Searching for gravitational waves

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LIGO-G0900923
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \quad (= 0 \text{ in vacuum}) \]

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have \( h = \Delta L/L \sim 10^{-21} \) and frequencies sweeping up to \( \sim 1400 \text{ Hz} \).

\[ h \approx \frac{4\pi^2 GMR^2 f_{\text{orb}}^2}{c^4 r} \]
How to detect gravitational waves

Einstein’s messengers,
National Science Foundation video

What the sources produce is \( h = \Delta L/L \)
What we measure is \( \Delta L = hL \)
Hundreds of people working on the experiment and looking at the data:
LIGO Scientific Collaboration
Existing worldwide network

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GW Detection: a difficult and fun experiment
Interferometer Noise

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

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Use username = “reader” and password = “readonly”
GW sources

Strain Sensitivity of the LIGO Interferometers
S5 Performance - May 2007    LIGO-G070366-00-E

Observational results in www.ligo.org
LIGO probes the gravitational wave background of the Universe.
### Observational results and LSC instrument papers

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<th>Run</th>
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<td>arXiv:0909.3833</td>
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<td>Searches for gravitational waves from known pulsars with S5 LIGO data</td>
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<td>Class. Quantum Grav. 25 (2008) 095004</td>
<td>arXiv:0710.0497</td>
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<td>A Joint Search for Gravitational Wave Bursts with AURIGA and LIGO</td>
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An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

Figure 1 | Sensitivities of LIGO interferometers. LIGO interferometers reached their design sensitivity in November 2005, resulting in interferometer strain noise at the level of $3 \times 10^{-22}$ r.m.s. in a 100 Hz band around 100 Hz. This figure shows typical strain sensitivities of LIGO interferometers during the subsequent science run S5. Also shown is the strain amplitude corresponding to the upper limit on the gravitational-wave energy density presented in this paper (grey dashed line). Note that this upper limit is $\sim 100$ times lower than the individual interferometer sensitivities, which illustrates the advantage of using the cross-correlation technique in this analysis.
Rotating stars produce GWs if they have asymmetries, if they wobble or through fluid oscillations.

There are many known pulsars (rotating stars!) that would produce GWs in the LIGO frequency band (40 Hz-2 kHz).

If pulsars are “spinning down”, the energy loss sets an upper limit on the emission of GWs.

Targeted searches for 97 known (radio and x-ray) systems in S5: isolated pulsars, binary systems, pulsars in globular clusters…

GWs (or lack thereof) can be used to measure (or set up upper limits on) the ellipticities of the stars.

Search for a sine wave, modulated by Earth’s motion, and possibly spinning down.

Astrophys. J. Lett. 683 (2008), LSC
Beating the spin-down limit on gravitational wave emission from the Crab pulsar

LIGO-G0900923
If system is optimally located and oriented, we can see even further: we are surveying hundreds of galaxies!

For higher masses (black holes), emitted amplitude just before coalescence is larger than for NS: we can see even farther (but waveforms are shorter).
FIG. 1: The cumulative distribution of events above a threshold IFAR, for in-time coincident events, shown as blue triangles, from all coincidence categories for the observation times H1H2L1, H1L1, and H2L1 respectively. The expected background (by definition) is shown as a dashed black line. The 100 experimental trials that make up our background are also plotted individually as the solid grey lines. The shaded region denotes the $N^{1/2}$ errors.

arXiv:0901.0302

Summary of the search for BNS, BBH, and BHNS systems. The horizon distance is the distance at which an optimally oriented and optimally located source with the appropriate mass would produce an trigger with an SNR of 8 in the 4 km detectors and averaged over the search. The cumulative luminosity from H1H2L1 time is rounded to two significant figures.
GW searches: bursts

- Search for coincident triggers with a wavelet algorithm
- Measure waveform consistency
- Compare with efficiency for detecting simple waveforms

S5 results:
http://www.arxiv.org/pdf/0908.3824v1
FIG. 8: Selected exclusion diagrams showing the 90% confidence rate limit as a function of signal amplitude for $Q=9$ sine-Gaussian (top) and Gaussian (bottom) waveforms for the results in this paper (S5) compared to the results reported previously (S1, S2, and S4).

GW searches: bursts

S5 results:
http://www.arxiv.org/pdf/0908.3824v1
Implications for the Origin of GRB 070201 from LIGO Observations

- Short GRB ($T_{90}=0.15$ s)
- Possible compact binary merger (NS/BH)
- Possible SGR
- Error-box of location overlay M31 ($D=770$ kpc)


arXiv:0711.1163

*Implications for the Origin of GRB 070201 from LIGO Observations*
Burst search:
- Cannot exclude a SGR in M31 distance
- Upper limit: $8 \times 10^{50}$ ergs ($4 \times 10^{-4} M_\odot c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)

Inspiral search:
- Binary merger in M31 scenario excluded at >99% level
- Exclusion of merger at larger distances: see plot

Search for gravitational-wave bursts associated with gamma-ray bursts using data from LIGO Science Run 5 and Virgo Science Run 1

Newer results: arXiv:0908.3824

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Predictions are difficult… especially about the future! (N. Bohr/ Y. Berra?)

- Rotating stars: we know the rates, but not the amplitudes: how lumpy are they?

- Supernovae, gamma ray bursts: again rates known, but not amplitudes…

- Cosmological background: optimistic predictions are very dependent on model…

- Binary black holes: amplitude is known, but rates and populations highly unknown… Some estimates promise S5/S6 results will be interesting!

- Binary neutron stars: amplitude is known, and galactic rates and population can be estimated: For R~86/Myr, initial LIGO rate ~1/100 yrs.
Neutron Star Binaries:
Initial LIGO: ~15 Mpc → rate ~1/100yrs
Advanced LIGO: ~ 200-300 Mpc
Most likely rate ~ 20-40/year!

x10 better amplitude sensitivity
⇒ x1000 rate=(reach)^3
⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO!

US NSF started funding Advanced LIGO in 2008!
- Predicted regular BNS detections
- Conclusions about (measurements of!) BBH population
- Stronger conclusions (measurements?) for continuous GWs
- Stronger (-est!) experimental constraints on cosmological background
- **Gravitational wave astrophysics!**
Worldwide network … and farther
• Predicted regular BNS detections
• Conclusions about (measurements of!) BBH population
• Stronger conclusions (measurements?) for continuous GWs
• Stronger (-est!) experimental constraints on cosmological background
• Gravitational wave astrophysics!