Title: Gravitational-wave astronomy: progress and prospects

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Abstract: Gravitational waves provide a unique way to study the Universe. From 2005 to 2007, the Laser Interferometer Gravitational-wave Observatory (LIGO) took data at design sensitivity. After describing gravitational waves and how LIGO works, I will discuss the status of searches for those waves and current astronomical constraints imposed by those searches. Data taking resumed in summer 2009 with enhanced LIGO detectors and the European Virgo detectors. I will discuss plans for combined electromagnetic and gravitational observing campaigns. Finally, I will highlight the prospects for gravitational-wave astronomy with Advanced LIGO over the next decade.

Ripples in Spacetime

Searching for gravitational waves with LIGO

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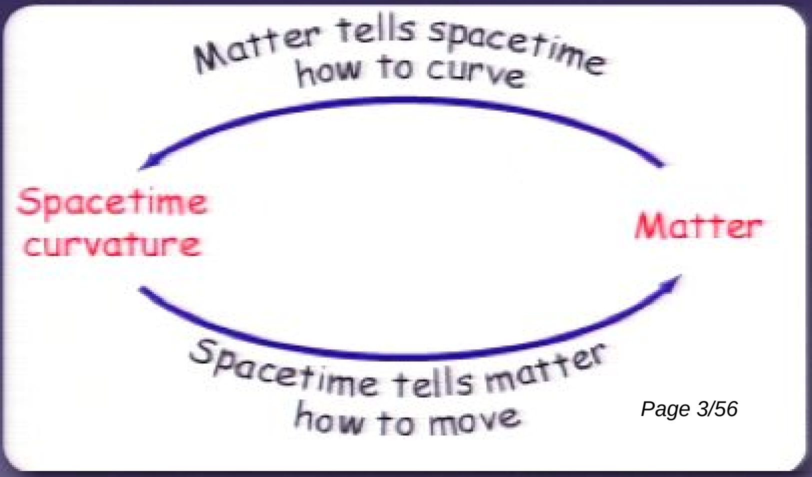
Center for Gravitation and Cosmology

General Relativity

- Einstein's field equations (1915)
  - Relate curvature of spacetime to stress-energy of matter

$$R_{ab} - \frac{1}{2}R g_{ab} = 8\pi T_{ab}$$

  - Gravitational force is extremely weak compared to electromagnetic force, difficult to measure small effects
  - According to Einstein, test bodies move along geodesics of spacetime
  - Geodesics are determined by curvature



Einstein on gravitational waves

Spacetime interval can be written as

$$ds^2 = (\eta_{\alpha\beta} + h_{\alpha\beta})dx^\alpha dx^\beta$$

where $\eta_{\alpha\beta}$ is the Minkowski metric and $h_{\alpha\beta}$ is a metric perturbation

For weak gravitational fields $h \ll 1$

$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right)\overline{h}^{\alpha\beta} = -16\pi T^{\alpha\beta}$$

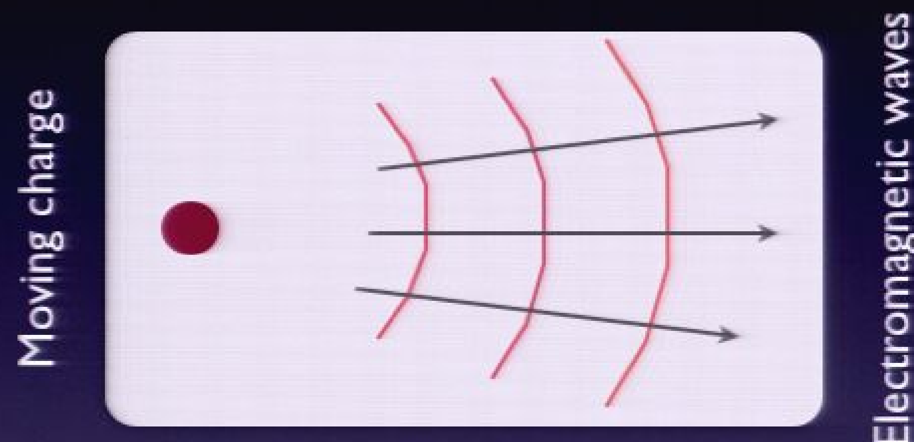
$$\overline{h}^{\alpha\beta} = h^{\alpha\beta} - \frac{1}{2}\eta^{\alpha\beta}h$$

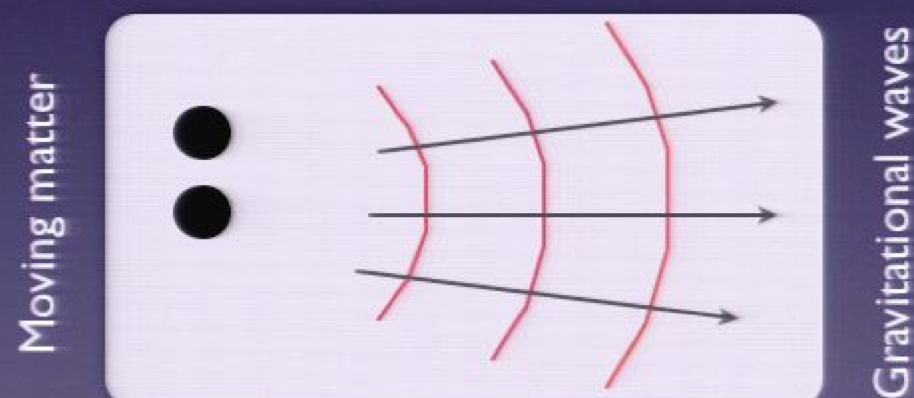
Solve the wave equation in vacuum

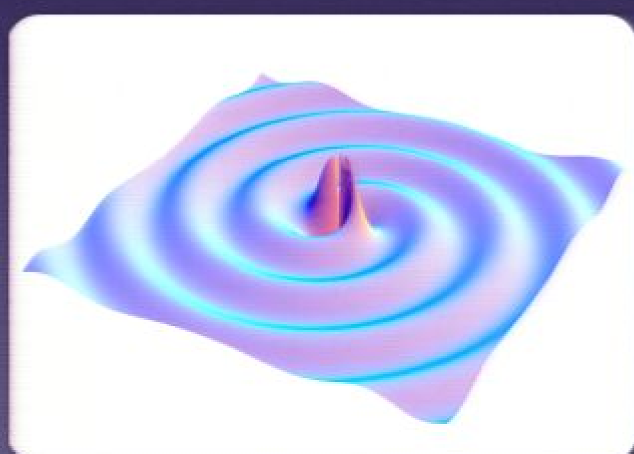
- $\overline{h}^{\alpha\beta} = A^{\alpha\beta}\exp(ik_\delta x^\delta)\,,\;k_\alpha k^\alpha = 0$
- Gravitational waves propagate at the speed of light
- Gravitational waves stretch and squeeze space

How to generate gravitational waves

- Einstein's equations
  - when matter moves or changes configuration, its gravitational field changes
  - this change propagates outward as a ripple in spacetime: a gravitational wave







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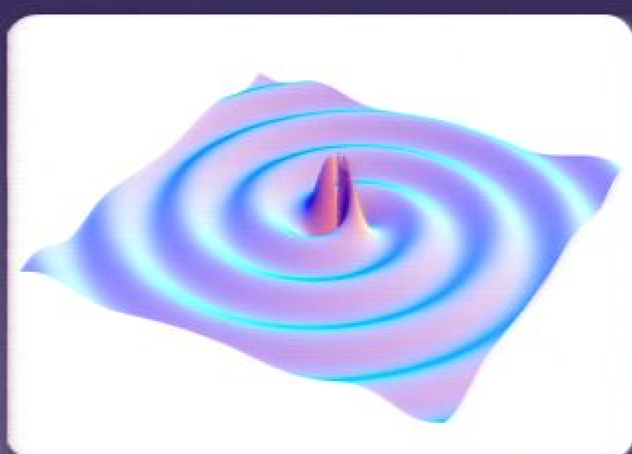

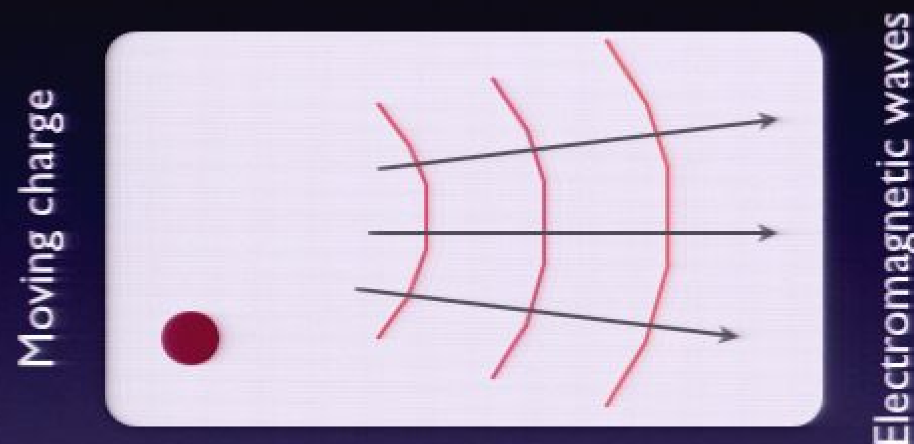

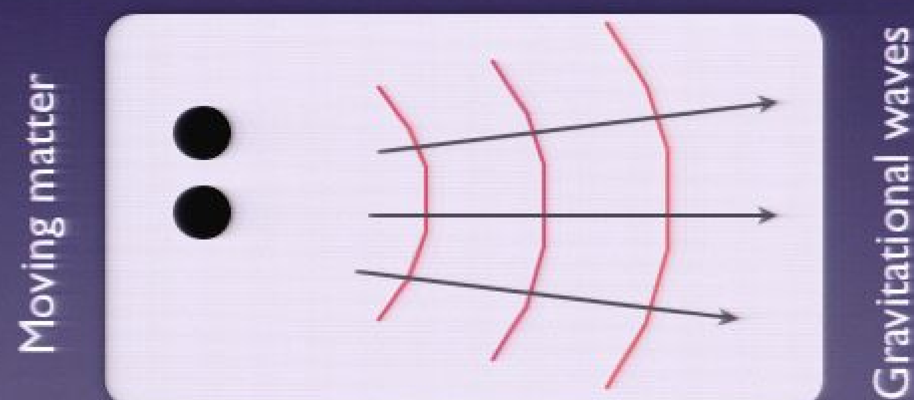

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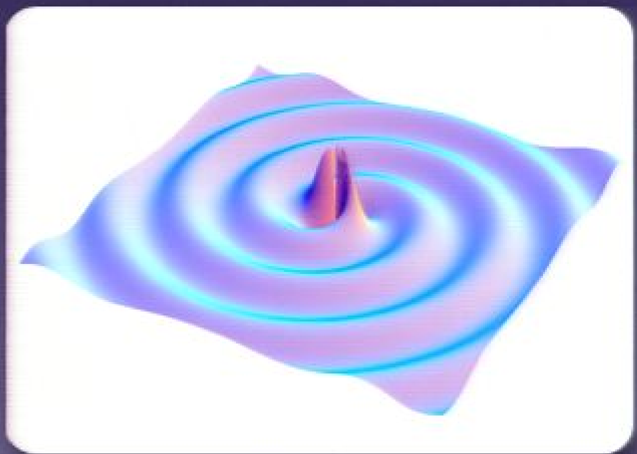

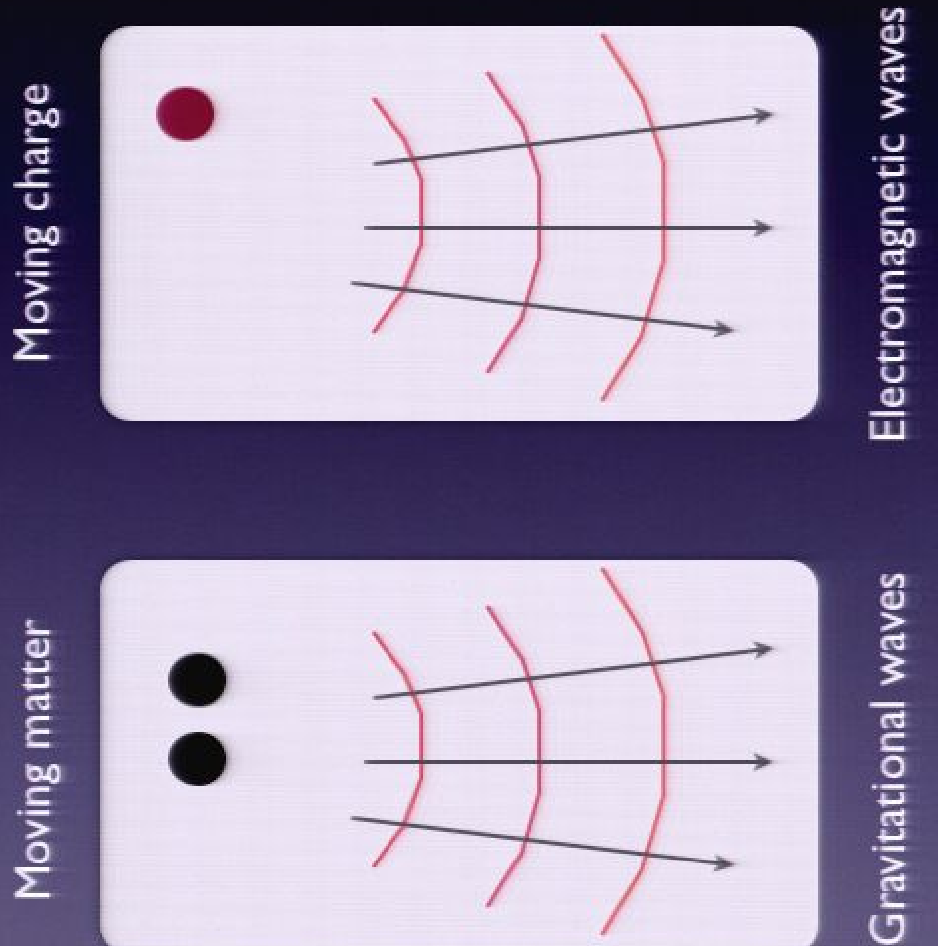

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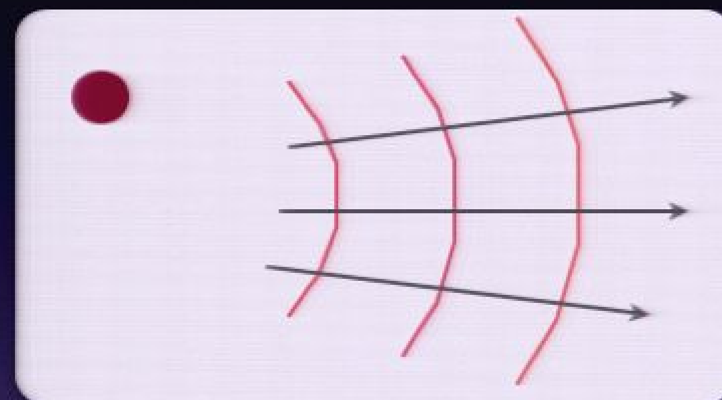
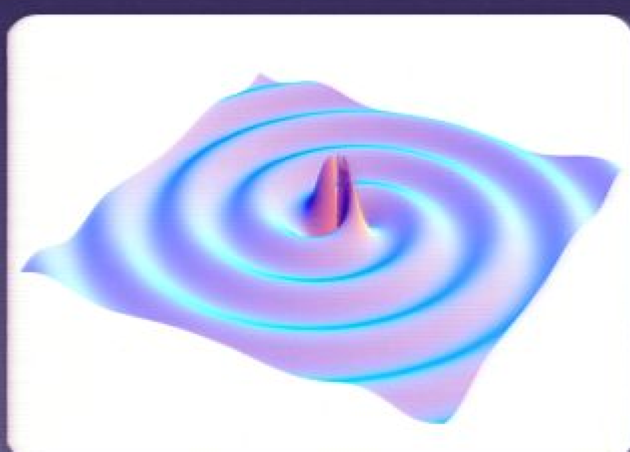
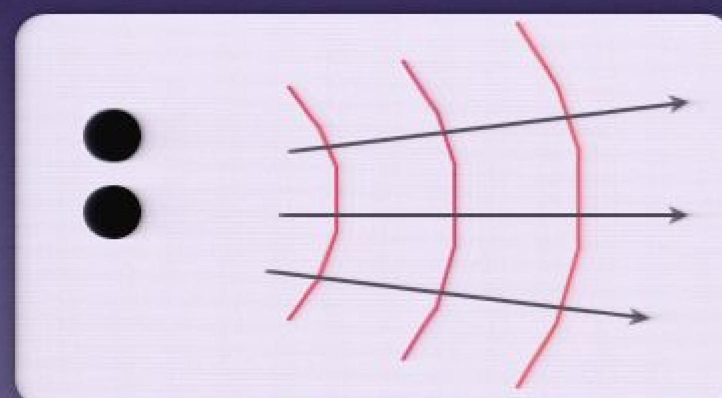
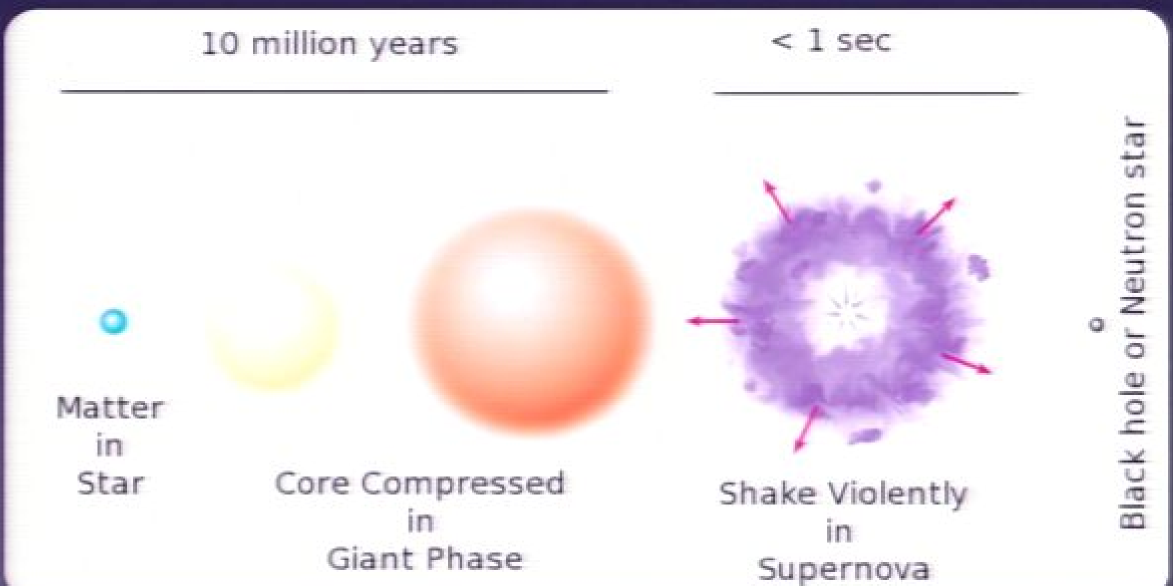






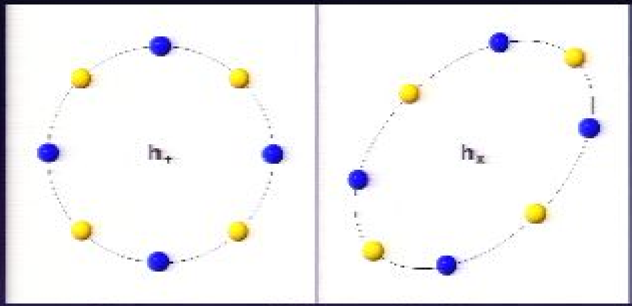
Recipe for GW

- Ingredients: matter
- Intructions: put lots of matter into a small space, keep it lumpy, and rotate very fast
- Nature does this for us:



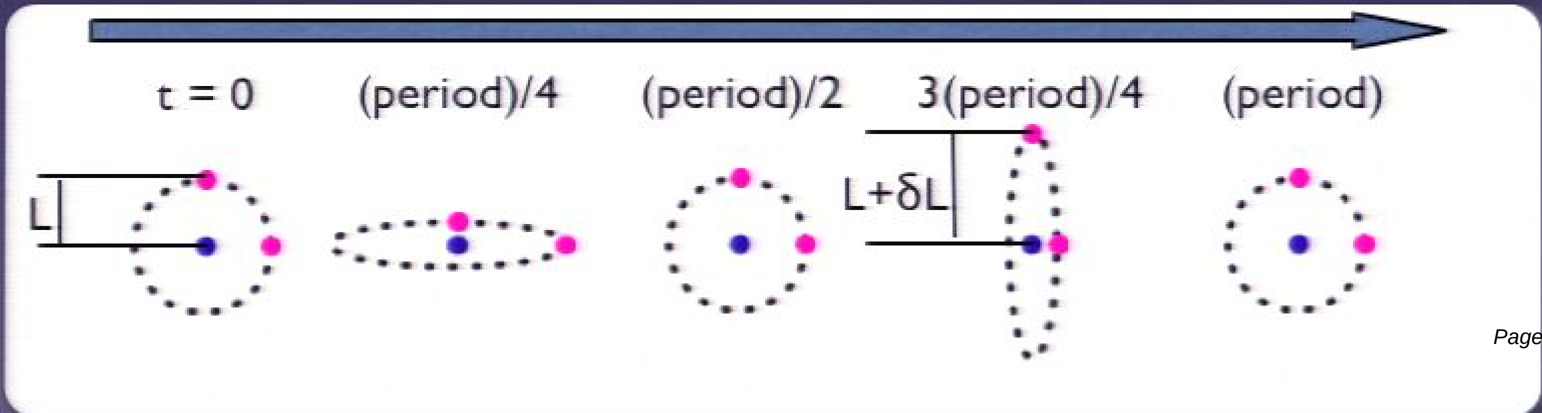
Physical Effects of the Waves

- As gravitational waves pass, they change the distance between neighboring bodies
- GR predicts two polarizations



Animations: Warren Anderson

- Fractional change in distance is the strain given by $h = \delta L / L$



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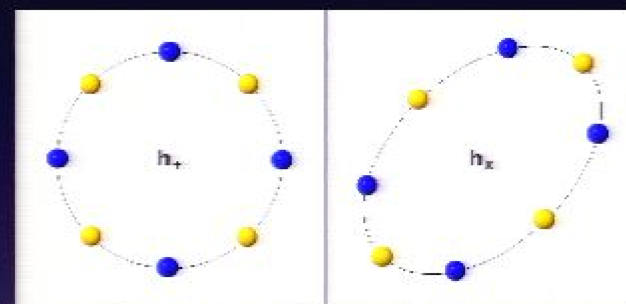

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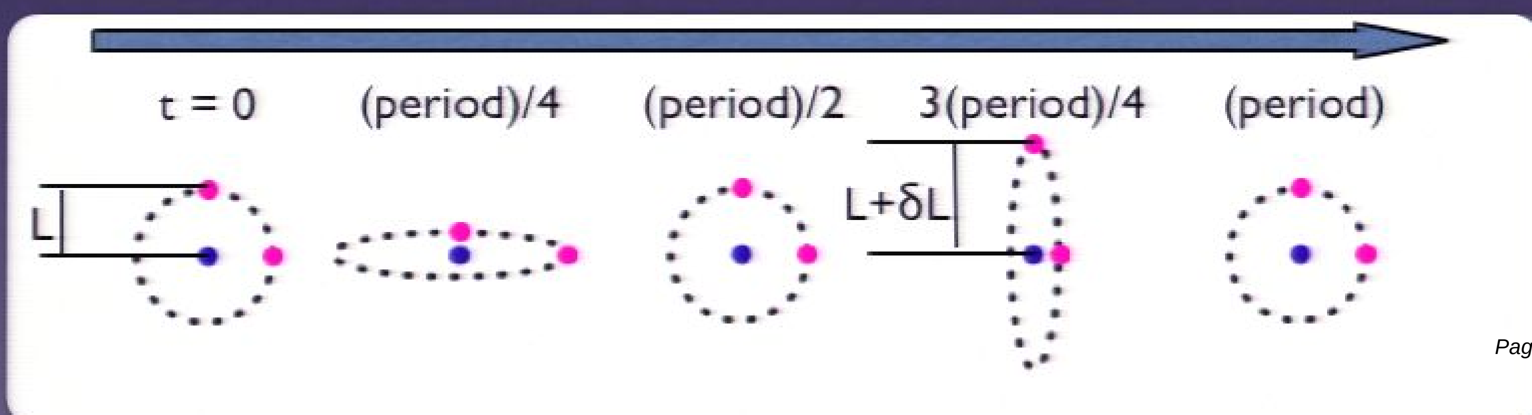

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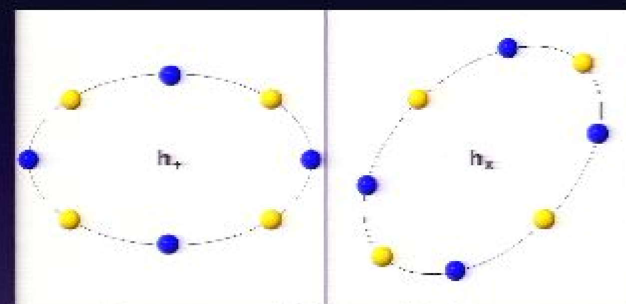

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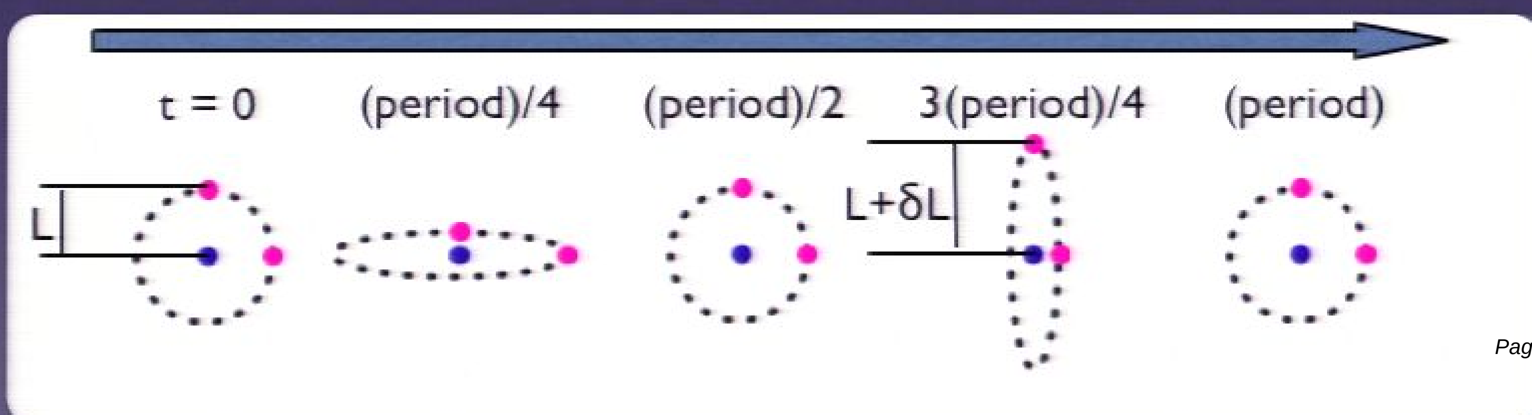
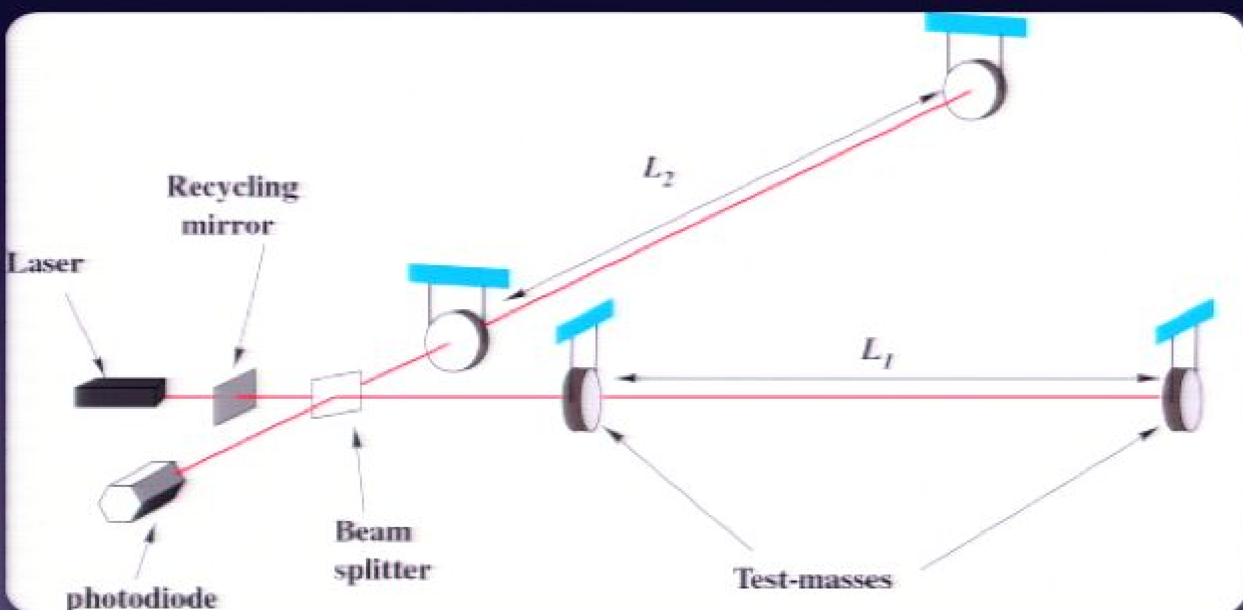


$$h \sim \frac{1}{r}$$

r → distance to source.

Schematic Detector

As a wave passes, one arm stretches
and the other shrinks ….



<u>LIGO design goal</u>
Measure fractional
change in arm length
h = δL/L ~ 10-21

…causing the interference pattern
to change at the photodiode

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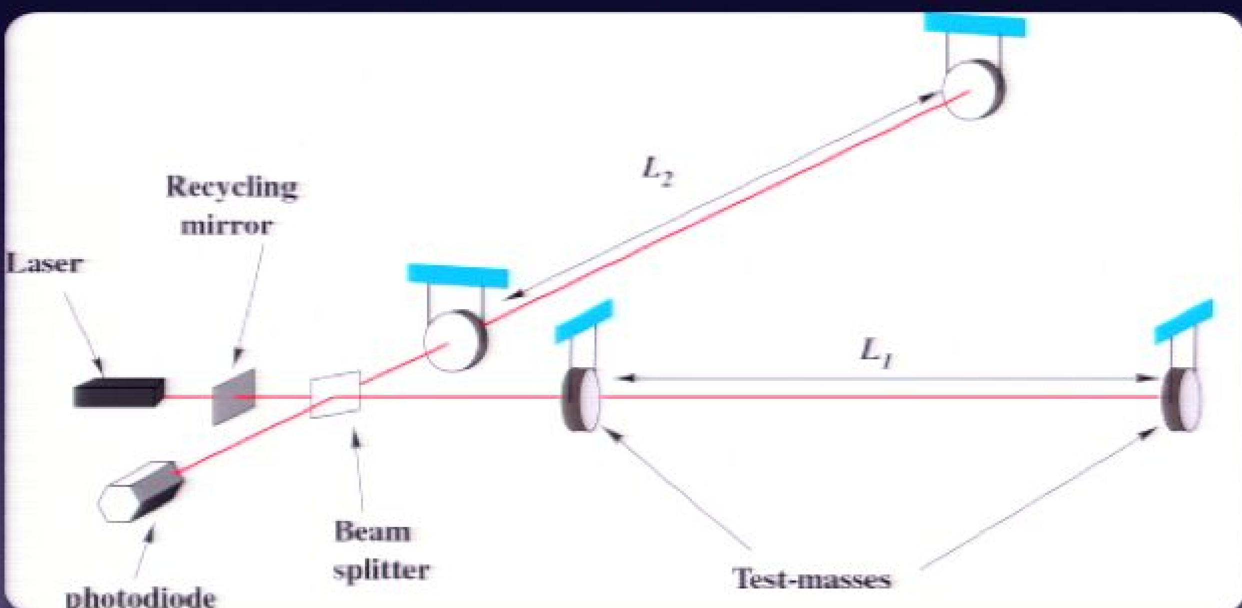

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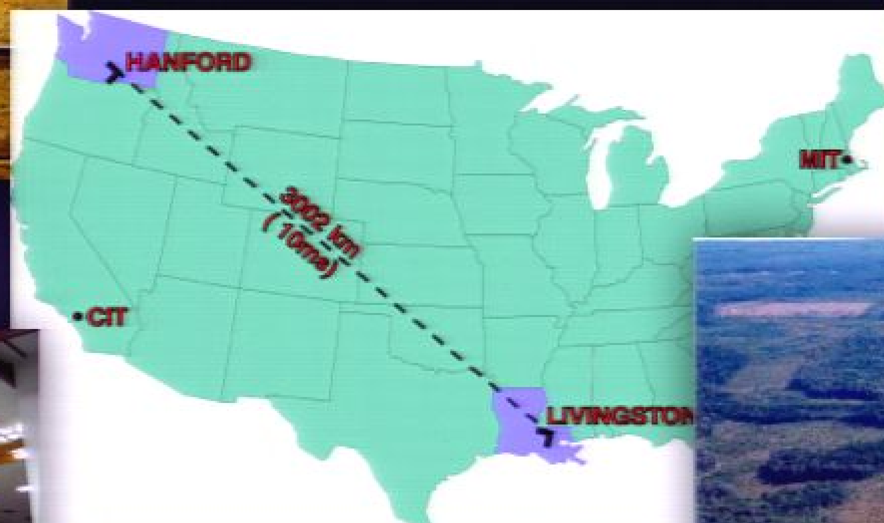
LIGO Observatories

Hanford: two interferometers in same vacuum envelope (4km, 2km)



Livingston: one interferometer (4km)

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LIGO Scientific Collaboration Research Group

Astrophysical Gravitational Wave Detection and Analysis

Center for Gravitation and Cosmology

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- General Computing
- Nemo Cluster
- Medusa Cluster
- Nagios Monitoring
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Data Analysis:

- LIGO-Virgo Portal
- LSC Burst Group
- Inspiral Group
- LSC Periodic Group
- LSC Stochastic Group

LSC:

- LIGO Scientific Collaboration
- LSC Newsletter
- Analysis Committee
- Computing Committee
- DetChar

LSC Software:

- DASWG

About Us

LIGO, which stands for Laser Interferometer Gravitational-Wave Observatory, is an ambitious physics project which aims to detect gravitational waves. The LIGO Scientific Collaboration research group of the University of Wisconsin-Milwaukee (UWM LSC) has been a significant contributor to this effort from its very beginning, more than ten years ago. At present, this gravitational physics group is among the nation's largest and most active. It is part of the UWM Center for Gravitation and Cosmology and it comprises more than twenty members and nine professors. It is part of the Center for Gravitation and Cosmology.

Research at the group includes the study of:

- Gravitational waves sources: gamma ray bursts, compact binaries systems, continuous wave sources, and stochastic background
- Data Analysis
- Cluster Computing

The UWM LSC is part of the LIGO Scientific Collaboration, with more than 600 scientists from 40 institutions around the world. It forms part of a worldwide network of gravitational-wave detectors which includes the British-German GEO, the French-Italian VIRGO and the Japanese TAMA. Scientific analysis of data from the LIGO, GEO and VIRGO instruments is carried out in common.

News

14 October 2009: New Associate or Senior Scientist Positions at UWM LSC Read more...

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24 March 2009: New Einstein@Home effort launched: thousands of home computers to search Arecibo data for new radio pulsars Read more...

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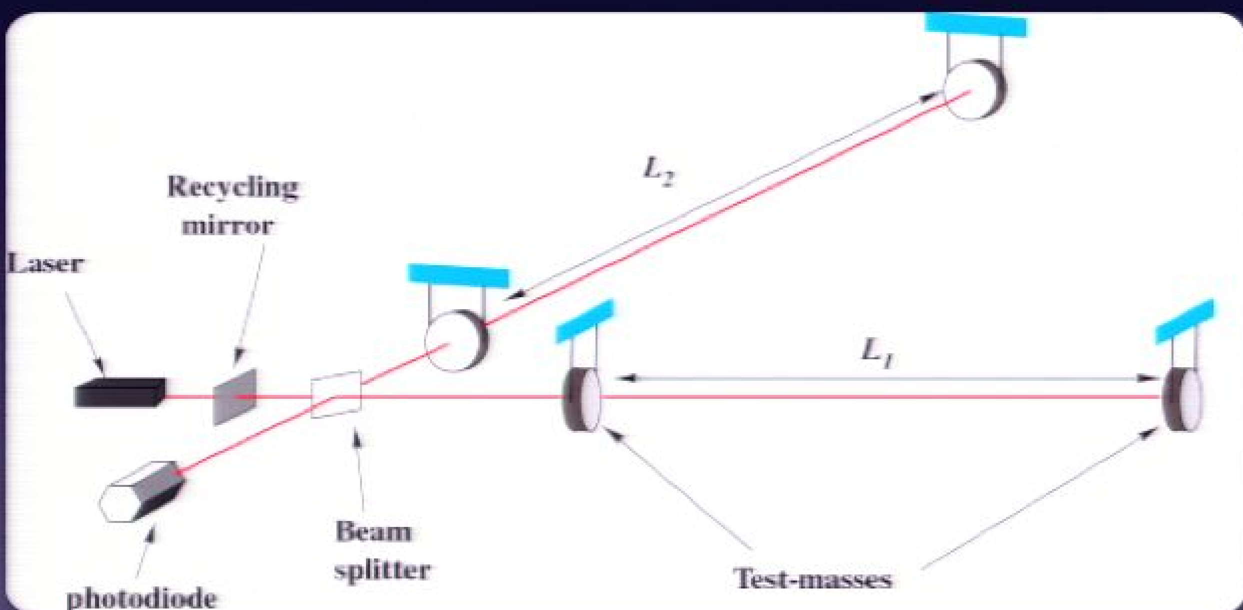

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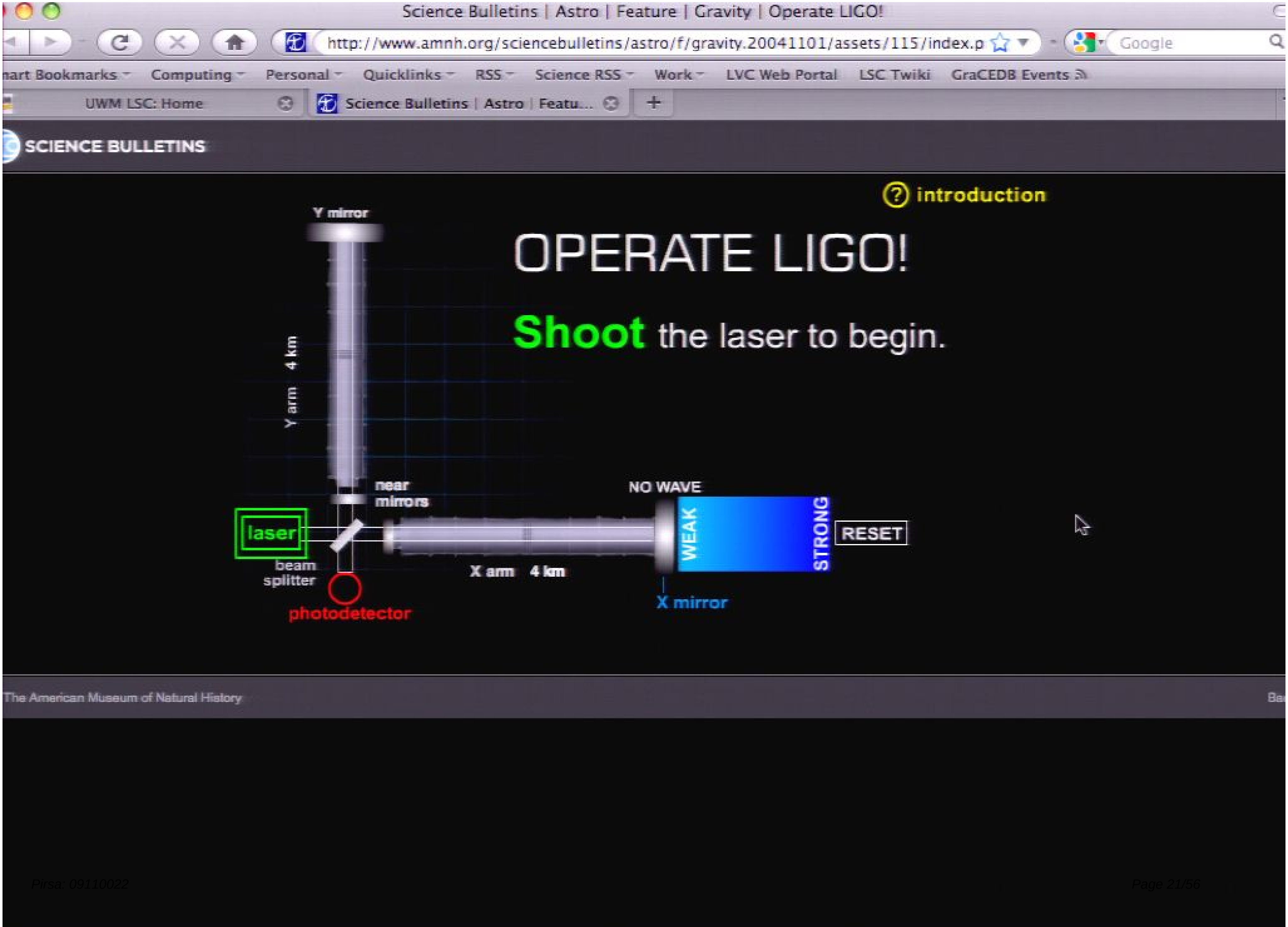
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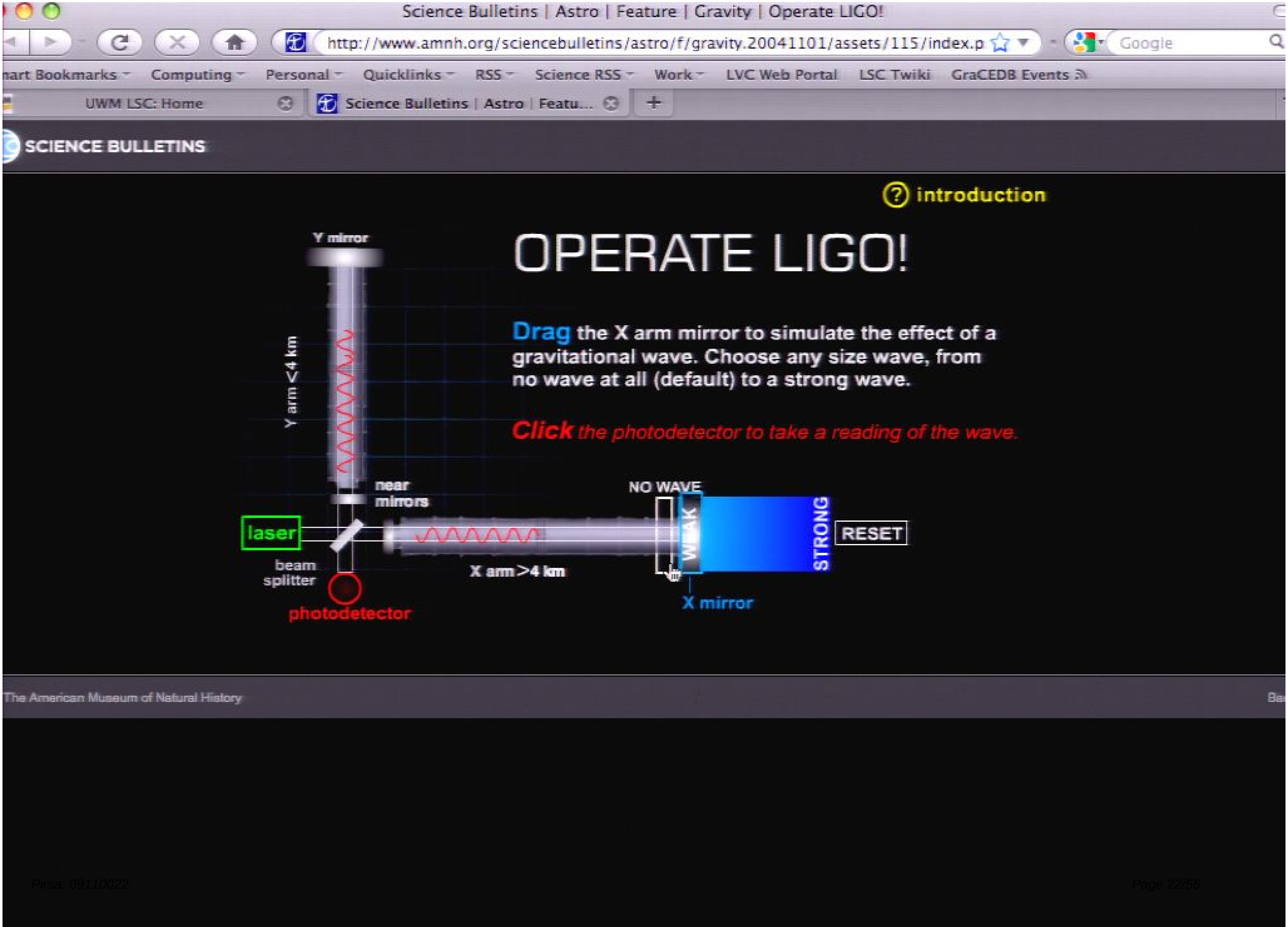
SCIENCE BULLETINS
introduction
OPERATE LIGO!
Shoot the laser to begin.
Y mirror
Y arm 4 km
near mirrors
laser
beam splitter
photodetector
X arm 4 km
NO WAVE
WEAK
STRONG
RESET
X mirror
The American Museum of Natural History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SCIENCE BULLETINS
introduction
OPERATE LIGO!
Drag the X arm mirror to simulate the effect of a gravitational wave. Choose any size wave, from no wave at all (default) to a strong wave.
Click the photodetector to take a reading of the wave.
Y mirror
Y arm <4 km
near mirrors
laser
beam splitter
photodetector
X arm >4 km
NO WAVE
WEAK
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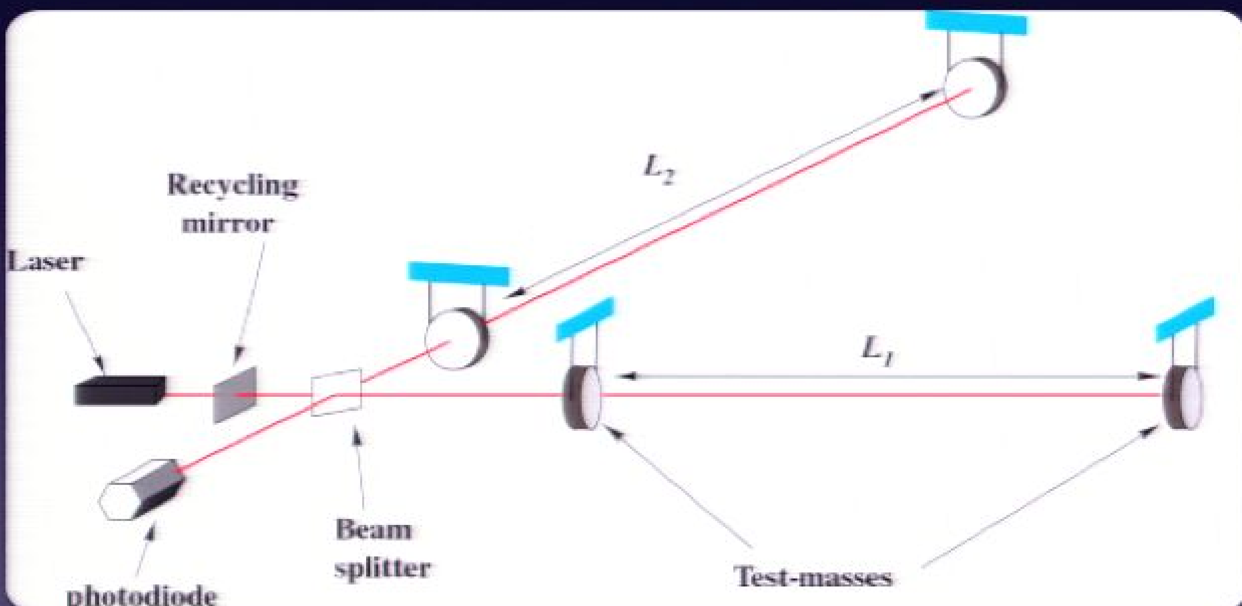

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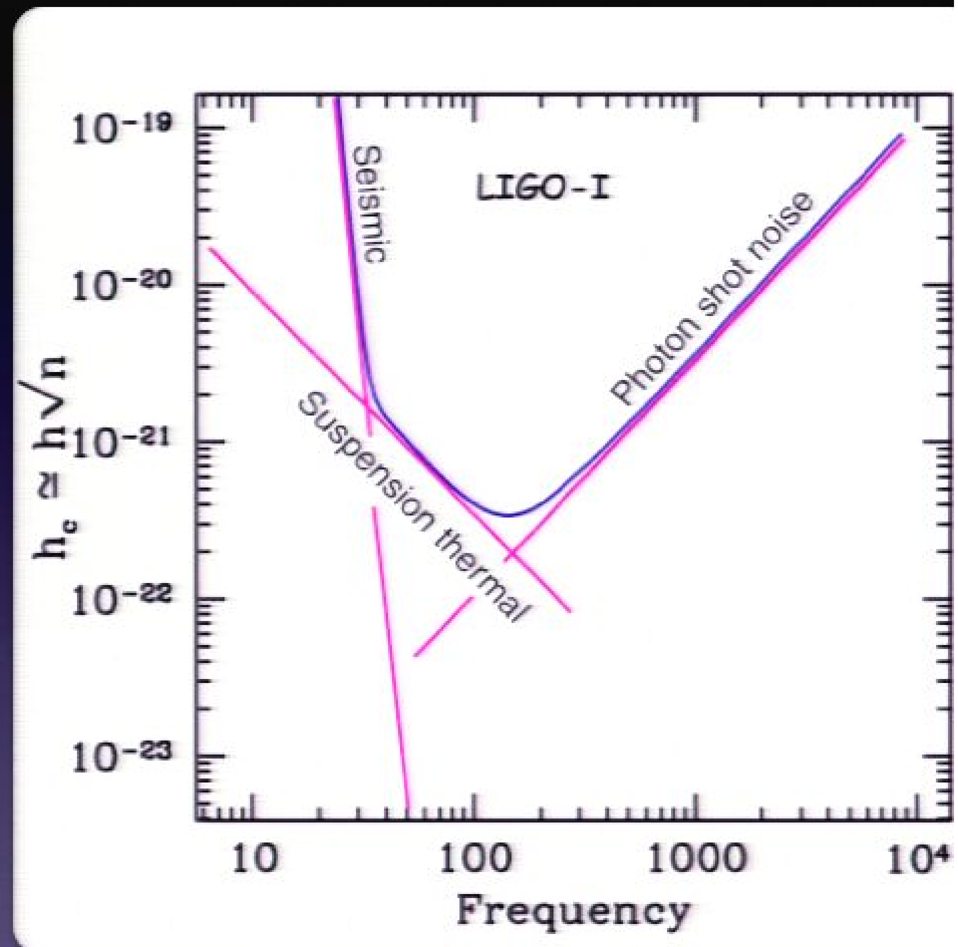
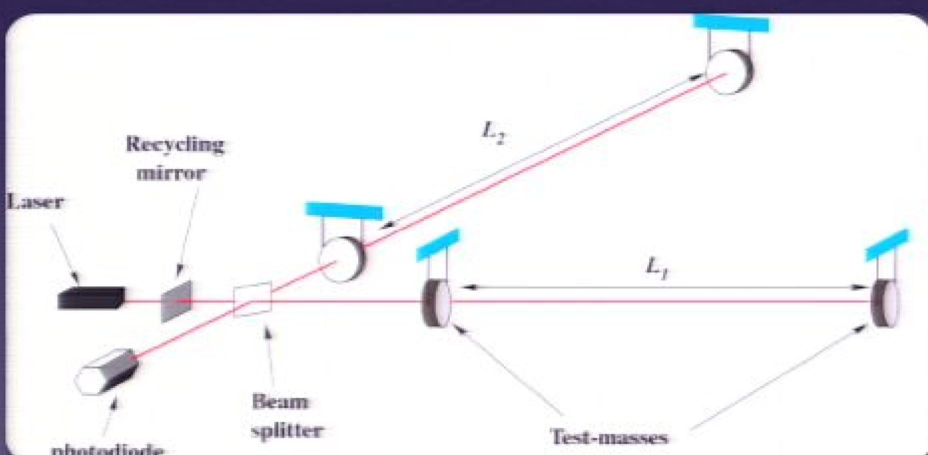
LIGO Sensitivity

- The noise in the LIGO interferometers is dominated by three different processes depending on the frequency band





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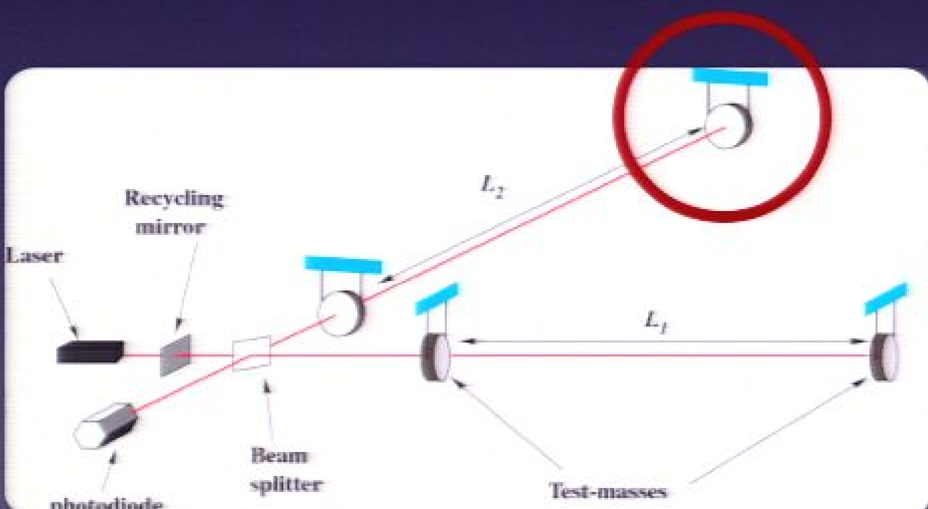

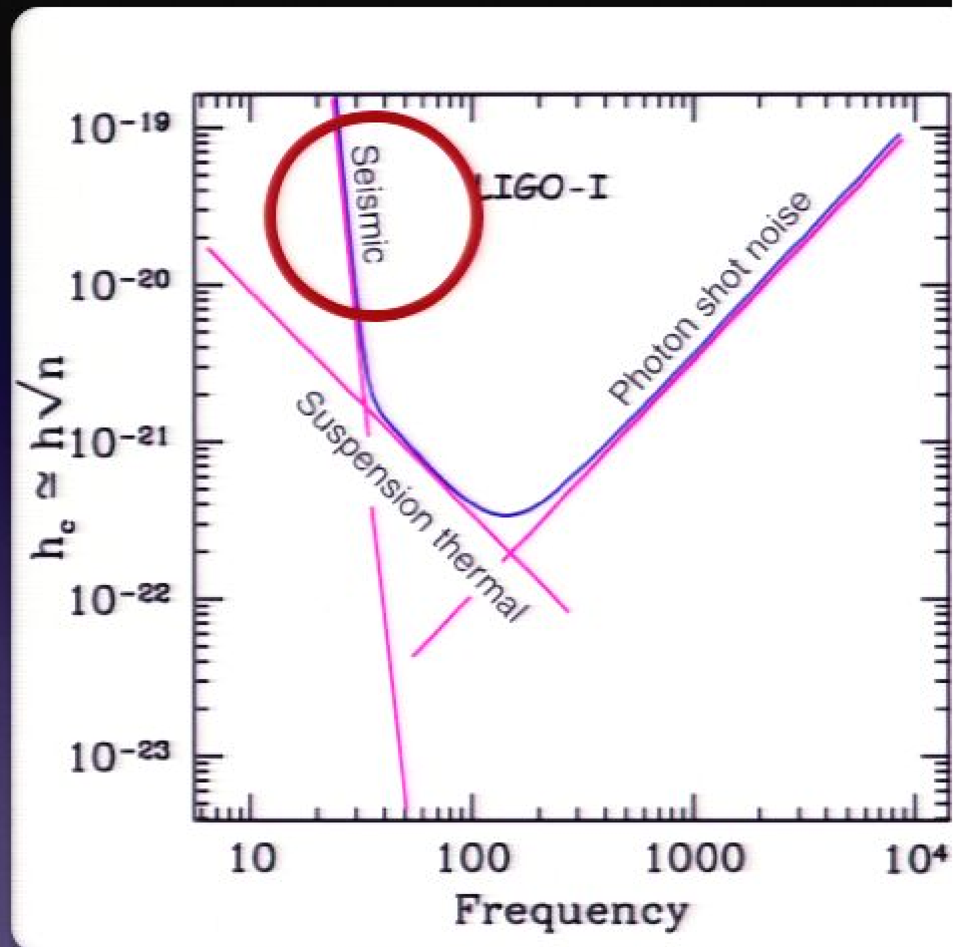

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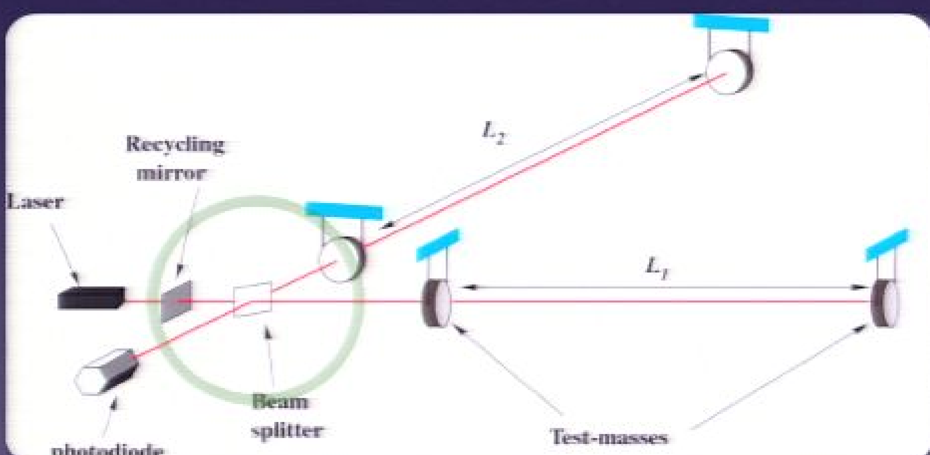

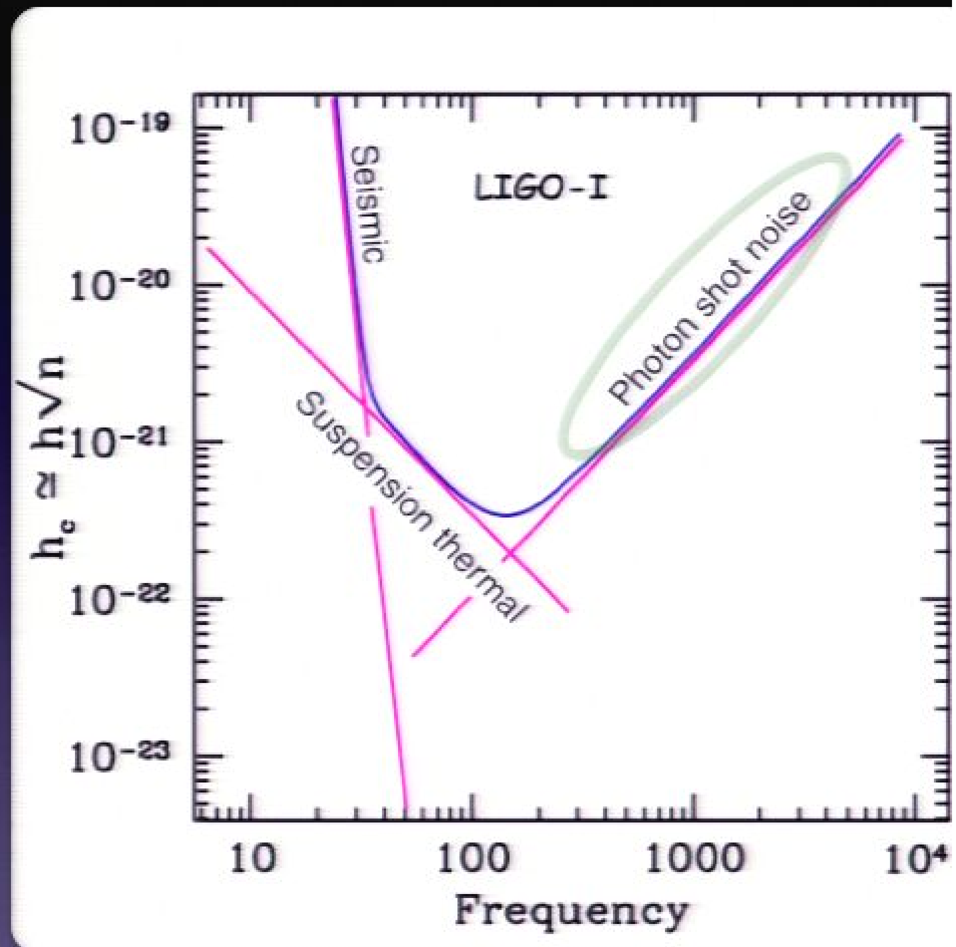

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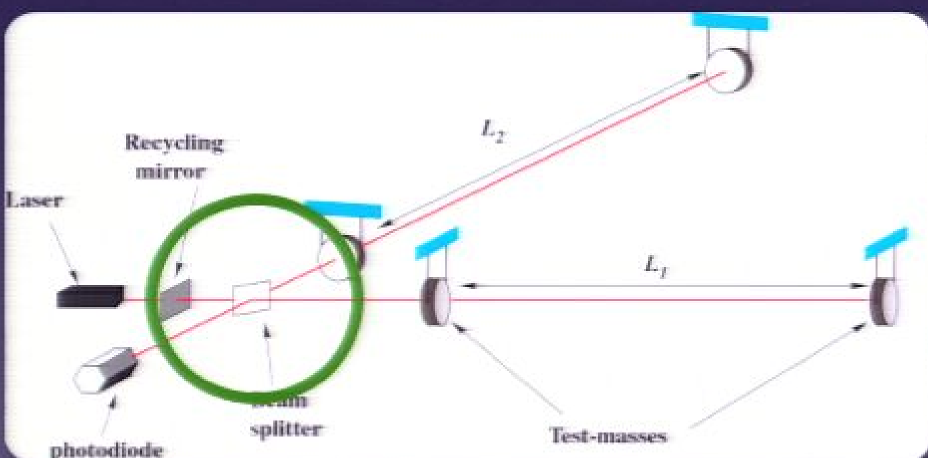
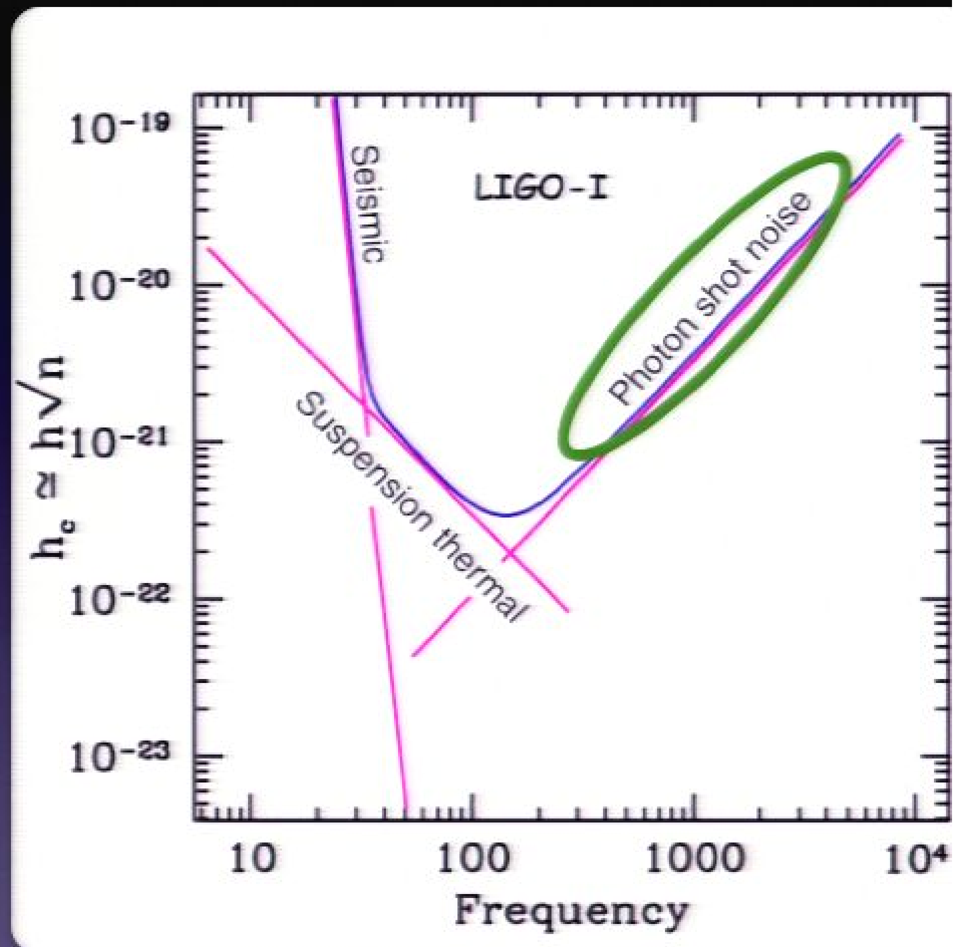




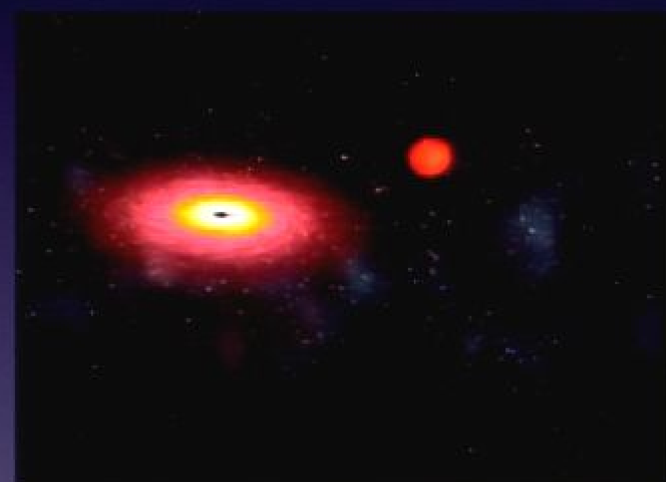
Commissiong/Running

Science Goals

- Direct verification of two dramatic predictions of Einstein's general relativity: gravitational waves and black holes
- Physics
  - Detailed tests of properties of gravitational waves including speed, polarization, strength, graviton mass, ...
  - Probe strong field gravity around black holes and in the early universe
  - Probe the neutron star equation of state
- Astronomy
  - By performing routine astronomical observations, understand compact binary populations, rates of supernovae explosions, test gamma-ray burst models

Compact Binaries

- Pairs of black holes, neutron stars, or a black hole and neutron star
- As they orbit one another, they emit gravitational waves and the objects get closer together, eventually merging
- LIGO is sensitive to last few minutes of inspiral and merger



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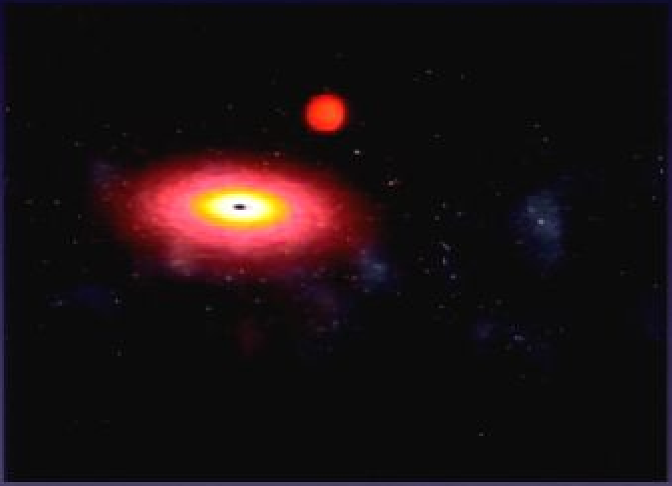

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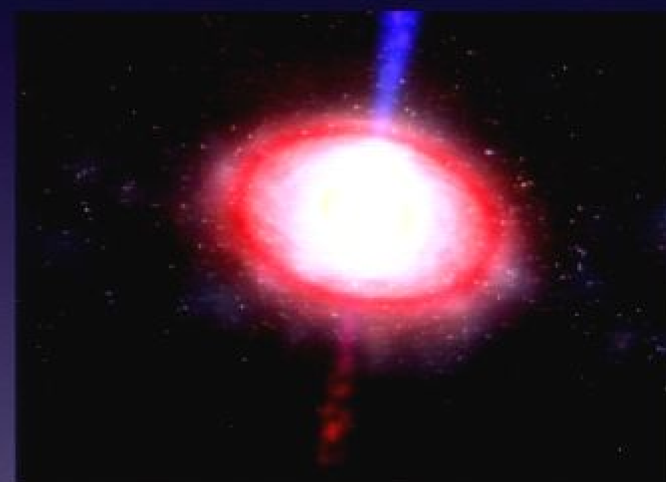
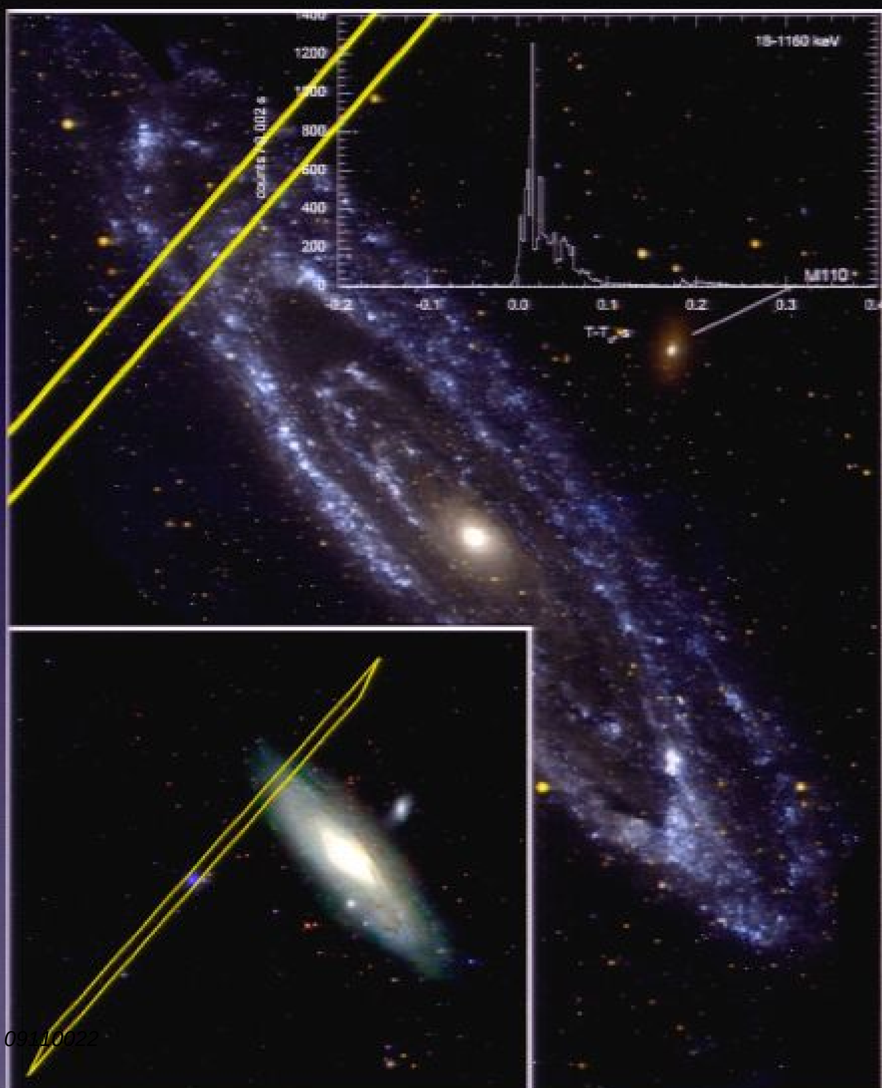


GRB 070201

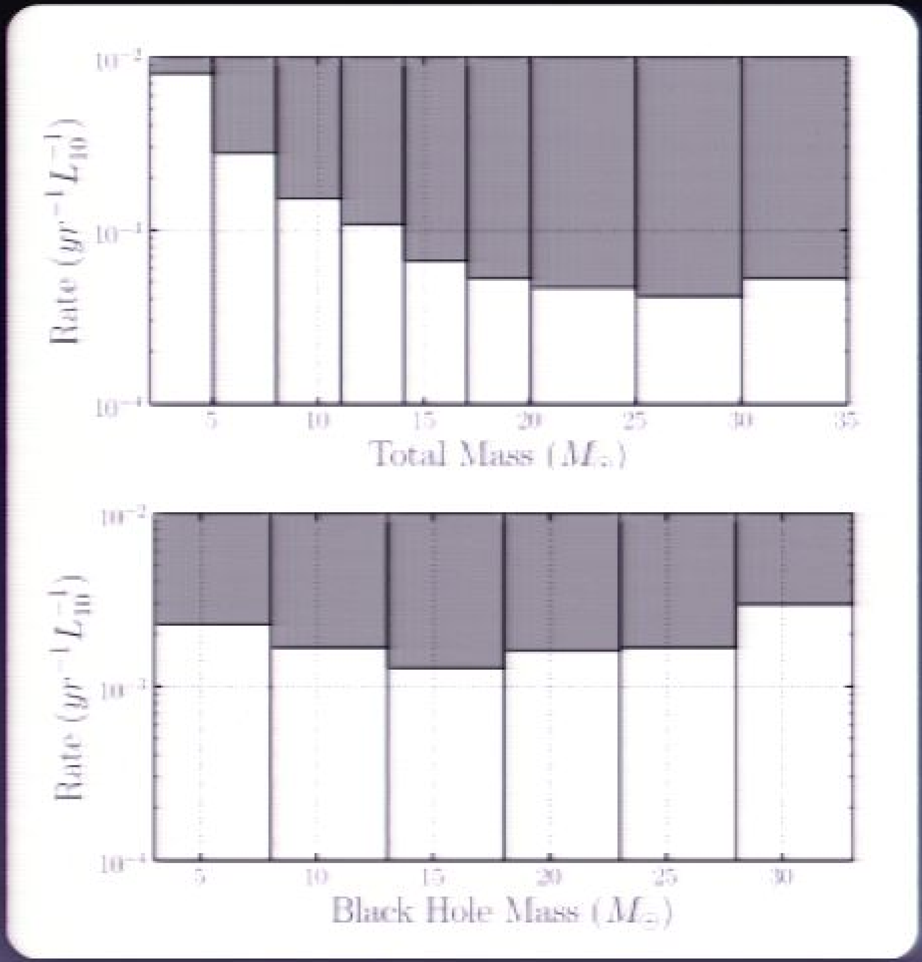
No plausible gravitational waves found



- Short gamma-ray burst
- IPN error box included M_{31}!
- Exclude any compact binary progenitor in our simulation space at the distance of M_{31} at > 99% confidence level
- Exclude compact binary progenitor with masses $1 M_{\odot} < m_1 < 3 M_{\odot}$ and $1 M_{\odot} < m2 < 40 M_{\odot}$ with D < 3.5 Mpc away at 90% CL

Searches for compact binaries

- Most likely rate for binary neutron stars is ~ 5×10^{-5} / yr / L_{10}
- L_{10} is unit of luminosity. Milky Way has ~1.7 L_{10}
- Neutron star black hole rates are ~1.5×10^{-6} / yr / L_{10}
- Black hole binaries are ~ 2×10^{-7} / yr / L_{10}



Abbott et al [LIGO and Virgo Collaboration], Phys. Rev. D 80 (2009) 047101

$$\delta L \approx 10^{-21} \times 4 \times 10^{3}\,m \qquad h \sim \frac{1}{r}$$

$$\approx 4 \times 10^{-18}\,m.$$

BNS $\longrightarrow$ 30–40 Mpc.

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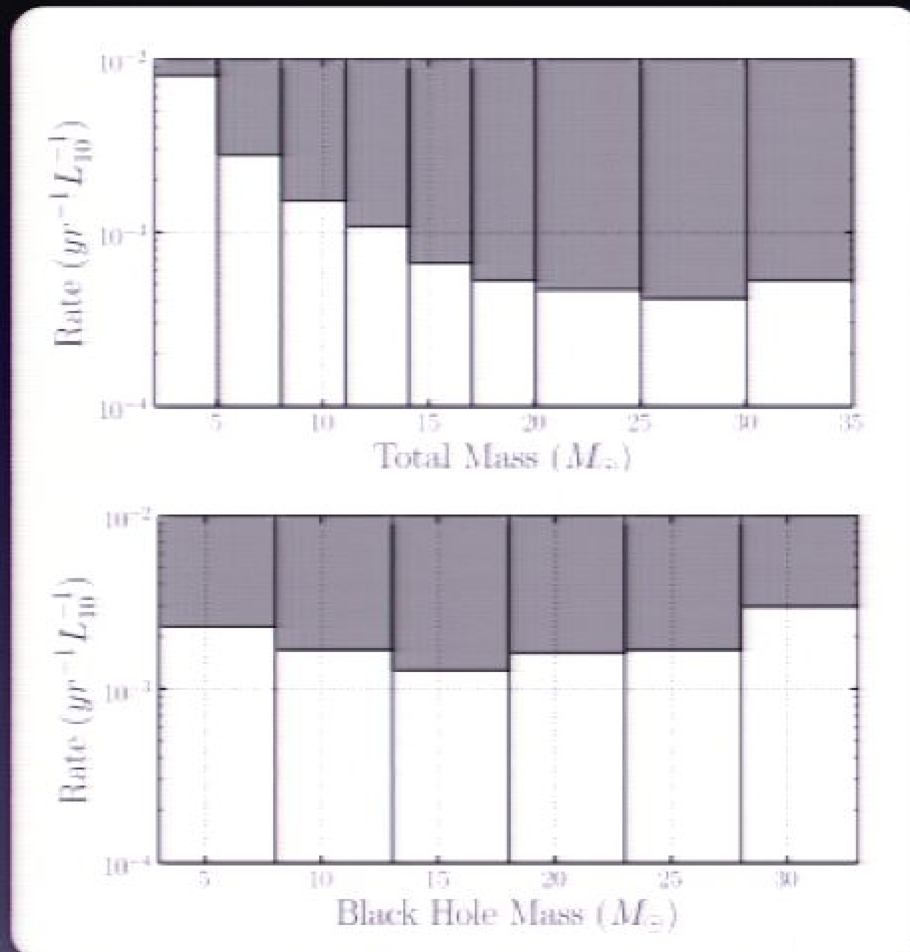

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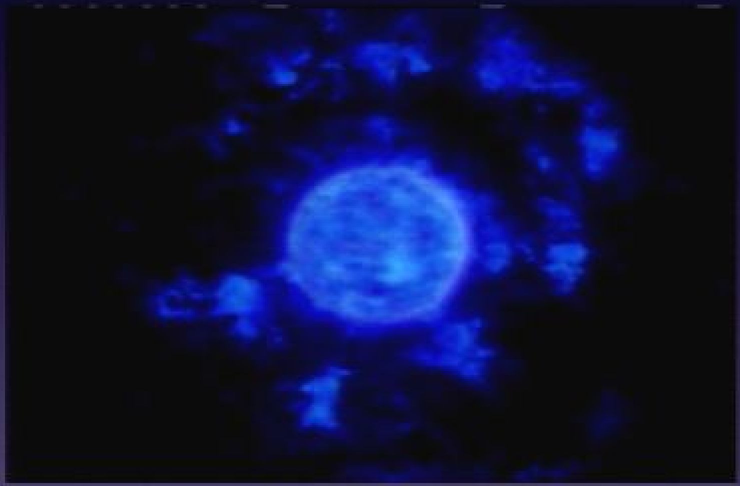
Gravitational-wave bursts

- Very short (< 1 sec) bursts of waves from violent astrophysical events
- Examples include supernova explosions, mergers of compact binaries, and cosmic string kinks and cusps



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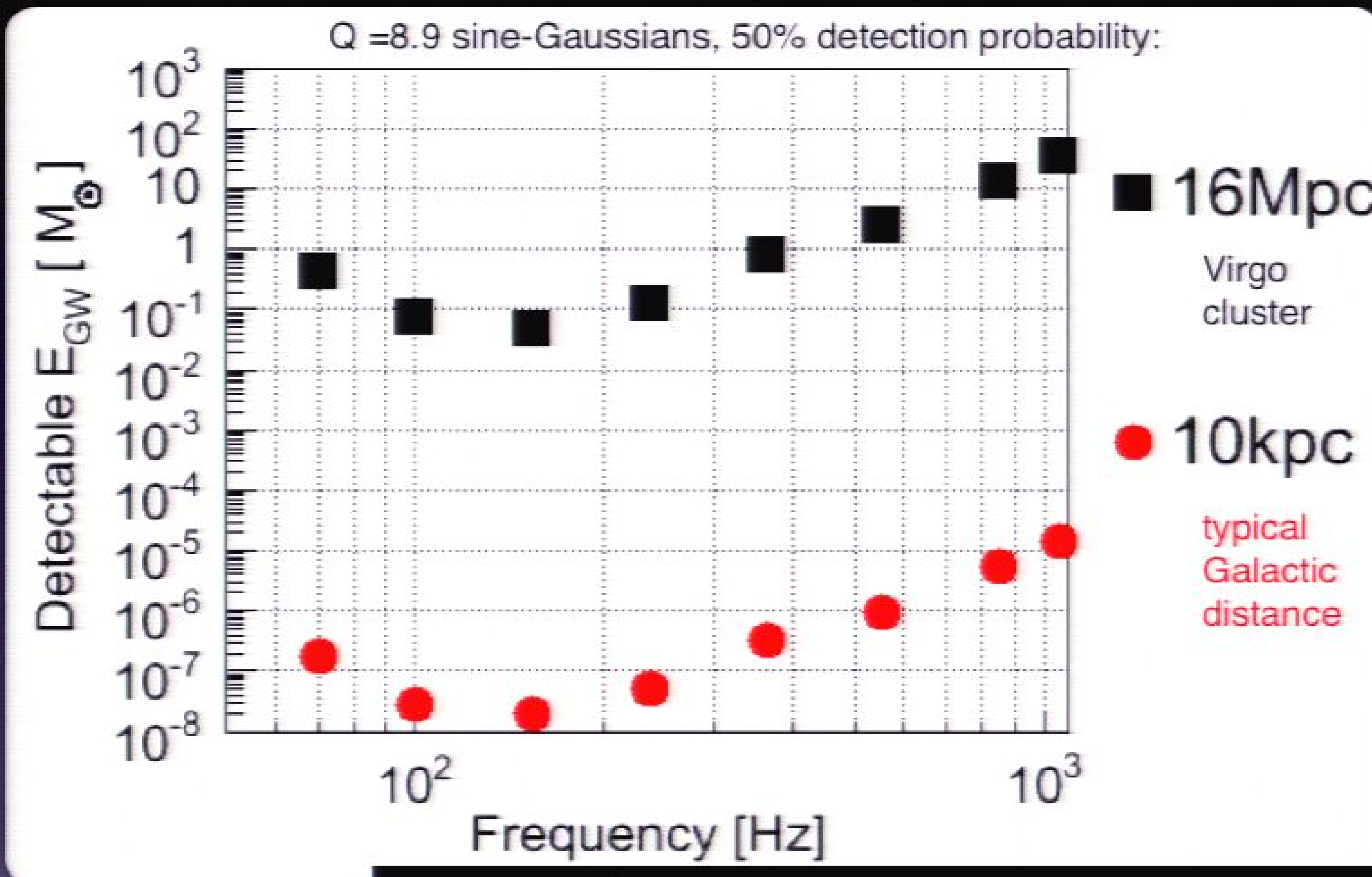

Courtesy: Laura Cadonati

For a 153 Hz, Q =8.9 sine-Gaussian, the S5 search can see with 50% probability:

~ $2 \times 10^{-8}\ M_\odot c^2$ at 10 kpc (typical Galactic distance)

~ $0.05\ M_\odot c^2$ at 16 Mpc (Virgo cluster)

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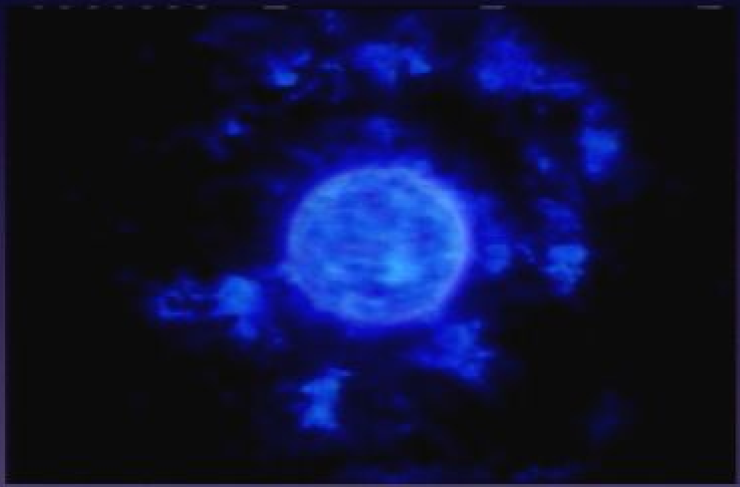
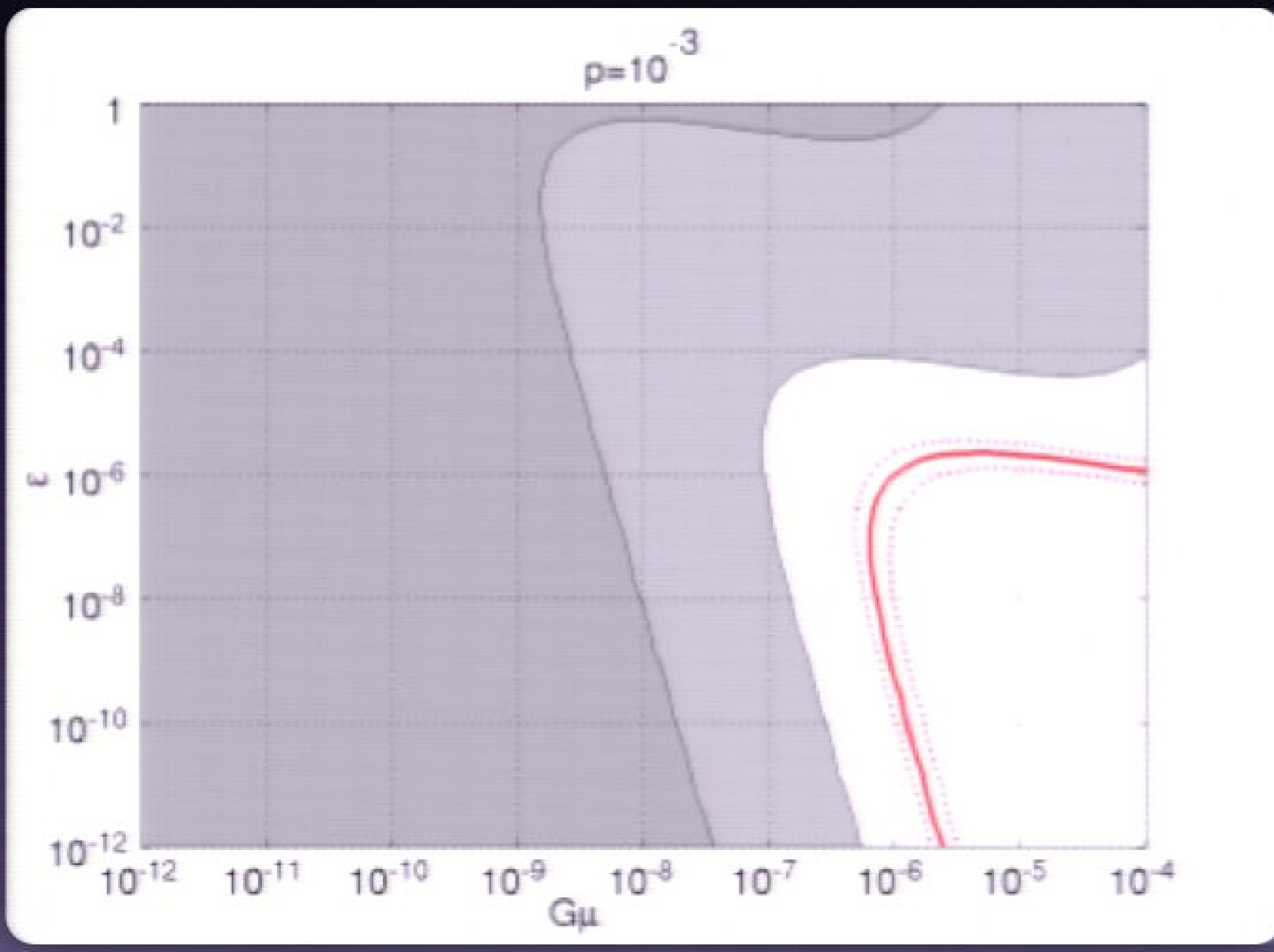


Bursts from cosmic strings (S4)



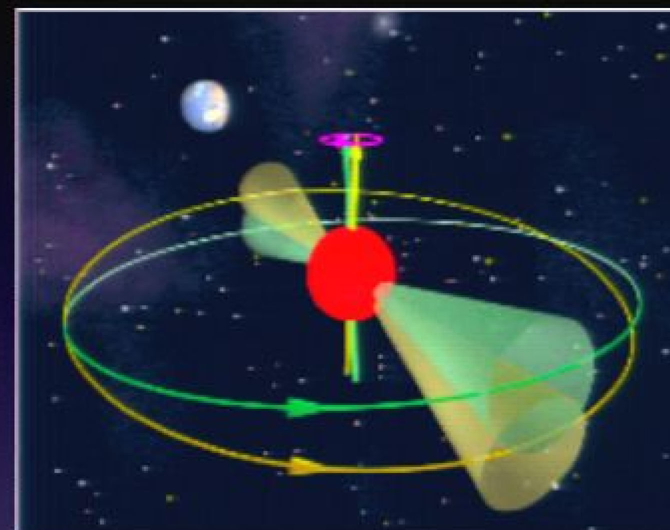
Abbott et al [LIGO Scientific Collaboration], Phys Rev D **80** (2009) 062002

Continuous Signals

- Signals lasting as long as, or longer than, the obervation time

- Known radio pulsars could also emit gravitational waves

- Unknown radio pulsars that are not beamed toward earth

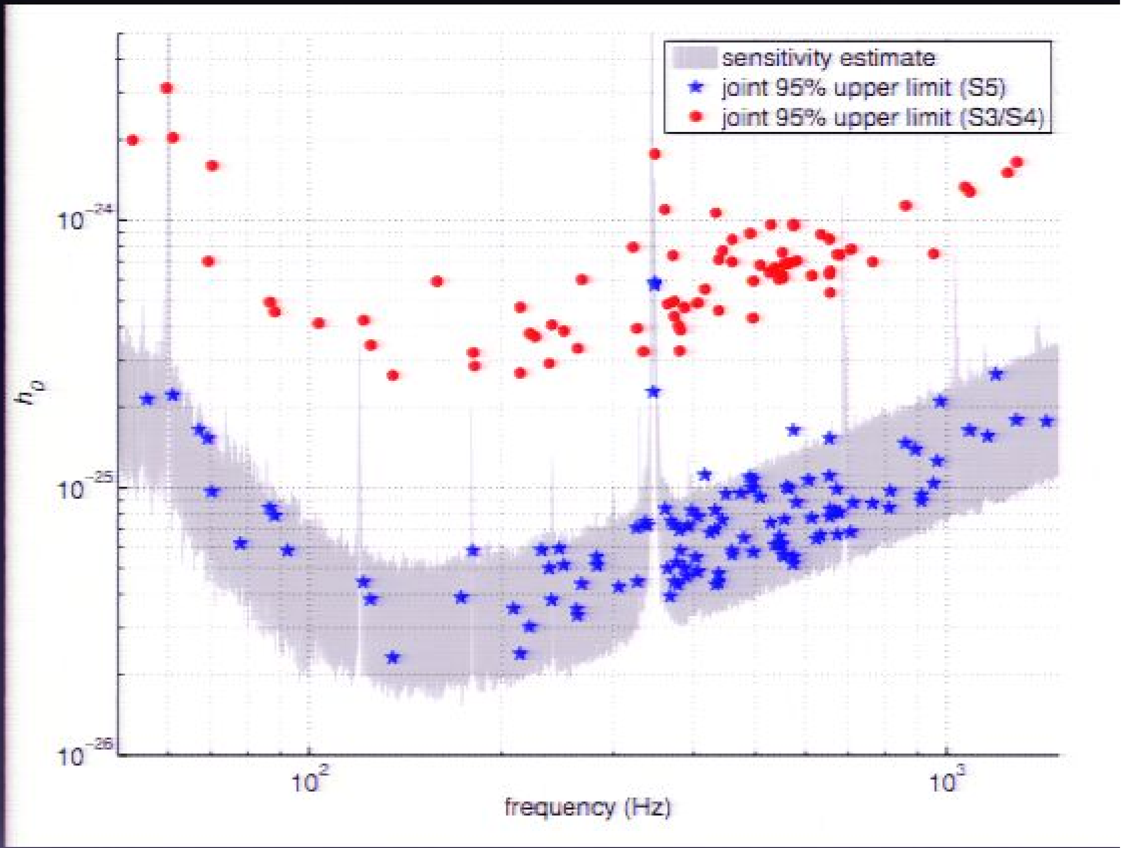


Credit: M. Kramer

Credit: Dana Berry/NASA

Searches for continuous waves

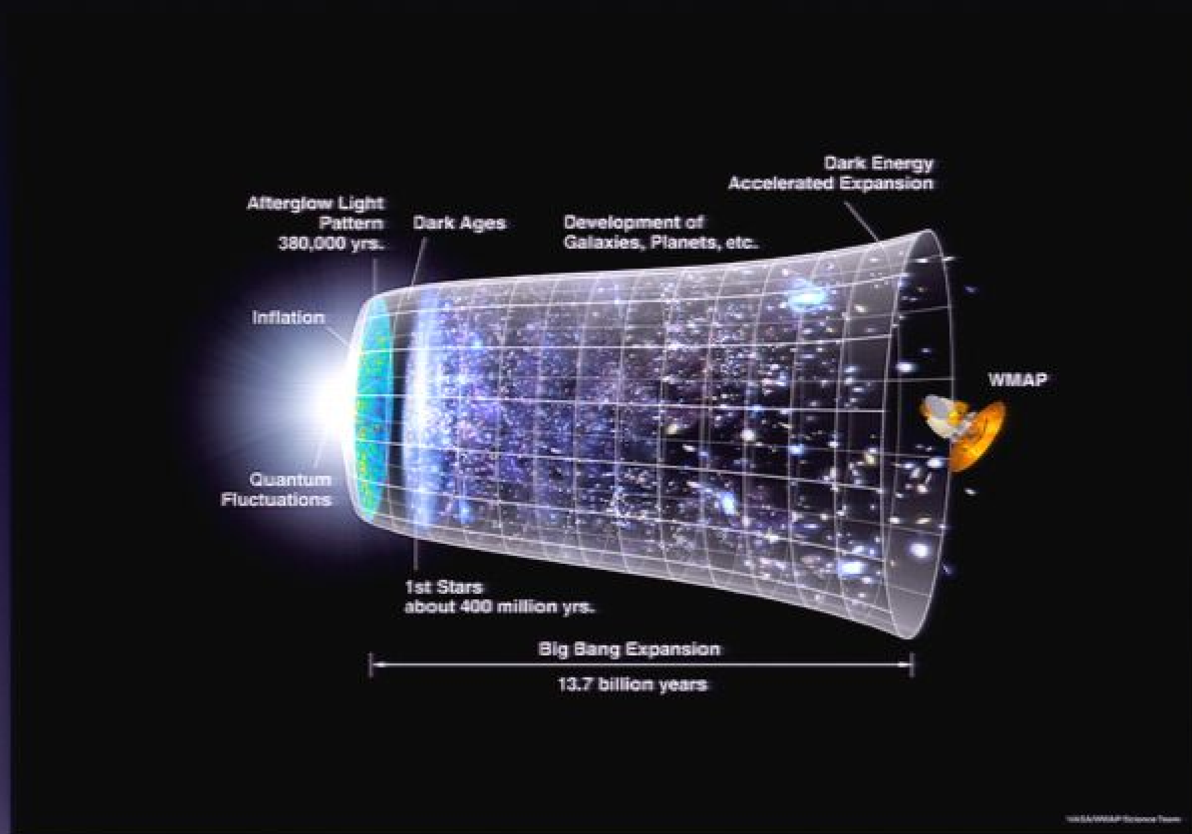
- Strength of gravitational waves depends on gravitational ellipticity
- Crab pulsar:
  - observed spindown allows maximum gravitational ellipticity around 10^{-3}
  - observations $< 10^{-4}$



Abbott et al [LIGO and Virgo Collaboration], arXiv:0909.3583

Stochastic Background

Credit: Jolien Creighton

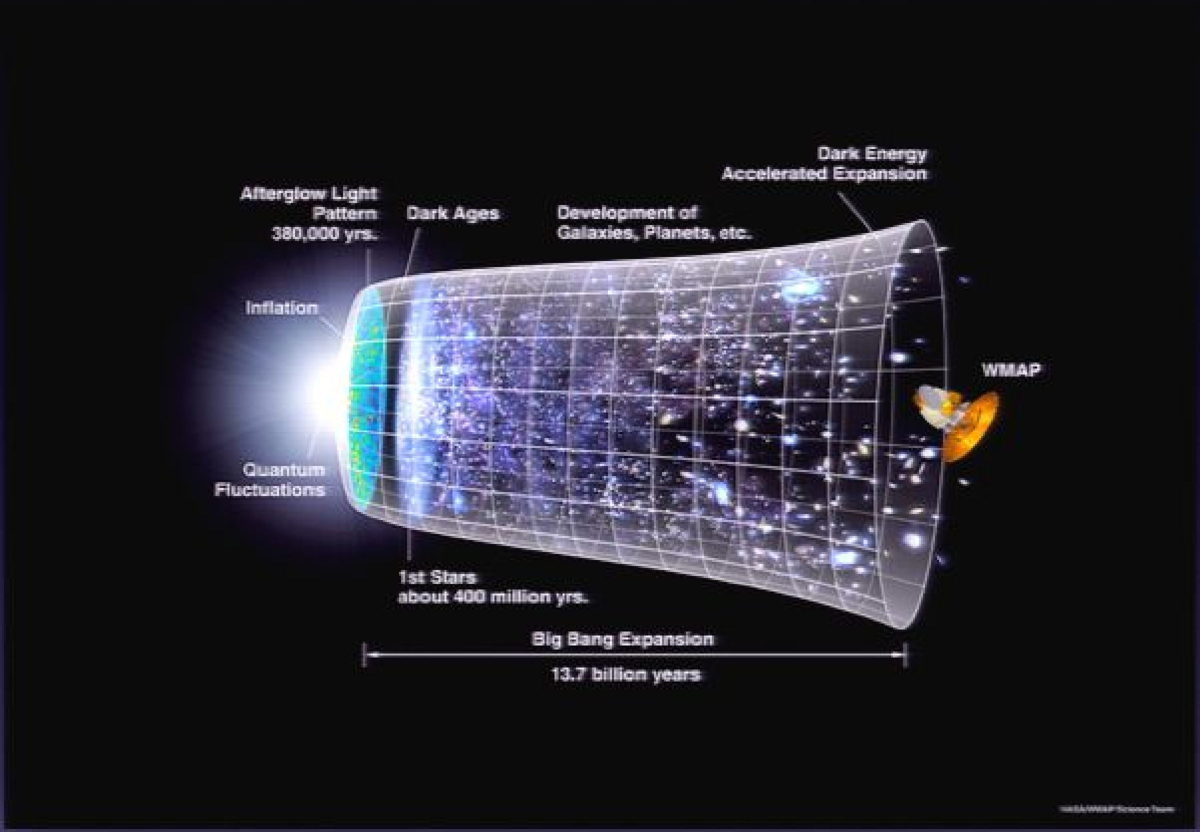


$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c} \frac{d\rho_{\mathrm{GW}}}{df}$$

Energy density in gravitational waves divided by critical density

Stochastic Background

Credit: Jolien Creighton



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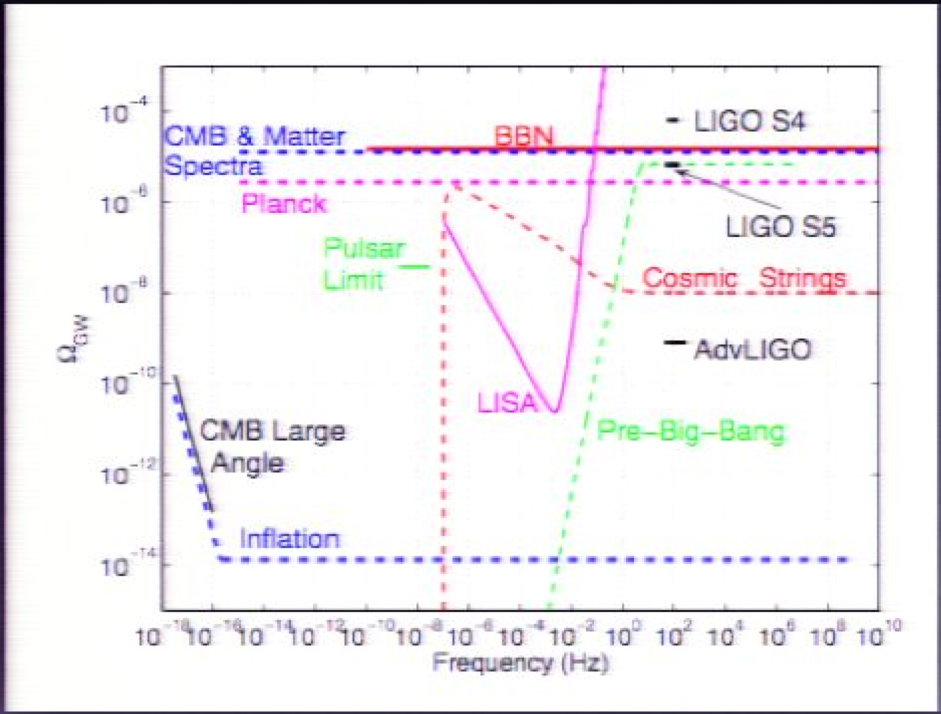
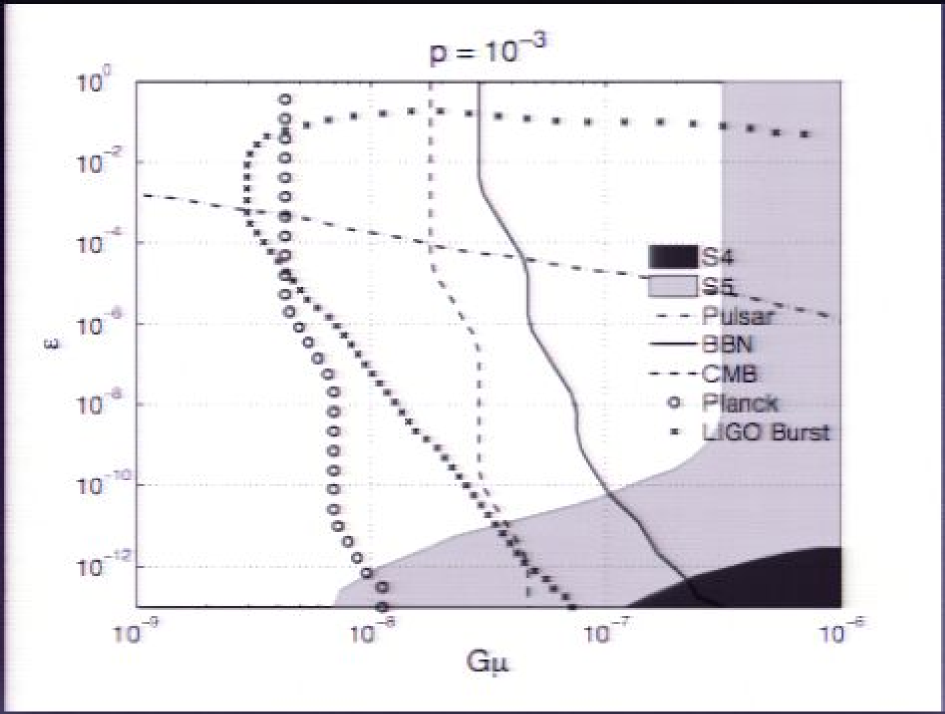


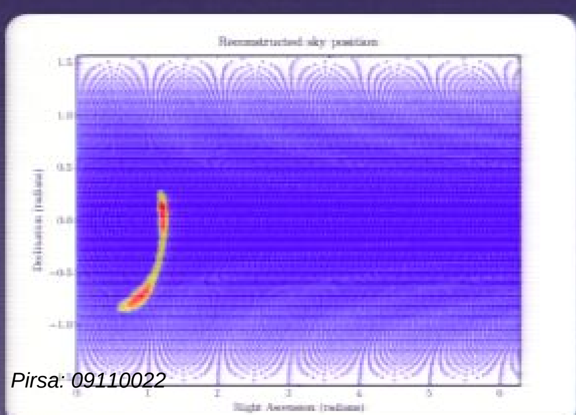


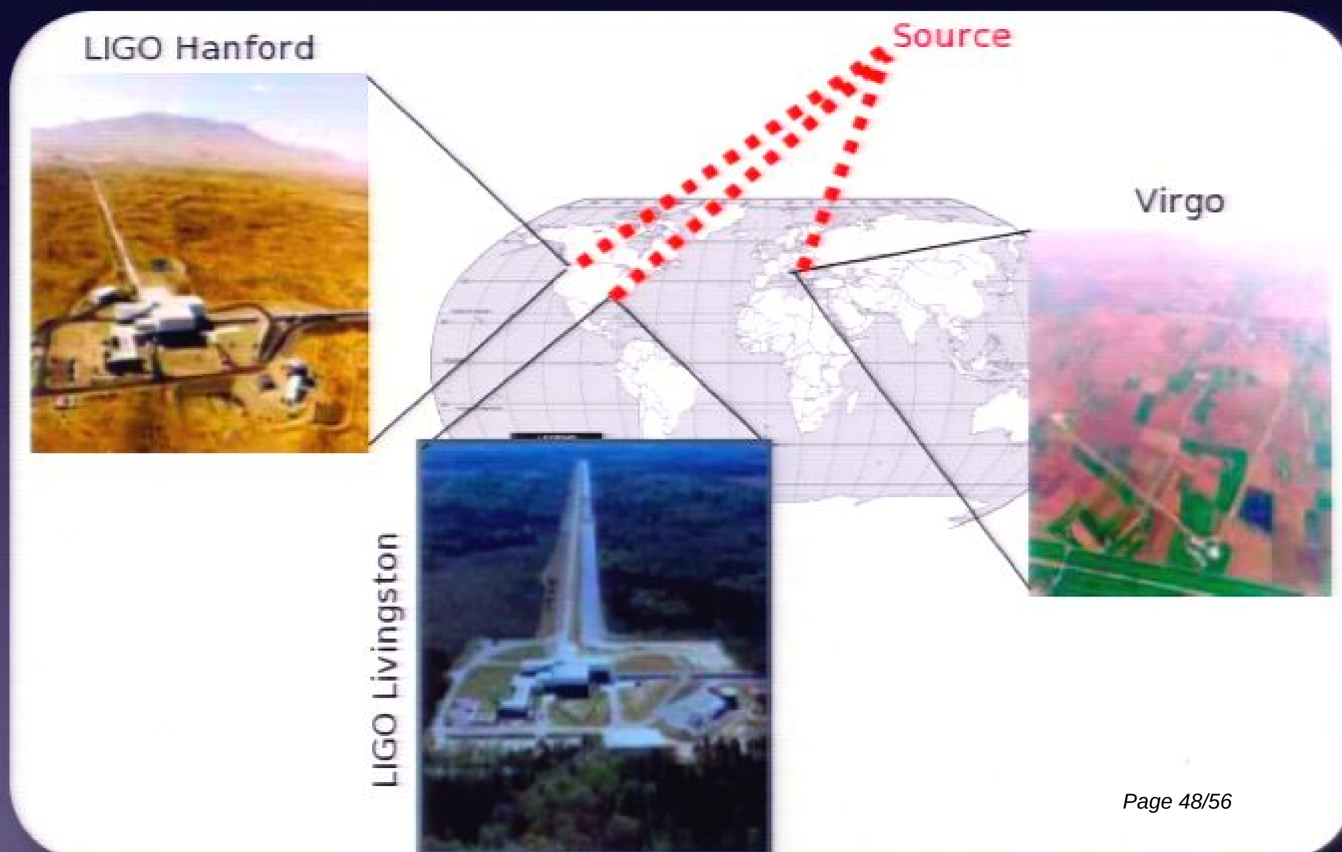
Abbott et al [LIGO Scientific Collaboration] Nature **460** (2009) 990

Current Activities (S6)

- LIGO and European Virgo detector operate as a network providing ability to localize on the sky

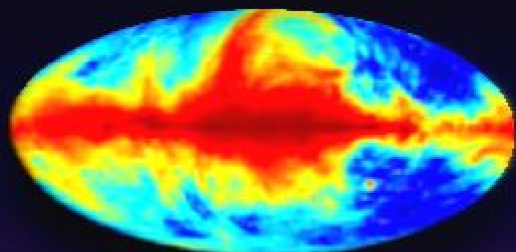
Simulated source localization with 3 detectors



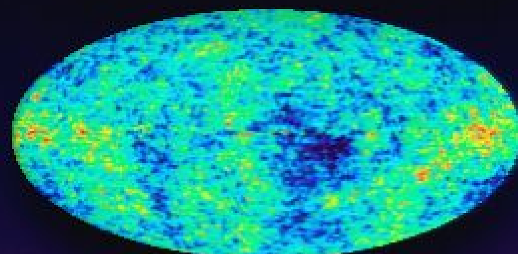


Current activities

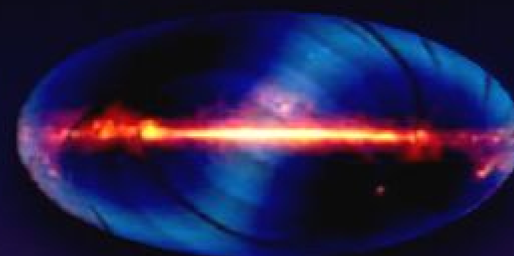
radio

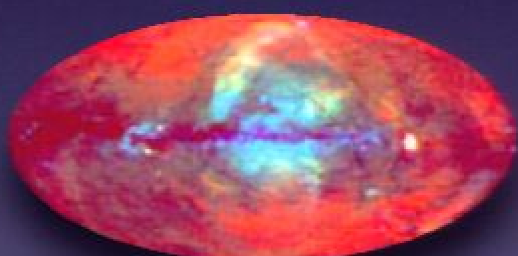


microwave

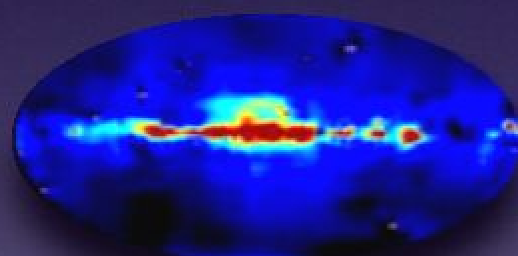


infrared





x-ray



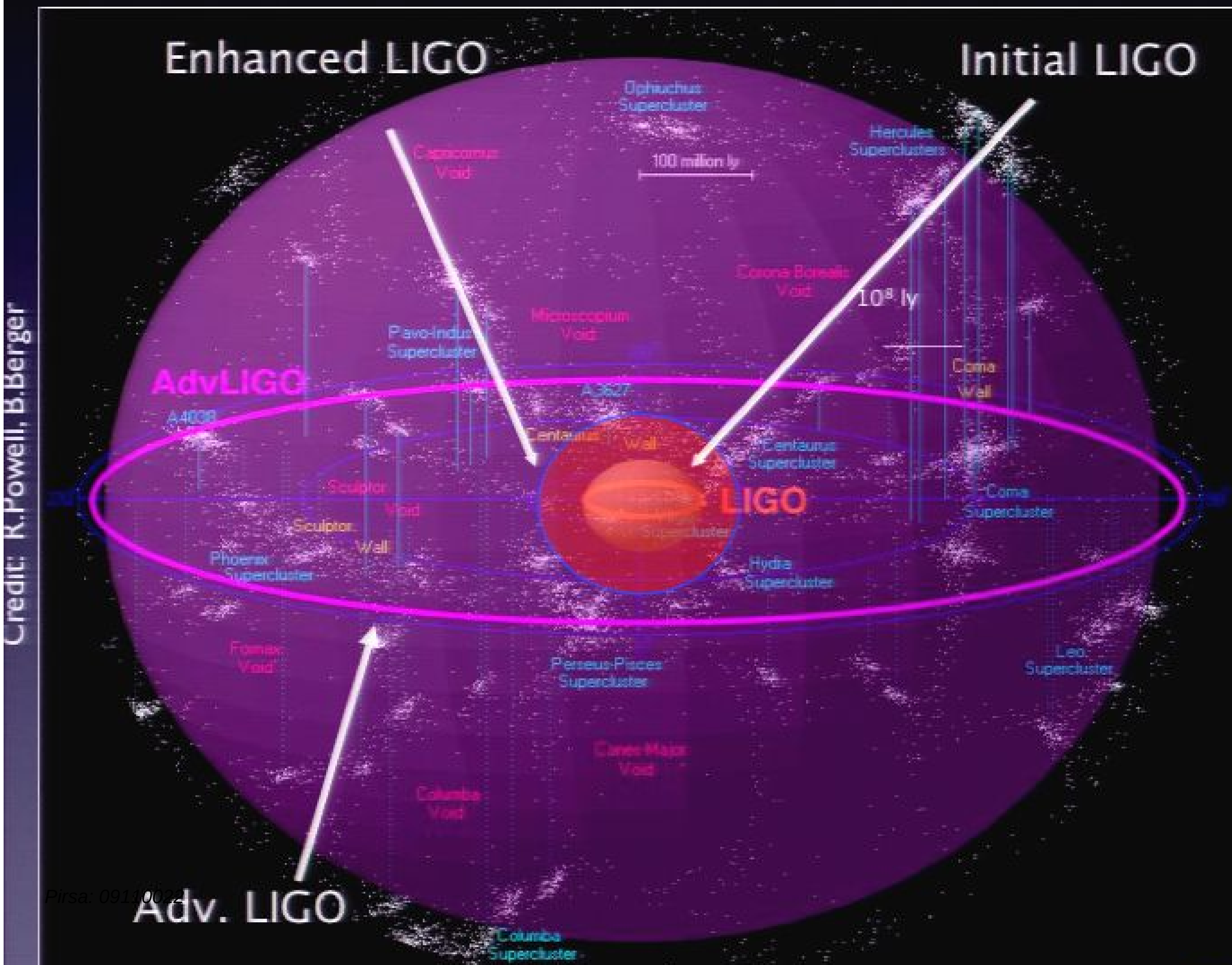
γ-ray

γ-ray bursts

- Instrumentation, networking, and computing has improved dramatically
- Automated follow-up observations of transients is now possible using many telescopes
- International Virtual Observatory is making strides to improve interoperability and access to information
- All-sky surveys will come of age during this decade

S6: It's time to bring gravitational wave observatories to the party

Prospects



- Advanced LIGO
  - funding approved
  - design in full swing
  - acceptance 2014/15
- 10 x Initial LIGO
- 1000 x more sources
- 40 BNS per year


Science Bulletins | Astro | Feature | Gravity | Operate LIGO!
http://www.amnh.org/sciencebulletins/astro/f/gravity.20041101/assets/115/index.p
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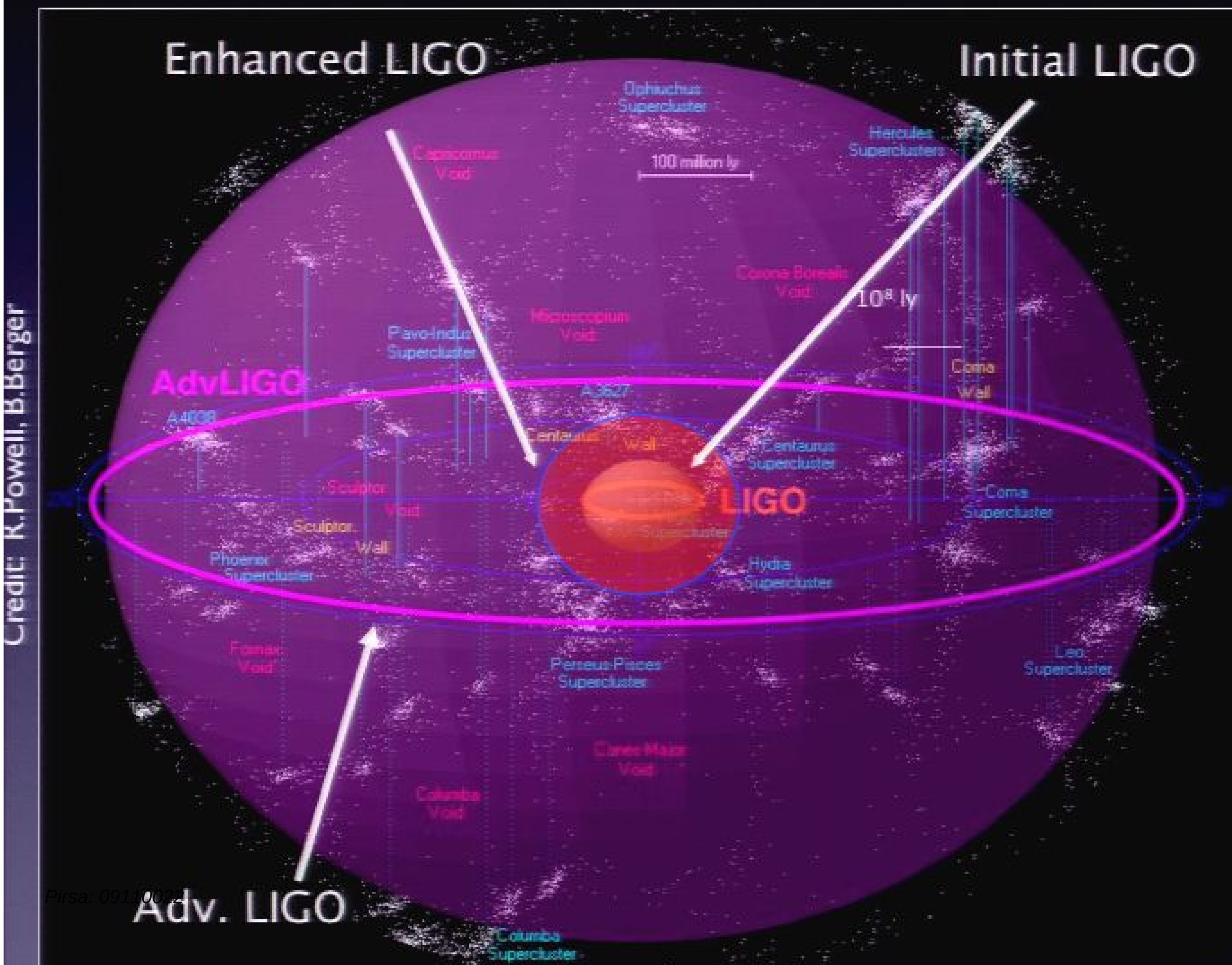
introduction
OPERATE LIGO!
Drag the X arm mirror to simulate the effect of a gravitational wave. Choose any size wave, from no wave at all (default) to a strong wave.
Click the photodetector to take a reading of the wave.
Y mirror
Y arm <4 km
near mirrors
laser
beam splitter
photodetector
X arm >4 km
NO WAVE
WEAK
STRONG
RESET
X mirror
The American Museum of Natural History

Prospects



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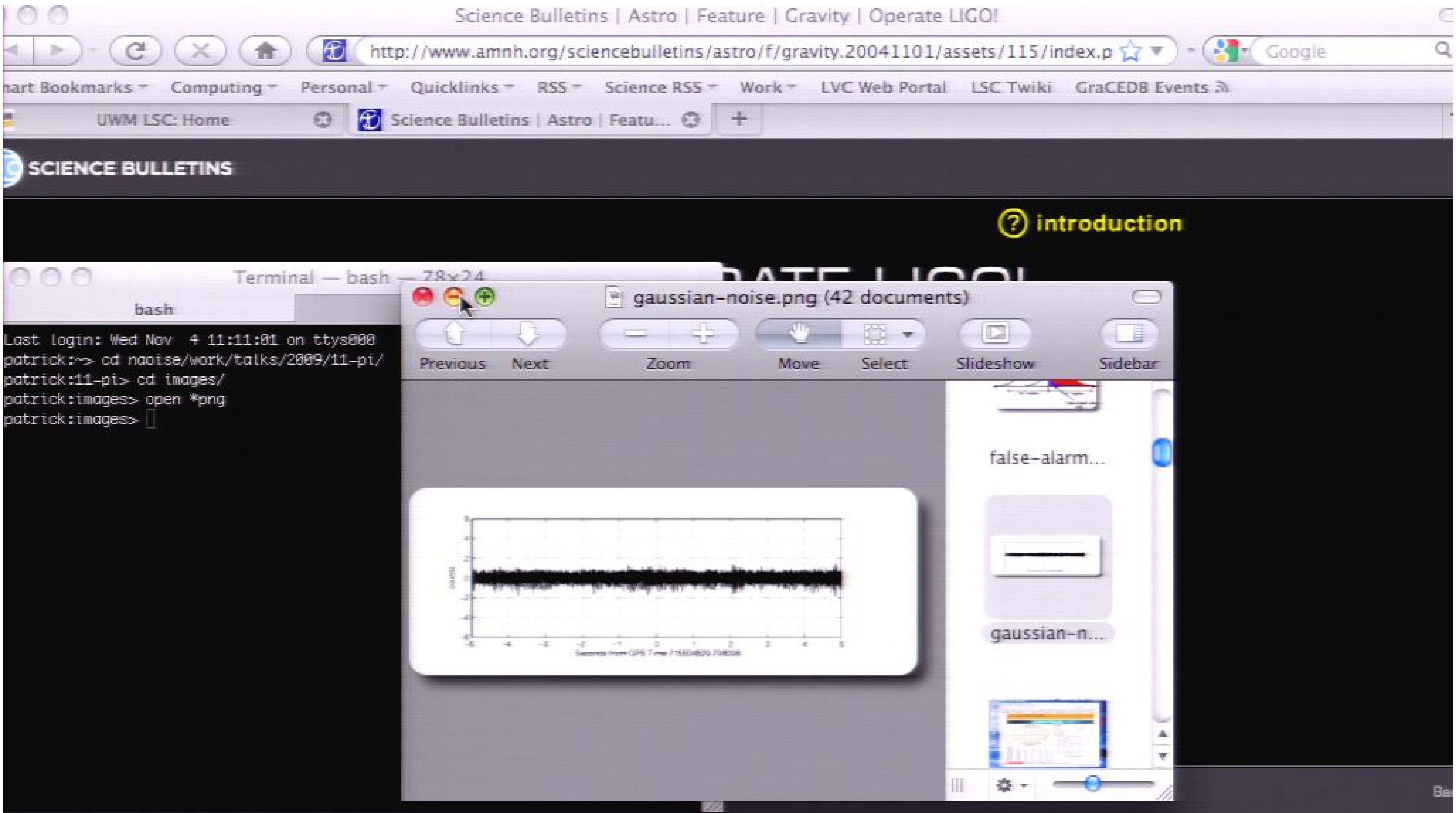

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Terminal — bash — 78x24
bash
Last login: Wed Nov 4 11:11:01 on ttys000
patrick:~> cd naoise/work/talks/2009/11-pi/
patrick:11-pi> cd images/
patrick:images> open *png
patrick:images>
gaussian-noise.png (42 documents)
Previous
Next
Zoom
Move
Select
Slideshow
Sidebar
false-alarm...
gaussian-n...

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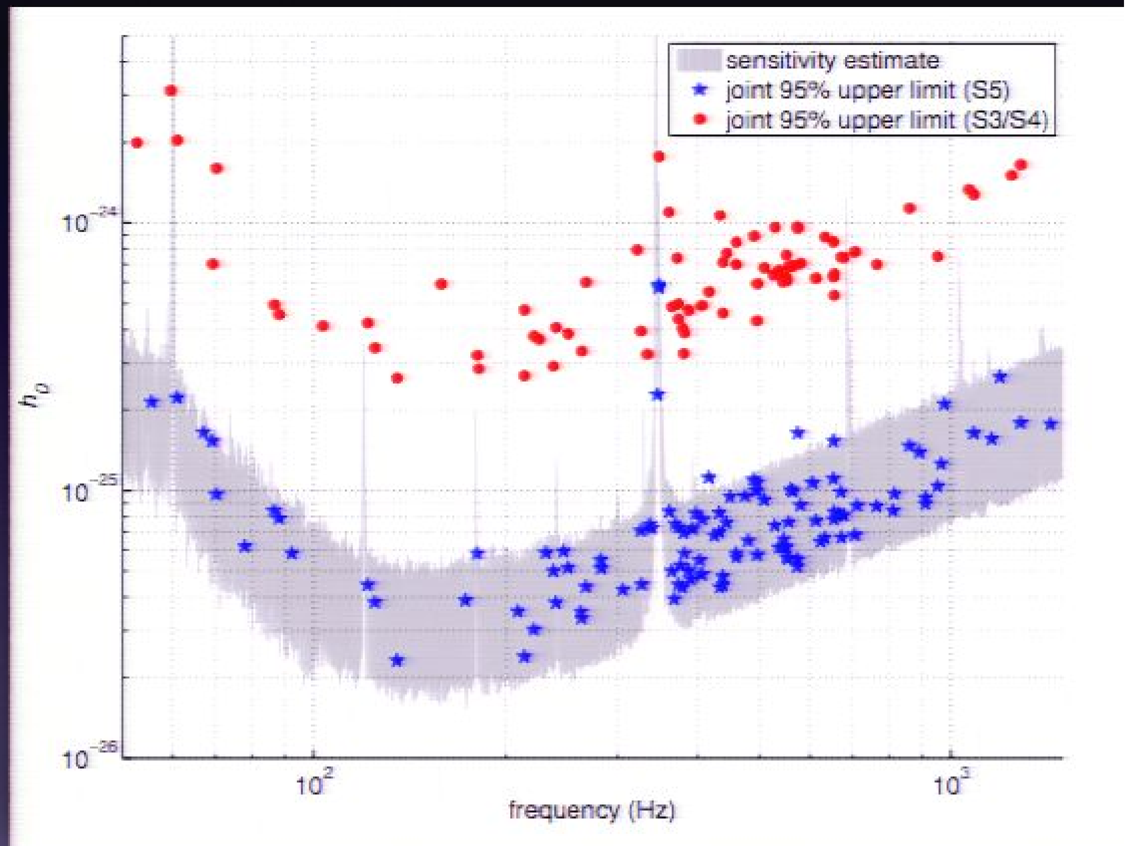

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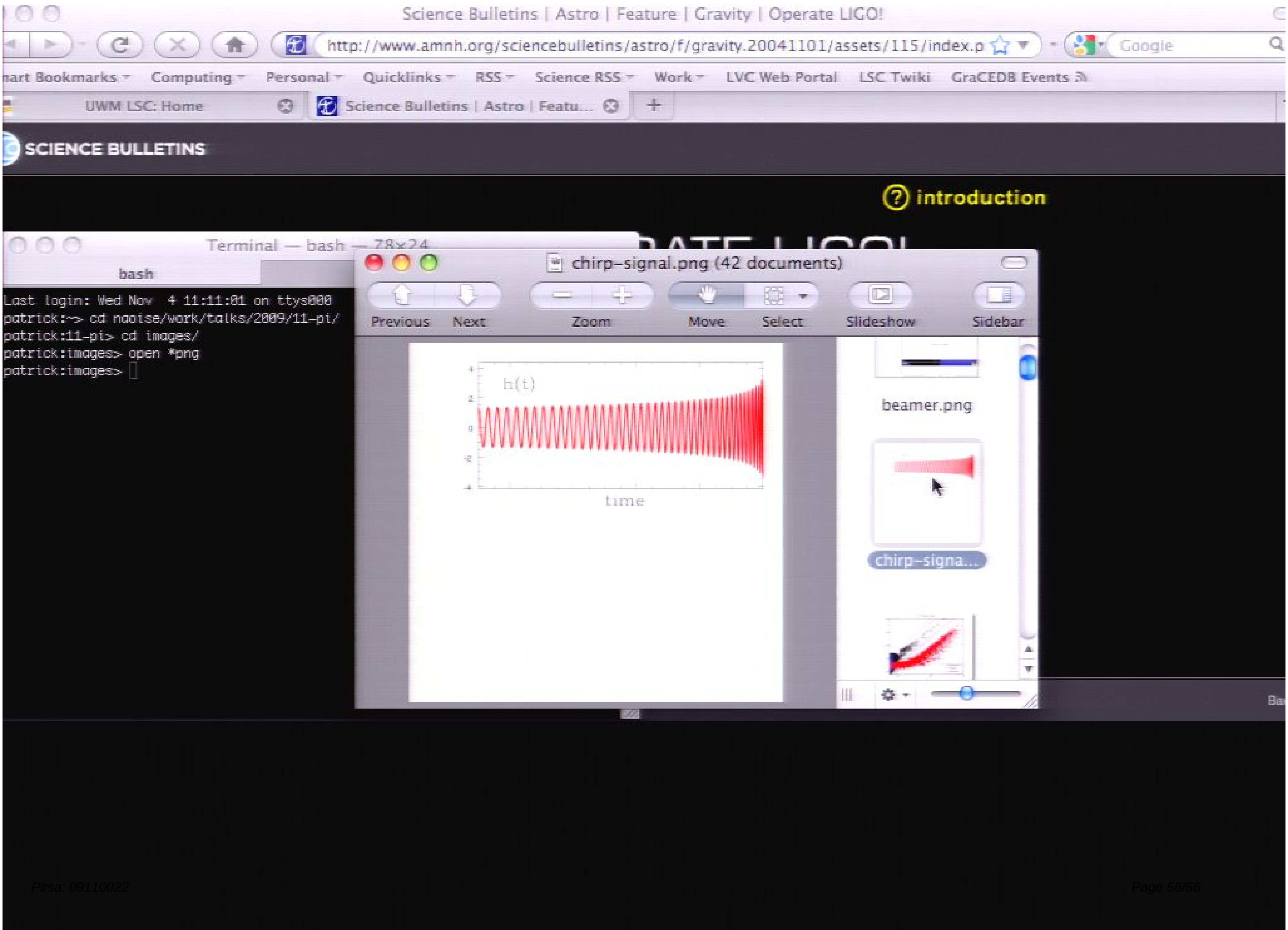
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time
beamer.png
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