LIGO Status
and Advanced LIGO Plans

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Science Goals

• **Physics**
  » Direct verification of the most “relativistic” prediction of general relativity
  » Detailed tests of properties of gravitational waves: speed, strength, polarization, …
  » Probe of strong-field gravity – black holes
  » Early universe physics

• **Astronomy and astrophysics**
  » Abundance & properties of supernovae, neutron star binaries, black holes
  » Tests of gamma-ray burst models
  » Neutron star equation of state
  » A new window on the universe
LIGO Observatories

Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

GEODETIC DATA (WGS84)
\[ h: 142.555 \text{ m} \quad X \text{ arm: N35.9993}\text{°W} \]
\[ \phi: N46^\circ27'18.527841'' \quad Y \text{ arm: S54.0007}\text{°W} \]
\[ \lambda: W119^\circ24'27.565681'' \]

Livingston Observatory
Louisiana
One interferometer (4km)

GEODETIC DATA (WGS84)
\[ h: -6.574 \text{ m} \quad X \text{ arm: S72.283\text{°W} \]
\[ \phi: N30^\circ33'46.419531'' \quad Y \text{ arm: S17.716}\text{°W} \]
\[ \lambda: W90^\circ46'27.265294'' \]
LIGO Commissioning and Science Timeline
Interferometer Noise Limits

- Seismic Noise
- Thermal (Brownian) Noise
- LASER test mass (mirror)
- Residual gas scattering
- Quantum Noise
- "Shot" noise
- Radiation pressure
- Photodiode
- "Wavelength & amplitude fluctuations"
- Beam splitter
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
Science Runs

- NN Binary Inspiral Range
  - S1 ~ 100 kpc
  - S2 ~ 0.9Mpc
  - S3 ~ 3 Mpc
  - E8 ~ 5 kpc
- Design ~ 18 Mpc

- Virgo Cluster
- Milky Way
- Andromeda
- Virgo Cluster
Best Performance to Date

Range ~ 6 Mpc
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”
Compact-object binary systems lose energy due to gravitational waves. Waveform traces history.

In LIGO frequency band (40–2000 Hz) for a short time just before merging: anywhere from a few minutes to <<1 second, depending on mass.

Waveform is known accurately for objects up to ~3 $M_\odot$

“Post-Newtonian expansion” in powers of $(Gm/rc^2)$ is adequate

⇒ Use matched filtering.
Preliminary S2 Binary Neutron Star Result

- Observation time \( T_{\text{obs}} \): 355 hours

- Conservative lower bound on \( N_G = 1.14 \)
  - Take the “worst case” for all systematic uncertainties to obtain this value

- Conservative upper limit:

  Preliminary S2 Upper Limit:
  \( R_{90\%} < 50 \) per year per MWEG
Astrophysical Sources

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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

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

GOAL

METHODS

‘Raw Data’ → Time-domain high pass filter

Time-Frequency Plane Search

‘TFCLUSTERS’

Pure Time-Domain Search

‘SLOPE’

Time-domain high pass filter

DATA

FILTER

8Hz

0.125s
During S2, GRB 030329 occurred.

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?

We searched, using cross-correlation between H1 and H2 as a measure of possible signal strength.
GRB030329

- 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? $E_{\text{GW}} > 10^5 M_8$
Astrophysical Sources

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Detection of Periodic Sources

- **Pulsars in our galaxy:**
  - 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 \( \varepsilon = \delta/l_{zz} \): \( 10^{-3}, 10^{-4}, 10^{-5} \) @ 8.5 kpc.

Crab Pulsar

PSR J1939+2134

1283.86 Hz
Upper limit on pulsar ellipticity

**J1939+2134**

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

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

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

Assumes emission is due to deviation from axisymmetry:
Multi-detector upper limits

**S2 Data Run**

- Performed joint coherent analysis for 28 pulsars using data from all IFOs.
- Most stringent UL is for pulsar J1629-6902 (~333 Hz) where 95% confident that $h_0 < 2.3 \times 10^{-24}$.
- 95% upper limit for Crab pulsar (~ 60 Hz) is $h_0 < 5.1 \times 10^{-23}$.
- 95% upper limit for J1939+2134 (~ 1284 Hz) is $h_0 < 1.3 \times 10^{-23}$. 

95% upper limits
Approaching spin-down upper limits

- For Crab pulsar (B0531+21) we are still a factor of ~35 above the spin-down upper limit in S2.

- Hope to reach spin-down based upper limit in S3!

- Note that not all pulsars analysed are constrained due to spin-down rates; some actually appear to be spinning-up (associated with accelerations in globular cluster).
Signals from the Early Universe

**stochastic background**

- **Gravitational Waves**
- **Neutrinos**
- **Photons**

**Cosmic Microwave background**

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

**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:

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

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

First LIGO Science Data

Hanford - Livingston
Gravitational Waves from the Early Universe

results
projected

LIGO

Adv LIGO
Advanced LIGO will dramatically extend our reach

Science from a few hours of Advanced LIGO observing should be comparable to 1 year of initial LIGO!
Advanced LIGO

improved subsystems

Multiple Suspensions

Active Seismic

Sapphire 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!

Virgo cluster

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