Detecting Gravitational Waves: How does LIGO work and how well does LIGO work?

Barry C. Barish
Caltech

"Colliding Black Holes"

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University of Kentucky
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Einstein’s Theory of Gravitation

- a necessary consequence of Special Relativity with its finite speed for information transfer

- gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light
General Relativity

Einstein’s equations have form similar to the equations of elasticity.

\[ P = Eh \quad (P = \text{stress}, \ h = \text{strain}, \ E = \text{Young’s mod.}) \]

\[ T = (c^4/8\pi G)h \quad T = \text{stress tensor,} \ G = \text{Curvature tensor} \]

and \( c^4/8\pi G \sim 10^{42} \text{N} \) is a space-time “stiffness” (energy density/unit curvature)

- Space-time can carry waves.
- They have very small amplitude
- There is a large mismatch with ordinary matter, so very little energy is absorbed (very small cross-section)
Einstein’s Theory of Gravitation

gravitational waves

• Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, $h_{\mu \nu}$. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the transverse traceless gauge the formulation becomes a familiar wave equation.

• The strain $h_{\mu \nu}$ takes the form of a plane wave propagating at the speed of light ($c$).

• Since gravity is spin 2, the waves have two components, but rotated by $45^0$ instead of $90^0$ from each other.

\[
(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2})h_{\mu \nu} = 0
\]

\[
h_{\mu \nu} = h_+ (t - z / c) + h_\times (t - z / c)
\]
Detection of Gravitational Waves

Gravitational Wave Astrophysical Source

Terrestrial detectors: Virgo, LIGO, TAMA, GEO, AIGO

Detectors in space: LISA
International Network on Earth simultaneously detect signal

decompose the polarization of gravitational waves
Detecting a passing wave ....

Free masses
Detecting a passing wave ....

Interferometer
Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4km
- Measure difference in length to one part in $10^{21}$ or $10^{-18}$ meters

...causing the interference pattern to change at the photodiode

Suspended Masses change in different ways....
Simultaneous Detection

LIGO

Hanford Observatory

Caltech

Livingston Observatory

MIT

3082 km
($c = 10$ ms)
LIGO Livingston Observatory
LIGO Hanford Observatory
LIGO Facilities

beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

Figure 2.1-1 -- Cross Section of Design Baseline at Hanford
LIGO beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- Girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld
Vacuum Chambers
vibration isolation systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Compensate for microseism at 0.15 Hz by a factor of ten
» Compensate (partially) for Earth tides
Seismic Isolation
springs and masses

Constrained Layer
damped spring
LIGO
vacuum equipment
Seismic Isolation

suspension system

support structure is welded tubular stainless steel

suspension wire is 0.31 mm diameter steel music wire

fundamental violin mode frequency of 340 Hz
LIGO Optics

- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q’s > 2 x 10^6

Caltech data

CSIRO data
Core Optics
installation and alignment
Lock Acquisition
Tidal Compensation Data

Tidal evaluation
21-hour locked section of S1 data

Predicted tides
Feedforward
Feedback
Residual signal on voice coils
Residual signal on laser
Controlling angular degrees of freedom
Interferometer Noise Limits

- Thermal (Brownian) Noise
- Residual gas scattering
- Wavelength & amplitude fluctuations
- "Shot" noise
- Quantum Noise
- Radiation pressure
- Seismic Noise

LASER → Beam splitter → photodiode → test mass (mirror)
What Limits LIGO Sensitivity?

- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals
Evolution of LIGO Sensitivity

Strain Sensitivities for the LIGO Interferometers

H1 Performance Comparison: S1 through post S3

LIGO-G040439-00-E

Graph showing the strain sensitivities for LIGO interferometers with different sensitivities indicated by different colors and markers.
Science Runs

- $S_1 \sim 100$ kpc
- $S_2 \sim 0.9$ Mpc
- $S_3 \sim 3$ Mpc
- $E_8 \sim 5$ kpc
- Design $\sim 18$ Mpc

Virgo Cluster

A Measure of Progress

NN Binary Inspiral Range

Milky Way and Andromeda

Virgo Cluster

strain/Hz vs. Hertz graph
Astrophysical Sources

**signatures**

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

- **Supernovae / GRBs:** “bursts”
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors

- **Pulsars in our galaxy:** “periodic”
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes

- **Cosmological Signal** “stochastic background”
Compact binary collisions

- Neutron Star – Neutron Star
  - waveforms are well described
- Black Hole – Black Hole
  - need better waveforms
- Search: matched templates

“chirps”
Template Bank

- Covers desired region of mass param space
- Calculated based on L1 noise curve
- Templates placed for max mismatch of $\delta = 0.03$
Optimal Filtering

frequency domain

- Transform data to frequency domain: \( \tilde{h}(f) \)
- Generate template in frequency domain: \( \tilde{s}(f) \)
- Correlate, weighting by power spectral density of noise:
  \[
  \frac{\tilde{s}(f) \tilde{h}^*(f)}{S_h(\|f\|)}
  \]

Then inverse Fourier transform gives you the filter output

\[
z(t) = 4 \int_{0}^{\infty} \frac{\tilde{s}(f) \tilde{h}^*(f)}{S_h(\|f\|)} e^{2\pi i ft} df
\]

at all times:

Find maxima of \(|z(t)|\) over arrival time and phase

Characterize these by signal-to-noise ratio (SNR) and effective distance
Matched Filtering

- Matched Filtering
- Correlation vs. time shift
- Data
- Time-shifted template

Graphs showing matched filtering and correlation over time.
Loudest Surviving Candidate

- Not NS/NS inspiral event
- 1 Sep 2002, 00:38:33 UTC
- S/N = 15.9, $\chi^2$/dof = 2.2
- $(m_1,m_2) = (1.3, 1.1)$ Msun

What caused this?

- Appears to be due to saturation of a photodiode
Results of Inspiral Search

Upper limit
binary neutron star
coalescence rate

LIGO S2 Data
R < 50 / yr / MWE

- Previous observational limits
  - Japanese TAMA → R < 30,000 / yr / MWE
  - Caltech 40m → R < 4,000 / yr / MWE

- Theoretical prediction R < 2 x 10^{-5} / yr / MWE

Detectable Range of S2 data reaches Andromeda!
Astrophysical Sources signatures

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Detection of Burst Sources

- **Known sources -- Supernovae & GRBs**
  - Coincidence with observed electromagnetic observations.
    - No close supernovae occurred during the first science run
    - Second science run – We analyzed the very bright and close GRB030329

- **Unknown phenomena**
  - Emission of short transients of gravitational radiation of unknown waveform (e.g. black hole mergers).
‘Unmodeled’ Bursts

**GOAL** search for waveforms from sources for which we cannot currently make an accurate prediction of the waveform shape.

**METHODS**

- **‘Raw Data’** → Time-domain high pass filter
- **Time-Frequency Plane Search**
  - ‘TFCLUSTERS’
- **Pure Time-Domain Search**
  - ‘SLOPE’

**Diagram Details**

- Time-domain high pass filter 0.125s
- Frequency 8Hz
- Time 610us

**Graphs**

- Data
- Filter
Coincidences and Efficiency

True coincidences at zero lag, and estimate of random coincidences from non-physical time lags.

Determination of search efficiency from artificial addition (in software) of trial signals to data.

Comparison of S1 and S2
Directed Burst Sources

- **GRB 030329**
  - Detected by HETE-2, Konus-Wind, Helicon/KoronasF
  - “Close”: $z = 0.1685$; $d_L = 800\text{Mpc}$
    (WMAP params)
  - Strong evidence for *supernova origin of long GRBs.*
  - H1, H2 operating before, during, after burst

- Radiation from a broadband burst at this distance?
- Exercise analysis

GRB030359

- No event exceeded analysis threshold
- Using simulations an upper limit on the associated gravitational wave strength at the detector at the level of $h_{\text{RSS}} \sim 6 \times 10^{-20} \text{ Hz}^{-1/2}$ was set
- Radiation from a broadband burst at this distance? $E_{\text{GW}} > 10^5 M_\odot$
Astrophysical Sources

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Detection of Periodic Sources

- **Pulsars in our galaxy:** “periodic”
  - search for observed neutron stars
  - all sky search (computing challenge)
  - r-modes

- Frequency modulation of signal due to Earth’s motion relative to the Solar System Barycenter, intrinsic frequency changes.

- Amplitude modulation due to the detector’s antenna pattern.
Two Search Methods

**Frequency domain**
- Best suited for large parameter space searches
- Maximum likelihood detection method + Frequentist approach

**Time domain**
- Best suited to target known objects, even if phase evolution is complicated
- Bayesian approach

First science run --- use both pipelines for the same search for cross-checking and validation
Directed Searches

NO DETECTION EXPECTED at present sensitivities

Limits of detectability for rotating NS with equatorial ellipticity $\varepsilon = \delta/l_{zz}$: $10^{-3}$, $10^{-4}$, $10^{-5}$ @ 8.5 kpc.

$\langle h_0 \rangle = 11.4 \sqrt{S_h(f_{GW})/T_{OBS}}$

Gravitational wave amplitude vs. frequency (Hz)

Crab Pulsar

PSR J1939+2134
1283.86 Hz
The Data

Time behavior

\[ \sqrt{\langle S_h \rangle} \times 10^{-18} \]

GEO 600

\[ \sqrt{\langle S_h \rangle} \times 10^{-19} \]

Livingston 4km

\[ \sqrt{\langle S_h \rangle} \times 10^{-19} \]

Hanford 4km

\[ \sqrt{\langle S_h \rangle} \times 10^{-19} \]

Hanford 2km
The Data

frequency behavior

$\sqrt{S_h}$

GEO 600

Livingston 4km

Hanford 4km

Hanford 2km

$\sqrt{S_h}$
Summary of S2 results
limits on strain

Crab pulsar

J1939+2134

J1910 – 5959D:

\[ h_0 = 1.7 \times 10^{-24} \]

Red dots: pulsars are in globular clusters - cluster dynamics hide intrinsic spin-down properties

Blue dots: field pulsars for which spin-downs are known

Marginalized Bayesian PDF for \( h \)

\[ 0.95 = \int_{h_0=0}^{h_{95}} dh_0 \int \int p(a|H1, H2, L1) d\iota d\psi d\phi_0 \]
Directed Pulsar Search

28 Radio Sources
Detection of Periodic Sources

- Known Pulsars in our galaxy
  - Frequency modulation of signal due to Earth’s motion relative to the Solar System Barycenter, intrinsic frequency changes.
  - Amplitude modulation due to the detector’s antenna pattern.

NEW RESULT
28 known pulsars

NO gravitational waves
\( e < 10^{-5} - 10^{-6} \)
(no mountains > 10 cm)

ALL SKY SEARCH
enormous computing challenge
Summary S2 results - ellipticity limits

\[ \epsilon \simeq 0.24 \left( \frac{h_0}{10^{-24}} \right) \left( \frac{D}{1 \text{kpc}} \right) \left( \frac{f}{1 \text{Hz}} \right)^{-2} \left( \frac{Izz}{10^{45} \text{gr cm}^2} \right)^{-1} \]

Best upper-limits:
- J1910 – 5959D: \( h_0 < 1.7 \times 10^{-24} \)
- J2124 – 3358: \( \epsilon < 4.5 \times 10^{-6} \)

How far are S2 results from spin-down limit? Crab: ~ 30X

Red dots: pulsars are in globular clusters - cluster dynamics hide intrinsic spin-down properties
Blue dots: field pulsars for which spin-downs are known
Einstein@Home

LIGO Pulsar Search using home pc’s

BRUCE ALLEN
Project Leader
Univ of Wisconsin
Milwaukee

LIGO, UWM, AEI, APS

http://einstein.phys.uwm.edu
Astrophysical Sources

signatures

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Signals from the Early Universe

stochastic background

Cosmic Microwave background

WMAP 2003
Signals from the Early Universe

- Strength specified by ratio of energy density in GWs to total energy density needed to close the universe:

\[ \Omega_{GW}(f) = \frac{1}{\rho_{\text{critical}}} \frac{d\rho_{GW}}{d(ln f)} \]

- Detect by cross-correlating output of two GW detectors:

**First LIGO Science Data**

Hanford - Livingston
## Results – Stochastic Backgrounds

<table>
<thead>
<tr>
<th></th>
<th>H-L</th>
<th>H1-H2</th>
<th>Freq range</th>
<th>Observation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S1 (upper limit)</strong></td>
<td>&lt; 23 +/- 4.6 (H2-L1)</td>
<td>seen instrumental noise</td>
<td>64-265 Hz</td>
<td>64 hours (08/23/03 – 09/09/04)</td>
</tr>
<tr>
<td><strong>PRD 69, 122004, 2004</strong></td>
<td></td>
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<tr>
<td><strong>S2 (upper limit)</strong></td>
<td>&lt; 0.018 +0.007- 0.003 (H1-L1)</td>
<td>seen instrumental noise</td>
<td>50-300 Hz</td>
<td>387 hours (02/14/03 – 04/14/04)</td>
</tr>
<tr>
<td><strong>Preliminary</strong></td>
<td></td>
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<tr>
<td><strong>S3 (sensitivity)</strong></td>
<td>~5 x 10^{-4} (H1-L1)</td>
<td>potentially ~10x lower than S3 H1-L1</td>
<td>50-300 Hz</td>
<td>~240 hours (10/31/04 – 01/09/04)</td>
</tr>
<tr>
<td><strong>Expected from noise curves</strong></td>
<td></td>
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<tr>
<td><strong>Design sensitivities</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>LIGO I</strong></td>
<td>~1 x 10^{-6}</td>
<td>~1.5 x 10^{-7}</td>
<td>50-300 Hz</td>
<td>1 year</td>
</tr>
<tr>
<td><strong>LIGO Advanced</strong></td>
<td>~1.5 x 10^{-9}</td>
<td>~3 x 10^{-10}</td>
<td>10-200 Hz</td>
<td>1 year</td>
</tr>
<tr>
<td><strong>nominal tuning</strong></td>
<td>~3.5 x 10^{-10}</td>
<td>~2.5 x 10^{-10}</td>
<td>10-50 Hz</td>
<td>1 year</td>
</tr>
<tr>
<td><strong>low-freq tuning</strong></td>
<td></td>
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</tbody>
</table>
Gravitational Waves from the Early Universe

Results
Projected

- Cosmic Strings
- Inflation
- Nucleosynthesis
- Phase Transitions
- Pulsar Timing

Log $[\Omega_{GW}]$ vs. Log $[f, \text{Hz}]$

Adv LIGO
Advanced LIGO
improved subsystems

Multiple Suspensions

Active Seismic

Improved Optics

Higher Power Laser
Advanced LIGO
Cubic Law for “Window” on the Universe

Improve amplitude sensitivity by a factor of 10x...

...number of sources goes up 1000x!

Nearby mass distribution in the Universe

Virgo cluster

3D visualization of cluster mass

Today  Initial LIGO  Advanced LIGO
Advanced LIGO

2007 +

Enhanced Systems
• laser
• suspension
• seismic isolation
• test mass

Rate Improvement
$\sim 10^4$

+ narrow band optical configuration
LIGO

- Construction is complete & commissioning almost complete

- New upper limits for neutron binary inspirals, a fast pulsar and stochastic backgrounds have been achieved from the first short science runs

- Sensitivity improvements are rapid -- second data run was 10x more sensitive and 4x duration and results are beginning to be reported ---- (e.g. improved pulsar searches)

- Enhanced detectors will be installed in ~ 5 years, further increasing sensitivity

- Direct detection should be achieved and gravitational-wave astronomy begun within the next decade!
Gravitational Wave Astronomy

LIGO will provide a new way to view the dynamics of the Universe