Gravitational Waves: Detected Events, Implications, and Future Prospects

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Gravitational Waves

Predicted to exist by Einstein’s general theory of relativity

... which says that gravity is really an effect of “curvature” in the geometry of space-time, caused by the presence of any object with mass

Expressed mathematically by the Einstein field equations

Solutions describe the regular (static) gravitational field, but also wave solutions which travel at the speed of light

These waves are perturbations of the spacetime metric — the effective distance between points in space and time

The geometry of space-time is dynamic, not fixed!

It alternately stretches and shrinks with a characteristic strain, $\frac{\Delta L}{L}$
Gravitational Waves in Motion

Direction of wave travel
Gravitational waves can be emitted by astrophysical systems with rapidly changing mass distribution:

- Compact binary \{neutron stars, black holes\} orbit, inspiral and merger
- Core collapse of a massive star (supernova engine)
- Non-axisymmetric spinning neutron stars
- Cosmic strings, early universe physics, …

GWs come directly from the central engine

- Not obscured or scattered by material
  - Complements photon and neutrino diagnostics of photosphere, outflows, circumburst medium, shocks

But challenging to detect…

- Strain amplitude is inversely proportional to distance from source
  - Have to be able to detect weak signals to search a large volume of space

Expected strain at Earth: $\Delta L / L \sim 10^{-21}$ or even smaller!
The LIGO* Observatories

* LIGO = Laser Interferometer Gravitational-wave Observatory

LIGO Hanford

LIGO Livingston

3000 km

H1

L1
Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum enclosure

Large, suspended mirrors with precise coatings form long Fabry-Perot optical cavities in the arms

High-power laser
Power recycling mirror
Signal recycling mirror
Output mode cleaner
Photodiode readout

Interferometric measurement of arm length difference
Signal Recorded on September 14, 2015

Signal arrived 7 ms earlier at L1

[Abbott et al. 2016, PRL 116, 061102]
Looks just like a binary black hole merger!

[Abbott et al. 2016, PRL 116, 061102]

[Simulating eXtreme Spacetimes Collaboration]
Looks just like a binary black hole merger!

-0.26s

Hanford, Washington (H1)

Livingston, Louisiana (L1)

Bandpass filtered Strain ($10^{-21}$)

-1.0  -0.5  0.0  0.5  1.0

-1.0  -0.5  0.0  0.5  1.0

H1 observed

L1 observed

H1 observed (shifted, inverted)

Numerical relativity

Reconstructed (wavelet)

Reconstructed (template)

Matches well to BBH template when filtered the same way

[Abbott et al. 2016, PRL 116, 061102]
Some Properties of GW150914

Final BH mass: $62 \pm 4 M_\odot$

Energy radiated: $3.0 \pm 0.5 M_\odot c^2$

Peak power $\sim 200 M_\odot c^2 / s$

Distance: $410^{+160}_{-180} \text{ Mpc}$

$= 1.3 \pm 0.5 \text{ billion light-years}$

$\Rightarrow$ Redshift $z \approx 0.09$

We can’t tell if the initial black holes had any “spin” (intrinsic angular momentum), but the spin of the final BH is $0.67^{+0.05}_{-0.07}$ of maximal spin allowed by GR $\left(\frac{Gm^2}{c}\right)$

Masses:

$36^{+5}_{-4} M_\odot$

and

$29^{+4}_{-4} M_\odot$

These are surprisingly heavy for stellar-remnant black holes!

More from Advanced LIGO’s First Observing Run (O1)

Analysis of the complete O1 run data revealed one additional significant binary black hole coalescence signal, GW151226.


Weaker than GW150914, but still detected with > 5σ significance.

Also a marginal candidate LVT151012 – we estimate 87% prob of being real.

[Abbott et al. 2016, PRX 6, 041015]
Another signal consistent with GR, but qualitatively different

Longer duration, lower amplitude, more “cycles” in band

⇒ Matched filtering was essential for detecting GW151226

[Abbott et al. 2016, PRL 116, 241103]
GW151226 has lower mass than GW150914

- Initial masses: $14.2 \pm 8.3$ and $7.5 \pm 2.3 \, M_\odot$
- Final BH mass: $20.8 \pm 6.1 \, M_\odot$
- Energy radiated: $1.0 \pm 0.1 \, M_\odot c^2$
- Luminosity distance: $440 \pm 180 \, \text{Mpc}$

... and nonzero spin!

Effective signed spin combination definitely positive
⇒ at least one of the initial BHs has nonzero spin
(we can’t tell how the spin is divided up between them due to waveform degeneracy)

[Abbott et al. 2016, PRL 116, 241103]
Another binary black hole merger

Masses in between GW150914 and GW151226

About twice as far away as GW150914 and GW151226

Spin parameter: $\chi_{\text{eff}} = -0.12^{+0.21}_{-0.30}$

[Abbott et al. 2017, PRL 118, 221101]
Astrophysical Implications

There are black hole binaries out there, orbiting closely enough to merge, and heavy!

For comparison, reliable BH masses in X-ray binaries are typically $\sim 10 \, M_\odot$

We presume that each of our BHs formed directly from a star

- Low metallicity is required to get such large masses
- Otherwise, strong stellar winds limit the final BH mass

We can’t tell when the binaries formed

- Inspiral may have taken many billion years

Astrophysical Implications

Different formation pathways are possible:

- A massive binary star system with sequential core-collapses
- Chemically homogeneous evolution of a pair of massive stars in close orbit
- Dynamical formation of binary from two BHs in a dense star cluster
- Binaries formed from a population of primordial black holes

Key piece of evidence: spins of the initial black holes

- **Orbit-aligned** components: $\chi_{\text{eff}} = 0.21^{+0.21}_{-0.10}$ for GW151226, but consistent with zero for the other events

- **In-plane** components (which would cause precession during inspiral):
  little information from the events detected so far

All we can really say now is that these binary systems did not have large black-hole spins positively aligned with the orbital axis

- Disfavors chemically homogeneous evolution model

[Abbott et al. 2017, PRL 118, 221101]
Tests of GR

We examine the waveforms of the detected events in several ways to see whether there is any deviation from the GR predictions.

Known through post-Newtonian (analytical expansion) and numerical relativity.

**Inspiral / merger / ringdown consistency**

Compare estimates of mass and spin from before vs. after merger.

Consider possibility of a massive graviton

Would distort waveform due to dispersion.

From lack of distortion, we place a limit on graviton Compton wavelength: \( \lambda_g > 1.5 \times 10^{13} \) km

\[ m_g < 7.7 \times 10^{-23} \text{ eV} / c^2 \]
LIGO/Virgo have done many *externally triggered* GW searches  
(deep analysis of GW data around the time and/or sky position of reported EM event)

and have collaborated on *joint* searches  
(compare sets of candidate events)

Over two dozen papers...

| CBC, Burst | GRBs | – using | public (GCN) and | private info |
| CW | Known pulsars | | public | private |
| SGR/magnetar flares | | public | private |
| Pulsar glitch (Vela) | | | |
| Burst | High-energy neutrinos | | private |
| Radio transients | | | private |
| Supernovae | | | public (CBET, etc.) |
| CBC | Offline follow-up with satellite | | public γ/X-ray data |

Also initiated an *EM follow-up program*, distributing GW event candidates to observers to enable them to search for counterparts
Generating and Distributing Prompt Alerts

LIGO & Virgo have signed MOUs with >90 groups for EM/neutrino follow-up, in addition to a number of triggered / joint search MOUs.
Follow-up Observations During O1

About half of those with observing capability responded to at least one of the 3 alerts during the run

For GW150914:
- Covered most of skymap area at a wide range of wavelengths starting within a few hours
- ~50 GCN Circulars, ~12 papers

Also strong response for GW151226, GW170104, and other candidates

A weak signal was detected by the Fermi Gamma-ray Burst Monitor (GBM) ~0.4 second after the time of GW150914

Intriguing but inconclusive! ($< 3\sigma$)


Many other searches for optical, radio, or X-ray counterparts have found nothing related so far

Searches for high-energy neutrinos carried out with IceCube & ANTARES

[Adrián-Martínez et al. 2016, PRD 93, 122010]
[Albert et al. 2017, PRD 96, 022005]
Compact binary mergers containing at least one neutron star are thought to cause most short GRBs

Strong evidence from host galaxy types and typical offsets  

Could be NS-NS or NS-BH, with post-merger accretion producing a jet

Beamed gamma-ray emission → many more mergers than GRBs

Some opening angles measured, e.g. $16 \pm 10^\circ$  

Also may be able to detect “kilonova” optical signature from ejecta

Peaks on day-to-week time scale  
Advanced GW Detector Network:
Under Construction → Operating

- LIGO Hanford 2015
- GEO-HF 2011
- Virgo 2017
- LIGO Livingston 2015
- KAGRA ~2019

3 separate collaborations working together

2011-2015: GEO-HF
2015-2019: LIGO Hanford and LIGO Livingston
2017-2024: Virgo and KAGRA
Will join the O2 run a week or so from now!

As its sensitivity gets closer to LIGO’s, having three detectors will improve sky localization and parameter estimation.

*For details, see talk by Antonino Chiummo on Wednesday afternoon*
The new neighbor in the Kamioka mine

**Underground ➔ less ground motion**

- Tunnels are complete,
- vacuum system installed,
- operated simple Michelson in 2016

Now preparing to install cryogenic mirror payloads for lower thermal noise

Ultimately will have sensitivity similar to LIGO and Virgo

*For details, see Wednesday afternoon talk by Yuta Michimura*
The Wide Spectrum of Gravitational Waves

likely sources

~ $10^{-17}$ Hz
Primordial GWs from inflation era

~ $10^{-8}$ Hz
Gravitational radiation driven Binary Inspiral + Merger
Supermassive BHs
Massive BHs, extreme mass ratios

~ $10^{-2}$ Hz
Ultra-compact Galactic binaries

~ 100 Hz
Spinning NSs
Stellar core collapse

Detection method

B-mode polarization patterns in cosmic microwave background

~ $10^{-17}$ Hz
Primordial GWs from inflation era

~ $10^{-8}$ Hz
Gravitational radiation driven Binary Inspiral + Merger
Supermassive BHs
Massive BHs, extreme mass ratios

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Projects

BICEP2/Keck, ACT, EBEX, POLARBEAR, SPTpol, SPIDER, ...

BICEP2

NANOGgrav, European PTA, Parkes PTA

David Champion

LISA, DECIGO

AEI/MM/exozet

LIGO, GEO 600, Virgo, KAGRA

LIGO Laboratory
Millisecond pulsars are precise clocks!

Look for **correlated variations** in the times of pulses arriving at Earth.

Timing campaigns are being carried out by three collaborations with access to different radio telescopes:

- NANOGrav (Arecibo, Green Bank)
- European Pulsar Timing Array
- Parkes Pulsar Timing Array

Also collaborating as the **International Pulsar Timing Array**
Sensitivity improves with observation time span, number of pulsars monitored, and pulse timing precision

New pulsars are added as they are discovered

Pulsar timing is getting close to the expected stochastic signal from supermassive black hole binaries in the universe

[Figure by A. Sesana, in Hobbs+Dai, arXiv:1707.01615]

Also search for individual black hole binaries, cosmic strings, and arbitrary transient signals

Note: some of these radio telescopes are at risk of being shut down! See article in July 2017 issue of Physics Today
Use laser interferometry to measure changes in the distances among a trio of spacecraft in orbit around the Sun. Forms two independent Michelson interferometers plus a Sagnac null channel.

~milliHertz sources:
- Supermassive black hole binaries
- Intermediate mass BH binaries
- Extreme mass ratio inspirals (maps spacetime near BH)
- Galactic compact binaries
- Stochastic GW background?

[Danzmann et al. 2017, LISA Proposal to ESA]
LISA Pathfinder mission was a great success!

- Demonstrated the free-fall gravitational reference (test mass) technology needed for LISA
- Mission ended July 18

The LISA mission was formally selected last month as the concept to be developed as ESA’s third large-scale science mission

Projected launch date: 2034

NASA planning to make a significant contribution

[Armano et al. 2016, PRL 116, 231101]
Summary and Outlook

With 3.87 events detected so far, we are starting to get a picture of the population of merging binary black hole systems

   Enabling tests of GR and constraints on astrophysical models
   When will we detect neutron star binary mergers? Other sources?

LIGO is running pretty well, but not yet at design sensitivity; Virgo, after its upgrade, is about to begin observing

   Next will be KAGRA, then LIGO-India
   Third-generation ground-based GW detector designs are being developed

Pulsar timing campaigns are pushing down limits

LISA has a launch date