Interferometric Gravitational Wave Detectors

"Colliding Black Holes"

Credit: National Center for Supercomputing Applications (NCSA)

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Caltech

TAUP
9-Sept-03
The Detectors

TAMA Japan 300m

Virgo Italy 3000m

AIGO Australia future

GEO Germany 600m

LIGO Louisiana 4000m

LIGO Washington 2000m & 4000m
Detection on Earth

network of detectors

LIGO

GEO

Virgo

TAMA

decompose the polarization of gravitational waves
Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4 km
- 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 arm lengths change in different ways....
Limiting Noise Sources

- 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

Louisiana Interferometer

First Science Run
17 days - Sept 02

Second Science Run
59 days - April 03

May 01
Jan 03
Astrophysical Sources

- **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"
Compact binary collisions

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

“chirps”
- Covers desired region of mass param space
- Calculated based on L1 noise curve
- Templates placed for max mismatch of $\mathcal{Q} = 0.03$

2110 templates
Second-order post-Newtonian
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:

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

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

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

![Graph showing matched filtering results]

- Blue line: Data
- Red line: Time-shifted template

Correlation vs. time shift

- Red line: Correlation
- Y-axis: Correlation
- X-axis: Time shift
Sensitivity

neutron binary inspirals

Star Population in our Galaxy

- Population includes Milky Way, LMC and SMC
- Neutron star masses in range 1-3 $M_{\odot}$
- LMC and SMC contribute ~12% of Milky Way

Reach for S1 Data

- **Inspiral sensitivity**
  - Livingston: $\langle D \rangle = 176$ kpc
  - Hanford: $\langle D \rangle = 36$ 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 / yr / MWEG
  » Caltech 40m → R < 4,000 / yr / MWEG

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

Detectable Range for S2 data will reach Andromeda!
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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 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’

Time-domain high pass filter

0.125s

8Hz

DATA

FILTER

610us
To measure our efficiency, we must pick a waveform.

1 ms Gaussian burst

Efficiency measured for ‘tfclusters’ algorithm

Detector efficiency vs amplitude, average over sources. GA \( \tau = 1.0 \) ms
Burst Upper Limit from S1

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 2.2 $\sigma$ excess of one event per day at strain level of $h \sim 2\times10^{-18}$
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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.
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 \( \epsilon = \frac{\mathcal{M}}{m^2} \): \( 10^{-3} \), \( 10^{-4} \), \( 10^{-5} \) @ 8.5 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**

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

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

**GEO 600**

**Livingston 4km**

**Hanford 4km**

**Hanford 2km**

9-Sept-03
The Data

**frequency behavior**

\[ \sqrt{S_h} \]

\[ \sqrt{S_h} \]

\[ \sqrt{S_h} \]

\[ \sqrt{S_h} \]

GEO 600

Livingston 4km

Hanford 4km

Hanford 2km
Frequency domain

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

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

- 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

J1939+2134

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

\( h_0 < 3 \times 10^{-22} \Rightarrow \varepsilon < 3 \times 10^{-4} \)

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

• assuming emission due to deviation from axisymmetry:
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Signals from the Early Universe

**stochastic background**

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**GRavitational Waves**

**Big-Bang Singularity**

Planck Time $10^{-43}$ seconds

Singularity creates Space & Time of our universe

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**Cosmic Microwave background**

WMAP 2003

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SASKATOON 3 YEAR DATA

COBE DMR 4 YEAR DATA
Stochastic Background

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

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

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

First LIGO Science Data
### Limits: Stochastic Search

<table>
<thead>
<tr>
<th>Interferometer Pair</th>
<th>90% CL Upper Limit</th>
<th>$T_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHO 4km-LLO 4km</td>
<td>$\mathcal{H}_\text{GW} (40\text{Hz} - 314 \text{Hz}) &lt; 72.4$</td>
<td>62.3 hrs</td>
</tr>
<tr>
<td>LHO 2km-LLO 4km</td>
<td>$\mathcal{H}_\text{GW} (40\text{Hz} - 314 \text{Hz}) &lt; 23$</td>
<td>61.0 hrs</td>
</tr>
</tbody>
</table>

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

- Previous best upper limits:
  - Measured: Garching-Glasgow interferometers: $\mathcal{H}_\text{GW}(f) < 3 \times 10^5$
  - Measured: EXPLORER-NAUTILUS (cryogenic bars): $\mathcal{H}_\text{GW}(907\text{Hz}) < 60$
Stochastic Background
LIGO Sensitivity

Livingston 4km Interferometer

First Science Run
17 days - Sept 02

Second Science Run
59 days - April 03

May 01
Jan 03
Advanced LIGO

Enhanced Systems

- laser
- suspension
- seismic isolation
- test mass

Improvement factor in rate
$\sim 10^4$

2007 +

narrow band optical configuration
Gravitational Waves: Interferometers

- Terrestrial and Space Based Interferometers are being developed
- Ground based interferometers in U.S. (LIGO), Japan (TAMA) and Germany (GEO) have done initial searches & Italy (Virgo) is beginning commissioning.
- New Upper limits already reported for neutron binary inspirals, a fast pulsar and stochastic backgrounds
- Sensitivity improvements are rapid -- second data run was 10x more sensitive and 4x duration
- Enhanced detectors will be installed in ~ 5 years, further increasing sensitivity
- Gravitational waves should be detected within the next decade!