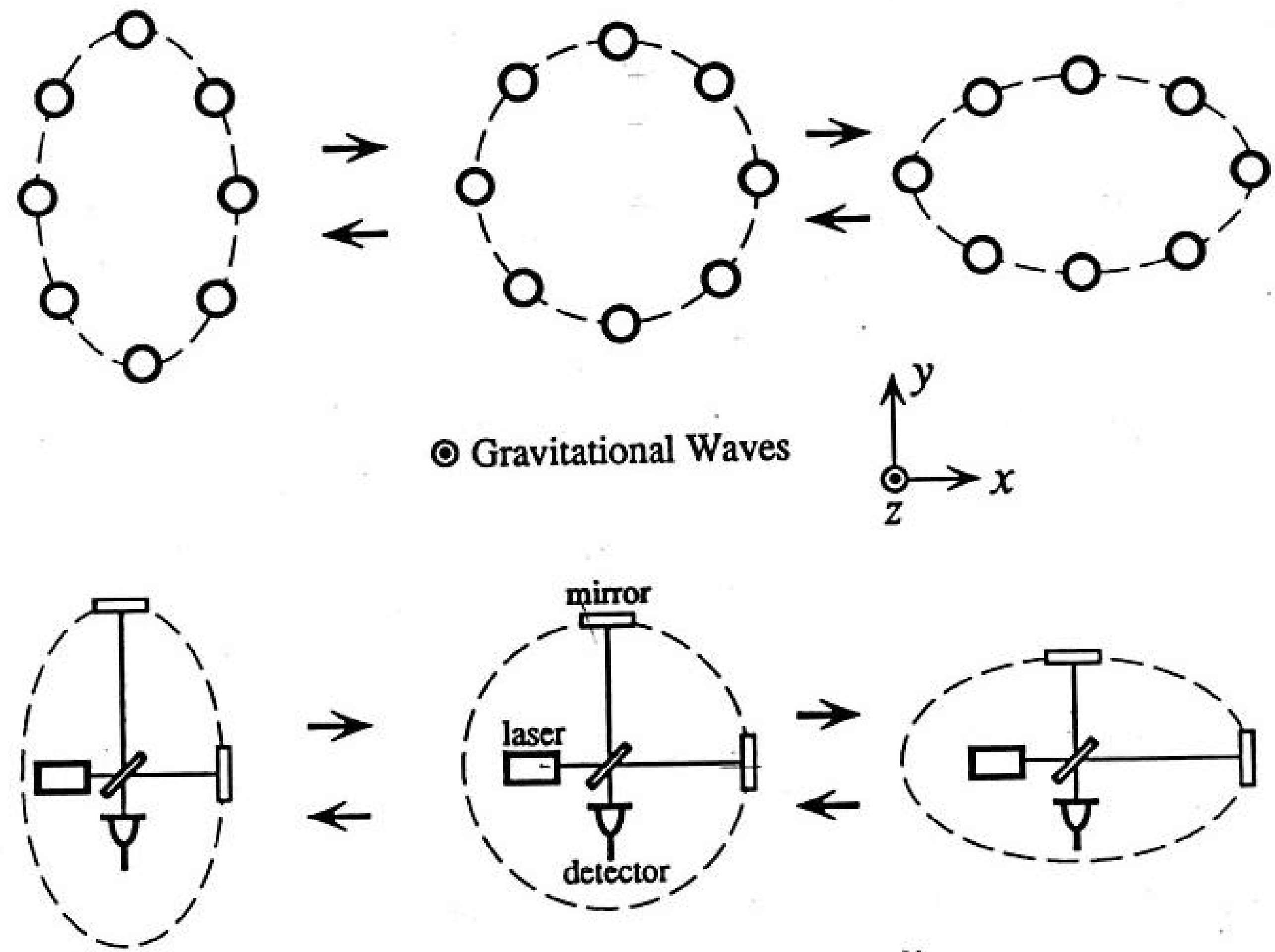


How does LIGO detect spacetime vibrations?

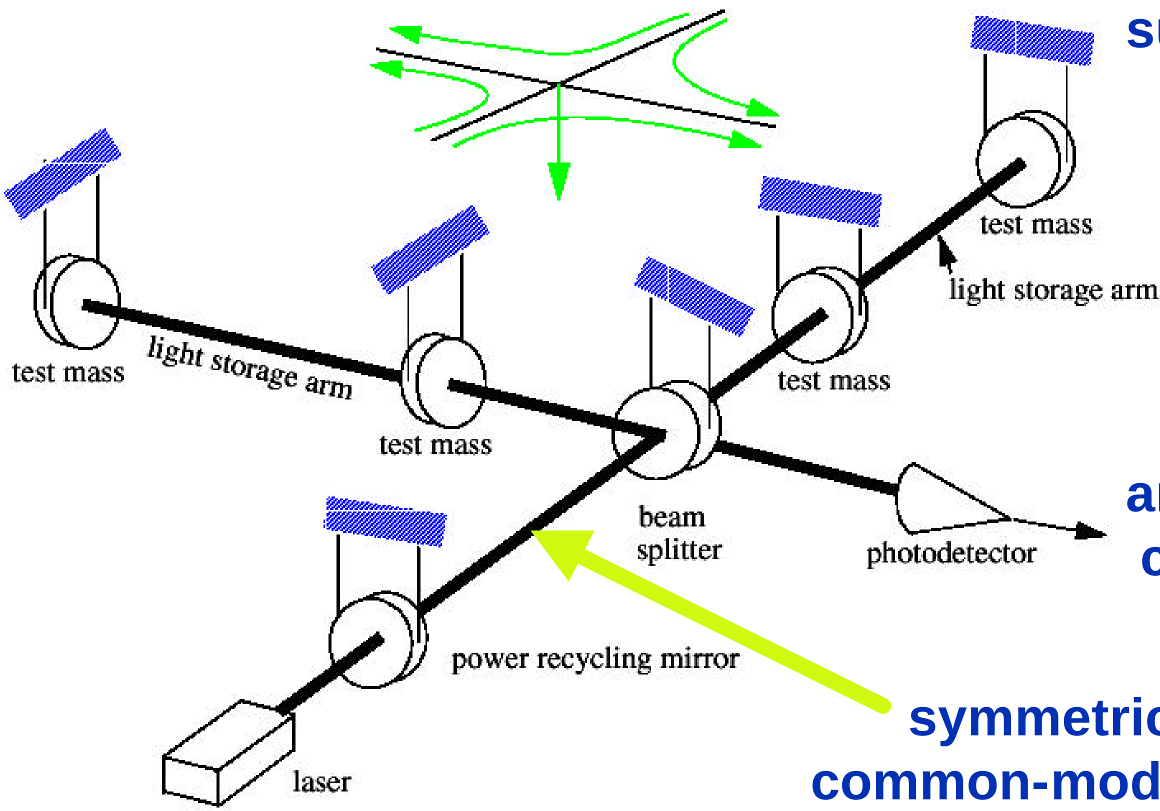


Leonardo da Vinci's Vitruvian man

Basic Signature of Gravitational Waves



Power-Recycled Fabry-Perot-Michelson Interferometer

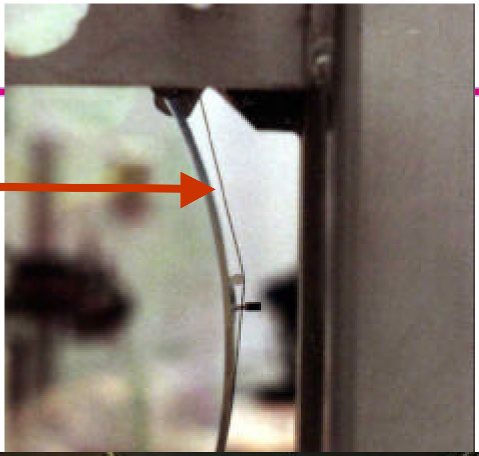


suspended mirrors mark inertial frames

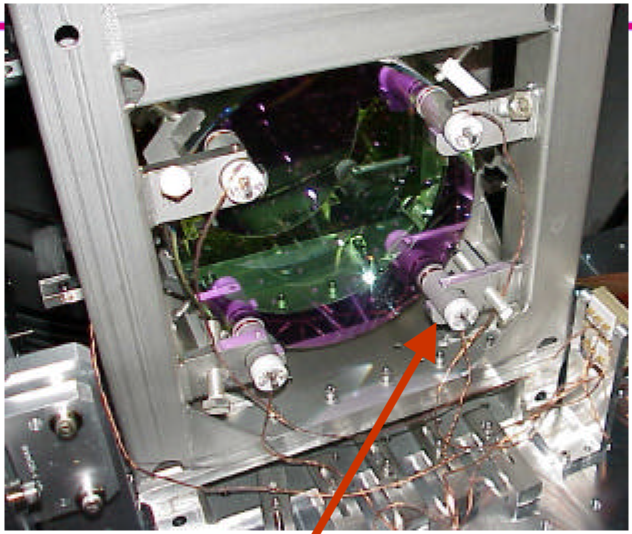
antisymmetric port carries GW signal

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

Core Optics Suspension and Control



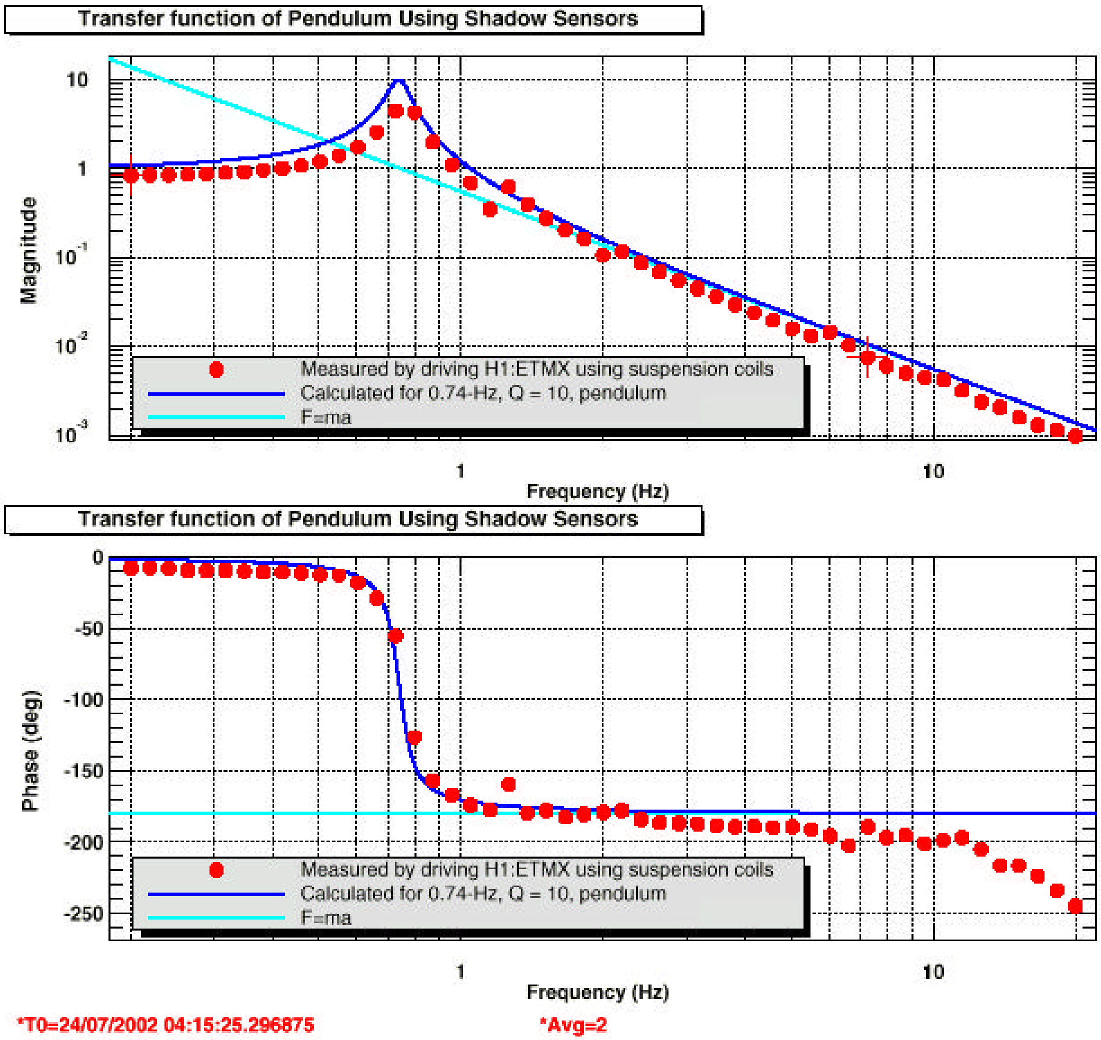
Optics suspended as simple pendulums



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

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

Suspended Mirror Approximates a Free Mass Above Resonance



Blue: suspended mirror XF

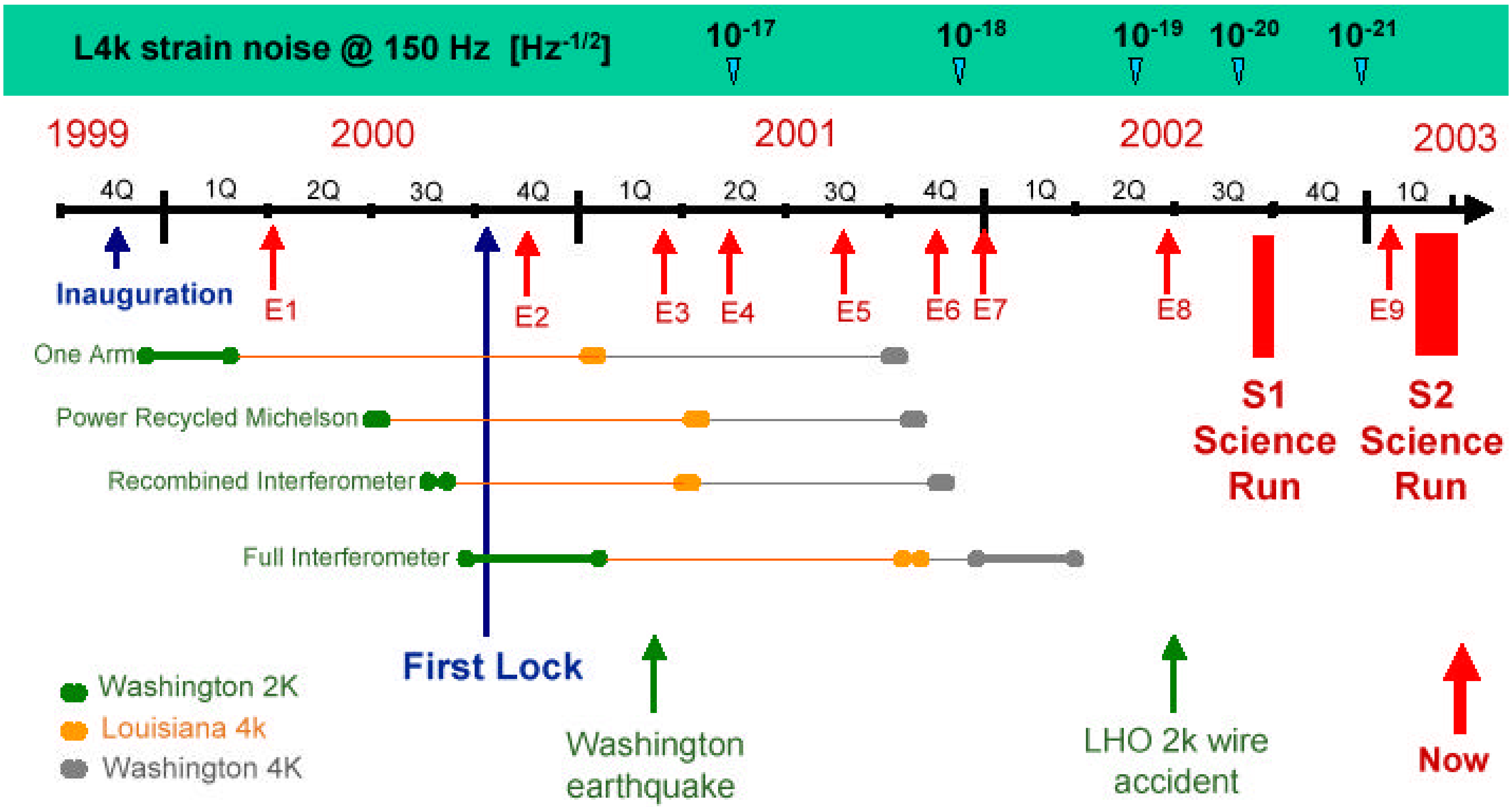
Cyan: free mass XF

Data taken using shadow sensors & voice coil actuators

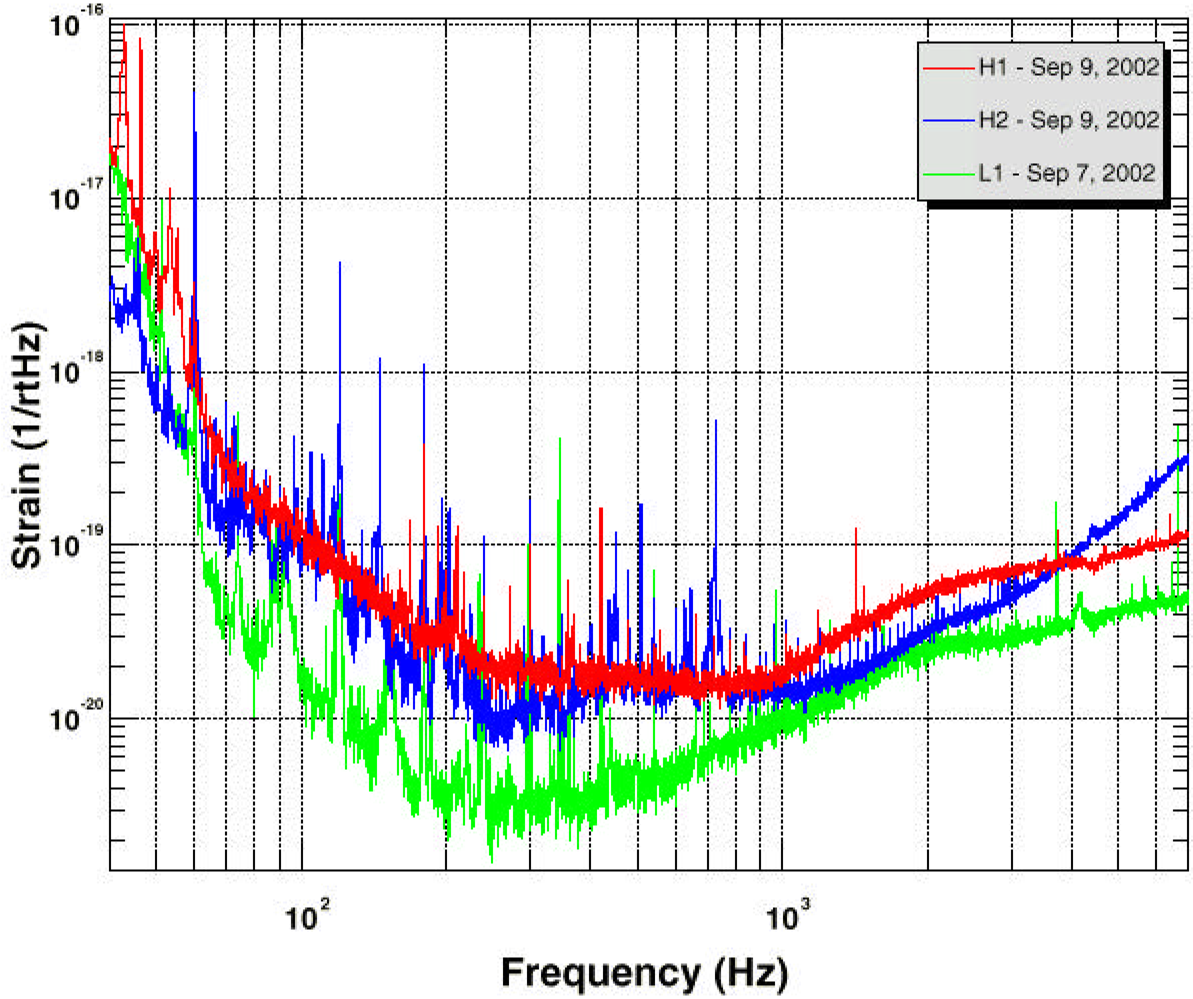
Some of the Technical Challenges

- 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 ($1/1000^{th}$ 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
- Each Interferometer incorporates ~100 control systems
- Data rates of ~3 MB/sec for each interferometer

Commissioning Time Line



Noise Equivalent Strain Spectra for S1



Binary Neutron Stars: S1 Range

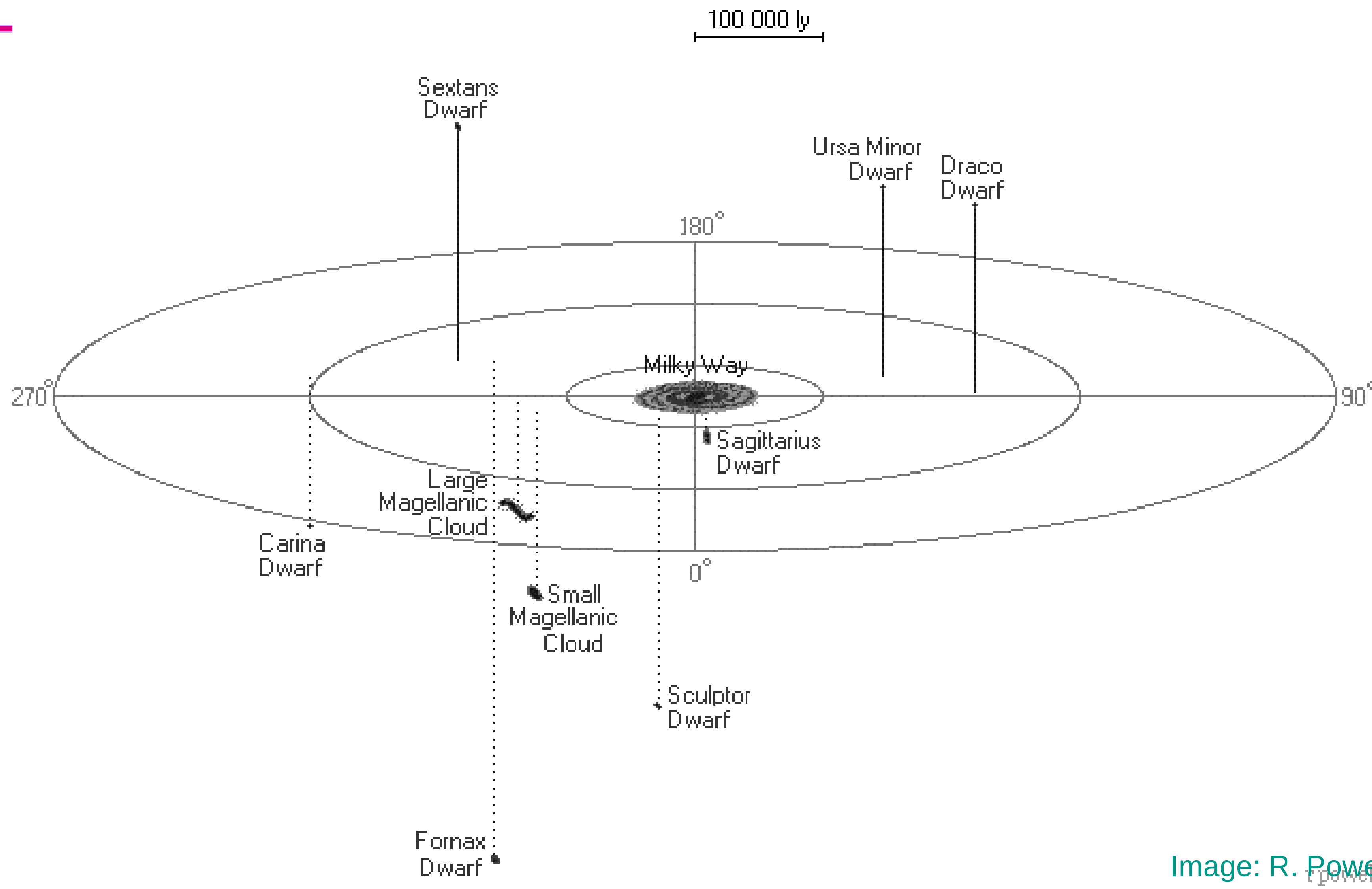
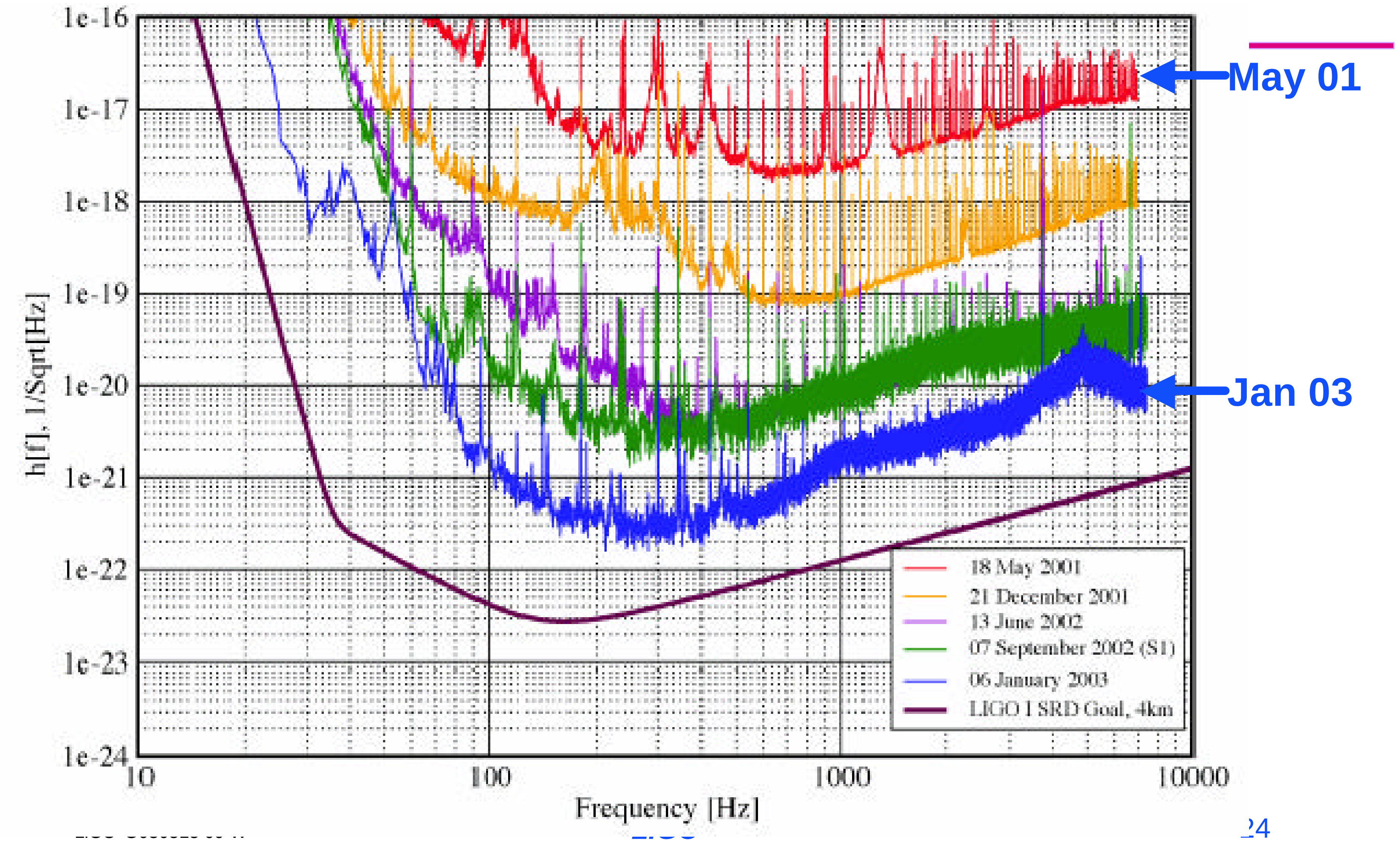


Image: R. Powell

LIGO Sensitivity Over Time

Livingston 4km Interferometer



Binary Neutron Stars: S2 Range

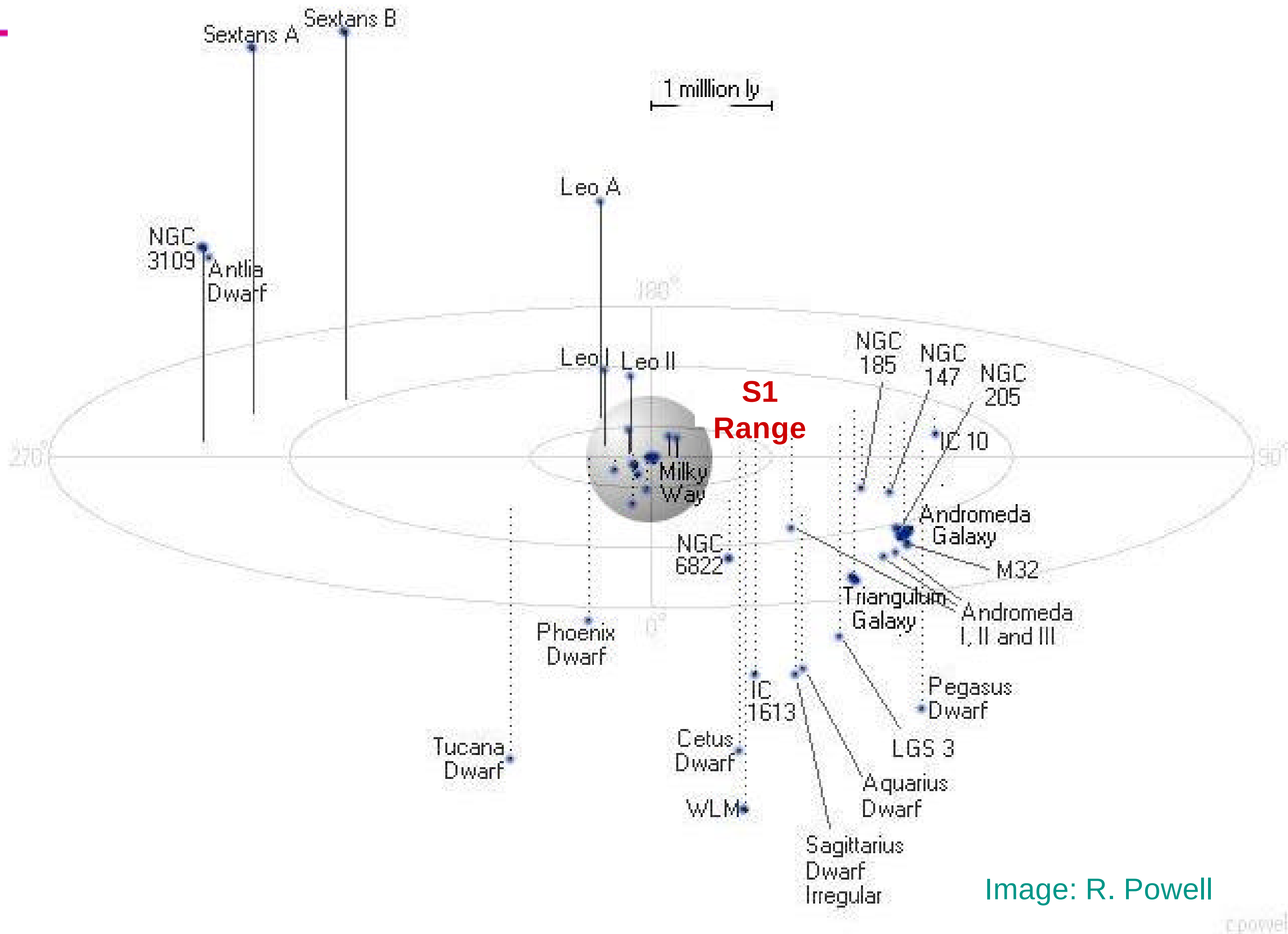


Image: R. Powell

Binary Neutron Stars:
Initial LIGO Target Range

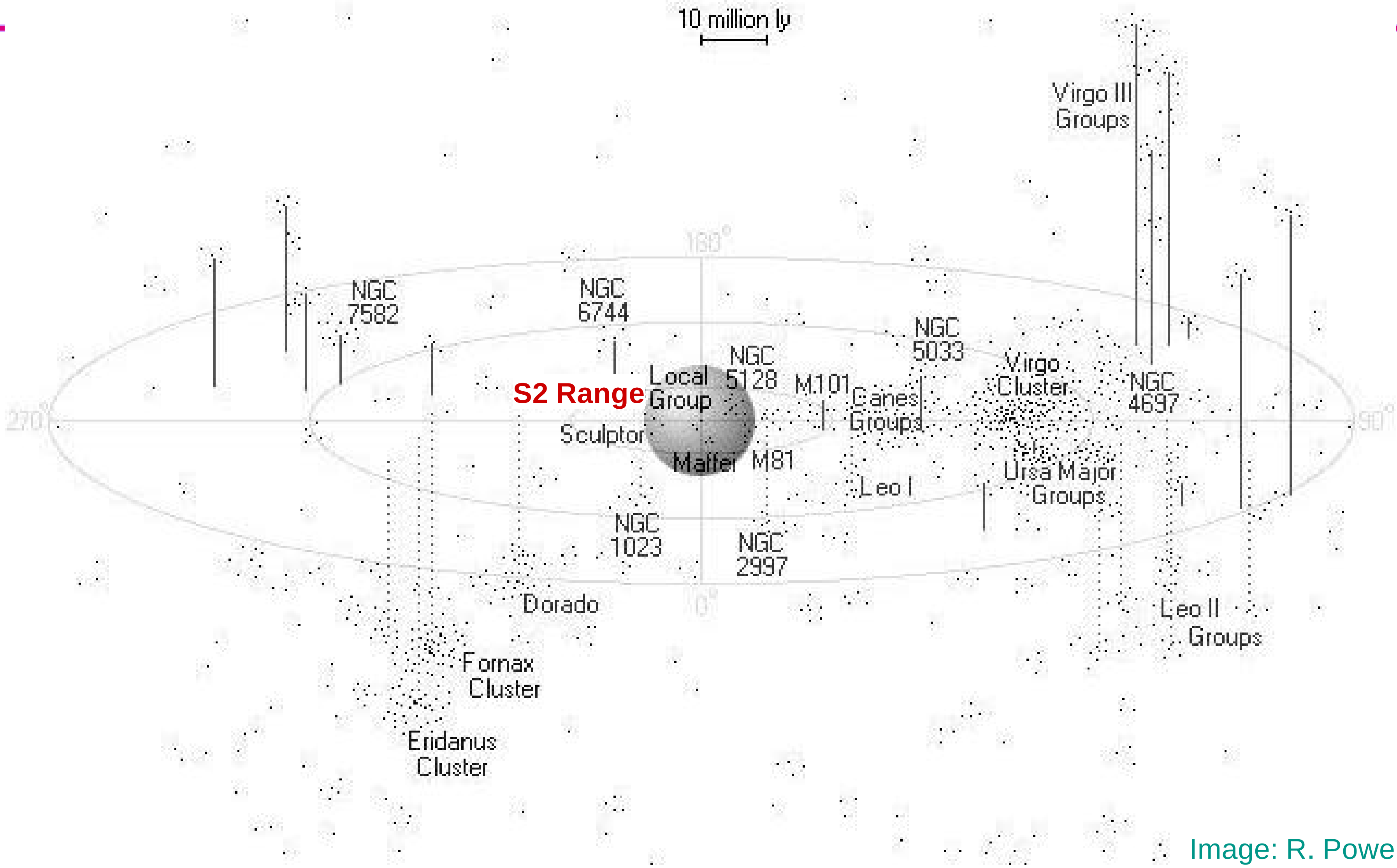
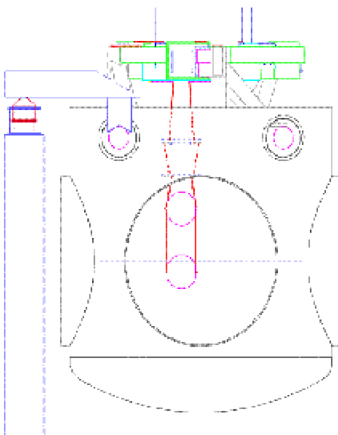


Image: R. Powell

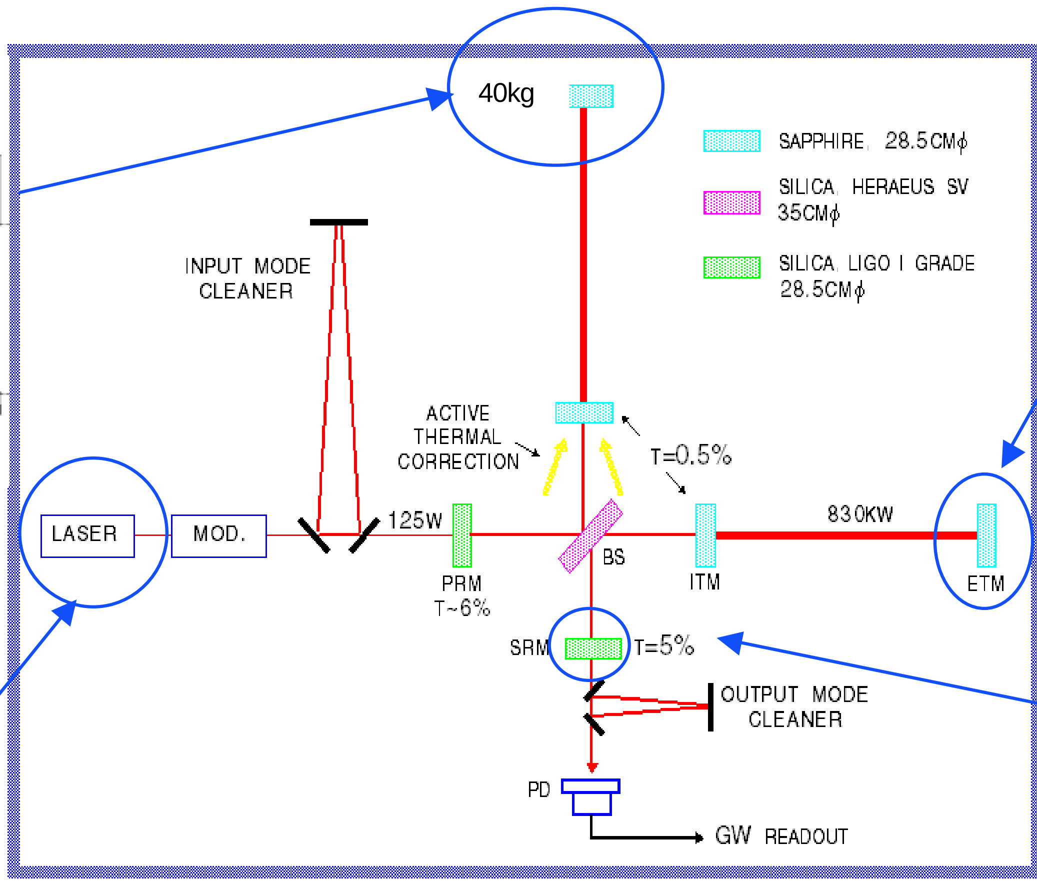
What's next? Advanced LIGO…

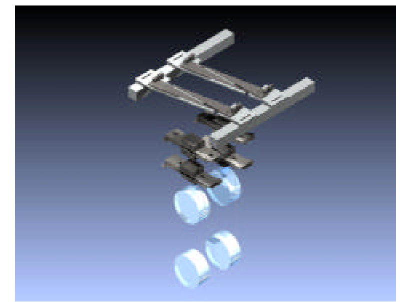
Major technological differences between LIGO and Advanced LIGO



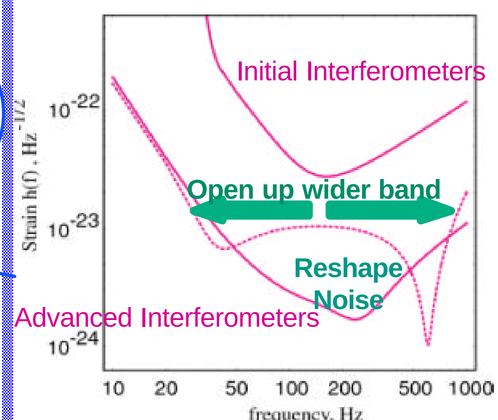
Active vibration isolation systems

High power laser (180W)





Quadruple pendulum
Sapphire optics
Silica suspension fibers



Advanced interferometry
Signal recycling

Binary Neutron Stars: AdLIGO Range

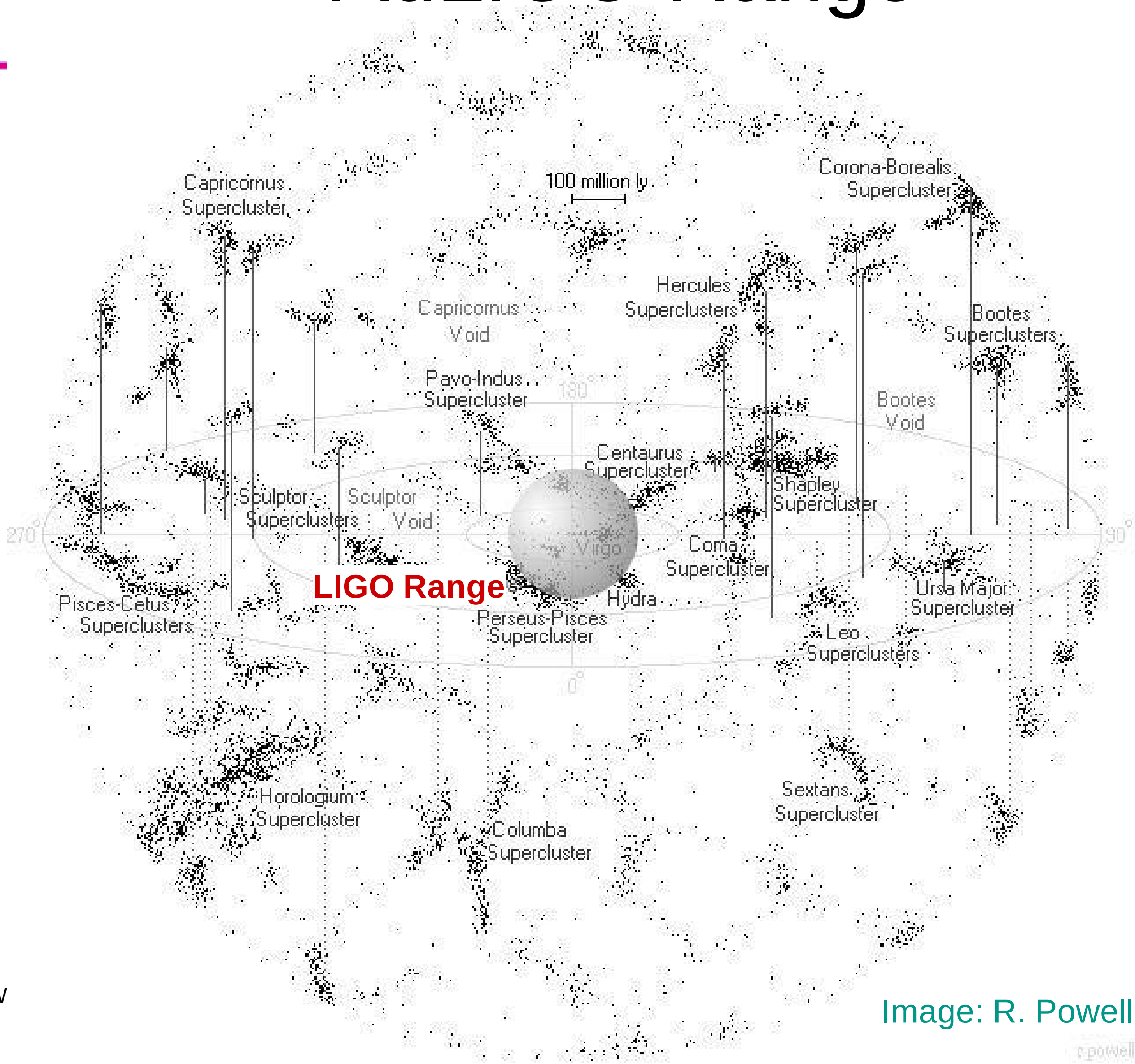
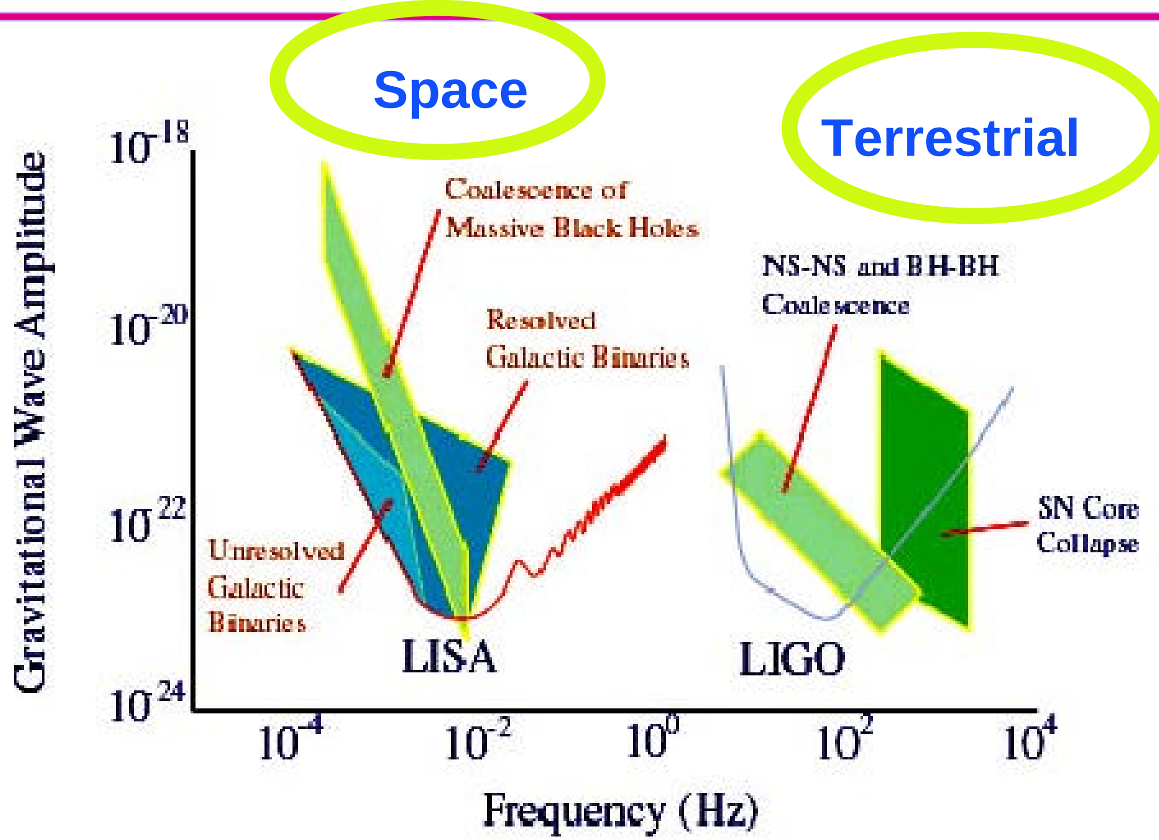


Image: R. Powell

...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

Summary and Highlights

- LIGO commissioning continues but science runs have begun
- New observational limits from S1 data -> Phys. Rev. D
  - » Rate of neutron star inspirals in Milky Way and Magellanic Clouds
  - » Ellipticity of nearby (~ 10 light yr), rapidly spinning pulsar
- New and better limits expected from ongoing S2 analysis
  - » Black hole inspirals as well as neutron insirals
  - » Search for GWs from all known radio pulsars and search for unknown pulsars in the galactic plane
  - » New direct observational limits on GWs from early universe
  - » Limit on GWs from GRB 030329
- S3 scheduled for 31Oct03-5Jan04
- Advanced LIGO proposal at NSF; UK portion funded; Germany and Australia will consider their contributions this autumn