Probing the Universe for Gravitational Waves: *First Upper Limits*

"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)

LIGO-G030353-00-M
“Research Progress”

L4k strain noise @ 150 Hz [Hz^{-1/2}]  

- 1999
  - Inauguration
  - One Arm
  - Power Recycled Michelson
  - Recombined Interferometer
  - Full Interferometer

- 2000
  - E1

- 2001
  - E2
  - E3
  - E4
  - E5
  - E6
  - E7

- 2002
  - E8

- 2003
  - E9

- 2002
  - S1 Science Run
  - S2 Science Run

- Now
  - LHO 2k wire accident
  - Washington earthquake

- Washington 2
- Louisiana 4k
- Washington 4k

- 24-June-03  
  
  RPM - LBNL
A Conceptual Problem is solved!

Newton’s Theory
“instantaneous action at a distance”

\[ F = G \frac{m_1 \times m_2}{d^2} \]

Einstein’s Theory
information carried by gravitational radiation at the speed of light

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} \]
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

Gravitational radiation

Binary inspiral

Of compact objects
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

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

• 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.

\[
h_{\mu\nu} = h_+ (t - z / c) + h_\times (t - z / c)
\]
The evidence for gravitational waves

**Hulse & Taylor**

**Neutron binary system**
- separation = $10^6$ 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

**PSR 1913 + 16**
Timing of pulsars

17 / sec

period ~ 8 hr
“Indirect” detection of gravitational waves

Comparison between observations of the binary pulsar PSR 1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves.
Detectors in space
LISA

Gravitational Wave Astrophysical Source

Terrestrial detectors
LIGO, GEO, TAMA, Virgo, AIGO
Detection on Earth

simultaneously detect signal

decompose the polarization of gravitational waves
Frequency range of astronomy

- EM waves studied over ~16 orders of magnitude
  - Ultra Low Frequency radio waves to high energy gamma rays
Frequency range of astrophysics sources

- Gravitational Waves over ~8 orders of magnitude
  - Terrestrial detectors and space detectors

Audio band

Space

Terrestrial
A New Window on the Universe

Gravitational Waves will provide a new way to view the dynamics of the Universe
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 Signals** "stochastic background"
The effect …

Leonardo da Vinci’s Vitruvian man

Stretch and squash in perpendicular directions at the frequency of the gravitational waves
Detecting a passing wave ....

Free masses
Detecting a passing wave ....

Interferometer
I have greatly exaggerated the effect!!

If the Vitruvian man was 4.5 light years high, he would grow by only a ‘hairs width’
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

As a wave passes, the arms lengths change in different ways....
The Laboratory Sites

Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford Observatory

Livingston Observatory

3002 km
(L/c = 10 ms)
Construction in Washington
Flooding in Louisiana
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
LIGO

vacuum equipment
LIGO
Livingston Observatory
Welcome to Louisiana

pet alligator

collecting bullet holes

24-June-03
LIGO
Hanford Observatory
Gliches at Hanford

LIGO as a car stop

a view from the bridge

LIGO as a fire break

desert on fire
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 Optic

**Substrates:** SiO$_2$
- 25 cm Diameter, 10 cm thick
- Homogeneity $< 5 \times 10^{-7}$
- Internal mode Q’s $> 2 \times 10^6$

**Polishing**
- Surface uniformity $< 1$ nm rms
- Radii of curvature matched $< 3$

**Coating**
- Scatter $< 50$ ppm
- Absorption $< 2$ ppm
- Uniformity $< 10^{-3}$
Core Optics
installation and alignment
Locking the Interferometers
Lock Acquisition
Making LIGO Work

L4k strain noise @ 150 Hz [Hz^{-1/2}]

- 10^{-17}
- 10^{-18}
- 10^{-19}
- 10^{-20}
- 10^{-21}

1999 | 2000 | 2001 | 2002 | 2003

- 4Q
- 1Q
- 2Q
- 3Q
- 4Q

- Inauguration
- E1
- E2
- E3
- E4
- E5
- E6
- E7
- E8
- E9

- S1 Science Run
- S2 Science Run

- Washington 2K
- Louisiana 4k
- Washington 4K

- First Lock
- Washington earthquake
- LHO 2k wire accident
- Now

24-June-03 RPM - LBNL
Detecting Earthquakes

From electronic logbook 2-Jan-02

An earthquake occurred, starting at UTC 17:38.
Detecting the Earth Tides
Sun and Moon

Eric Morgenson
Caltech Sophomore
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
Controlling angular degrees of freedom

Trend Ch 2: H1:LSC-LA_SPOB_NORM

Trend Ch 1: H1:LSC-LA_PRTT_NORM

WFS1, WFS2A, WFS3, WFS4 not engaged

WFS1, WFS2A, WFS3, WFS4 engaged
Improving the Sensitivity

- 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
LIGO Sensitivity
Livingston 4km Interferometer

First Science Run
17 days - Sept 02

Second Science Run
59 days - April 03
The First Science Run

L4k strain noise @ 150 Hz [Hz^{-1/2}]

1999  2000  2001  2002  2003

4Q  1Q  2Q  3Q  4Q  1Q  2Q  3Q  4Q  1Q

Inauguration

E1  E2  E3  E4  E5  E6  E7  E8  E9

One Arm

Power Recycled Michelson

Recombined Interferometer

First Lock

Full Interferometer

Washington 2K

Louisiana 4k

Washington 4K

First Lock

Washington earthquake

LHO 2k wire accident

Now

24-June-03  RPM - LBNL  44
LIGO S1 Run

“First Upper Limit Run”

- 23 Aug–9 Sept 2002
- 17 days
- All interferometers in power recycling configuration

GEO in S1 RUN

Ran simultaneously in power recycling
Lesser sensitivity

Sensitivity during S1

Strain Sensitivities for the LIGO Interferometers for S1

23 August 2002 - 09 September 2002

LIGO-G020461-01-E
In-Lock Data Summary from S1

**H1**: 235 hrs

**H2**: 298 hrs

**L1**: 170 hrs

**3X**: 95.7 hrs

Red lines: integrated up time

Green bands (w/ black borders): epochs of lock

- **August 23 – September 9, 2002**: 408 hrs (17 days).
  - **H1** (4km): duty cycle 57.6%; Total Locked time: 235 hrs
  - **H2** (2km): duty cycle 73.1%; Total Locked time: 298 hrs
  - **L1** (4km): duty cycle 41.7%; Total Locked time: 170 hrs

- **Double coincidences**:
  - **L1** & & **H1**: duty cycle 28.4%; Total coincident time: 116 hrs
  - **L1** & & **H2**: duty cycle 32.1%; Total coincident time: 131 hrs
  - **H1** & & **H2**: duty cycle 46.1%; Total coincident time: 188 hrs

**Triple Coincidence**: **L1**, **H1**, and **H2**: duty cycle 23.4%; total 95.7 hours
Astrophysical Sources \signatures

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  - r-modes

- **Cosmological Signals** "stochastic background"
Compact binary collisions

“chirps”

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

*binary inspirals*

- Binary in tight orbit emits gravitational waves
- Loss of angular momentum causes orbit to decay
  - Decay rate accelerates as orbital distance shrinks

Waveform is well known if masses are small

![Waveform Image]

"Chirp" waveform

Enters LIGO sensitive band ~seconds before coalescence

**Binary neutron star systems are known to exist!**

- e.g. PSR 1913+16 — but, must wait one million years!!
Matched Filtering

Data
Time-shifted template

Correlation vs. time shift

Time shift

Correlation
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 at all times:

\[
z(t) = 4 \int_0^{\infty} \tilde{s}(f) \frac{\tilde{h}^*(f)}{S_h(|f|)} e^{2\pi ift} df
\]

Find maxima of \[ |z(t)| \] over arrival time and phase
Characterize these by signal-to-noise ratio (SNR) and effective distance
Template Bank

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

2110 templates
Second-order post-Newtonian
Sensitivity

neutron binary inspirals

Star Population in our Galaxy

- Population includes Milky Way, LMC and SMC
- Neutron star masses in range 1-3 Msun
- LMC and SMC contribute ~12% of Milky Way

Reach for S1 Data

- Inspiral sensitivity
  - Livingston: \(<D> = 176\) kpc
  - Hanford: \(<D> = 36\) kpc
- Sensitive to inspirals in
  - Milky Way, LMC & SMC
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 saturation of a photodiode
Results of Inspiral Search

Upper limit binary neutron star coalescence rate

LIGO S1 Data
R < 160 / yr / MWEG

- Previous observational limits
  - Japanese TAMA \( R < 30,000 / \text{yr} / \text{MWEG} \)
  - Caltech 40m \( R < 4,000 / \text{yr} / \text{MWEG} \)

- Theoretical prediction \( R < 2 \times 10^{-5} / \text{yr} / \text{MWEG} \)

Detectable Range for S2 data will reach Andromeda!
Burst Sources

signatures

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

- **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’

- Frequency
- Time
- 8Hz
- 0.125s
Determination of Efficiency

To measure our efficiency, we must pick a waveform.

1ms Gaussian burst

Efficiency measured for ‘tfclusters’ algorithm

Detector efficiency vs amplitude, average over sources. GA \( \text{tau}=1.0\text{ms} \)
Upper Limit
1ms gaussian bursts

Result is derived using ‘TFCLUSTERS’ algorithm

Upper limit in strain compared to earlier (cryogenic bar) results:

- IGEC 2001 combined bar upper limit: < 2 events per day having $h=1\times10^{-20}$ per Hz of burst bandwidth. For a 1kHz bandwidth, limit is < 2 events/day at $h=1\times10^{-17}$

- Astone et al. (2002), report a one sigma excess of one event per day at strain level of $h \sim 2\times10^{-18}$
Astrophysical Sources

**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.

An afterlife of stars
Directed searches

NO DETECTION EXPECTED at present sensitivities

\[ \langle h_0 \rangle = 11.4 \sqrt{S_h f_{GW}} / T_{OBS} \]

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

PSR J1939+2134
1283.86 Hz
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
The Data

time behavior

\[
\sqrt{< S_h >} \times 10^{-18}
\]

GEO 600

\[
\sqrt{< S_h >} \times 10^{-19}
\]

Livingston 4km

\[
\sqrt{< S_h >} \times 10^{-19}
\]

Hanford 4km

\[
\sqrt{< S_h >} \times 10^{-19}
\]

Hanford 2km
The Data

**frequency behavior**

\[ \sqrt{S_h} \]
PSR J1939+2134

Frequency domain

- Fourier Transforms of time series
- Detection statistic: $F$, maximum likelihood ratio with respect to unknown parameters
- Use signal injections to measure F’s pdf
- Use frequentist’s approach to derive upper limit

Injected signal in LLO: $h = 2.83 \times 10^{-22}$

95% Measured F statistic

Distribution of $2F$
PSR J1939+2134

Time domain

- time series is heterodyned
- noise is estimated
- Bayesian approach in parameter estimation: express result in terms of posterior pdf for parameters of interest

Injected signals in GEO: $h=1.5, 2.0, 2.5, 3.0 \times 10^{-21}$

$95\%$ confidence interval for $h = 2.1 \times 10^{-21}$
Results: Periodic Sources

**J1939+2134**

- No evidence of continuous wave emission from PSR J1939+2134.

- Summary of 95% upper limits on $h$:

<table>
<thead>
<tr>
<th>IFO</th>
<th>Frequentist FDS</th>
<th>Bayesian TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>$(1.94 \pm 0.12) \times 10^{-21}$</td>
<td>$(2.1 \pm 0.1) \times 10^{-21}$</td>
</tr>
<tr>
<td>LLO</td>
<td>$(2.83 \pm 0.31) \times 10^{-22}$</td>
<td>$(1.4 \pm 0.1) \times 10^{-22}$</td>
</tr>
<tr>
<td>LHO-2K</td>
<td>$(4.71 \pm 0.50) \times 10^{-22}$</td>
<td>$(2.2 \pm 0.2) \times 10^{-22}$</td>
</tr>
<tr>
<td>LHO-4K</td>
<td>$(6.42 \pm 0.72) \times 10^{-22}$</td>
<td>$(2.7 \pm 0.3) \times 10^{-22}$</td>
</tr>
</tbody>
</table>

- Best previous results for PSR J1939+2134:
  
  $h_0 < 10^{-20}$  
  (Glasgow, Hough et al., 1983),
Upper limit on pulsar ellipticity

\[ h_0 = \frac{8\pi^2 G I_{zz} f_0^2}{c^4 R \varepsilon} \]

\[ h_0 < 3 \times 10^{-22} \Rightarrow \varepsilon < 3 \times 10^{-4} \]

(M=1.4M\text{\(_{\odot}\)}, r=10\text{km}, R=3.6\text{kpc})

• assuming emission due to deviation from axisymmetry:
Early Universe

stochastic background

‘Murmurs’ from the Big Bang

Cosmic Microwave background

Planck Time
$10^{-43}$ SECONDS
Singularity creates
Space & Time of our universe

1 SECOND

100,000 YEARS

EARTH NOW

10 billion YEARS

GRavitational Waves

Neutrinos

Photons

LIGO

24-June-03

RPM - LBNL
Stochastic Background

- 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
Non-negligible LHO 4km-2km (H1-H2) instrumental cross-correlation; currently being investigated.

Previous best upper limits:

- Measured: Garching-Glasgow interferometers: \( \Omega_{GW}(f) < 3 \times 10^5 \)
- Measured: EXPLORER-NAUTILUS (cryogenic bars): \( \Omega_{GW}(907Hz) < 60 \)
Stochastic Background
sensitivities and theory

- Cosmic Strings
- Inflation
- Nucleosynthesis
- Phase Transitions

Results projected

Adv LIGO
LIGO Sensitivity
Livingston 4km Interferometer

First Science Run
17 days - Sept 02

Second Science Run
59 days - April 03
Advanced LIGO
improved subsystems

Multiple Suspensions

Active Seismic

Sapphire Optics

Higher Power Laser
Enhanced Systems

- laser
- suspension
- seismic isolation
- test mass

Improvement factor in rate
\[ \sim 10^4 \]
Probing the Universe with LIGO

a glimpse at the science

- LIGO commissioning is well underway
  » Good progress toward design sensitivity

- Science Running is beginning
  » Initial results from our first LIGO data run

- Our Plan
  » Improved data “in the can” from second data run – S2
  » Our goal is to obtain one year of integrated data at design sensitivity before the end of 2006
  » Advanced interferometer with dramatically improved sensitivity – 2007+

- LIGO should be detecting gravitational waves within the next decade!