Gravitational Waves from Binary Black Hole Mergers
Gravitational Waves (GWs)

- The waves of the electromagnetic force are realized as (electric and magnetic) fields which propagate through space and time. [Maxwell, 1865]

- General Relativity describes gravity in terms of a spacetime which is deformable. [Einstein, 1915]

- GWs are oscillations of that spacetime. [Einstein, 1916]

- “ripples in spacetime”
Gravitational Waves in General Relativity (GR)

In special relativity:

\[ ds^2 = (c\, dt)^2 - \left( dx^2 + dy^2 + dz^2 \right) = \sum \eta_{\mu\nu} dx_\mu dx_\nu \]

Einstein, 1905

\[ \eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \]

GR:

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \quad G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \]

Einstein, 1915

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

\[ \left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = -16\pi T_{\mu\nu} \]

Einstein, 1916
Gravitational waves and LIGO: short version

Binary black hole system

As detected by LIGO:

GW ripples are a space strain $h$, where $h = \Delta L / L$

Realistic sources: $h \sim 10^{-23}$

$\Rightarrow \Delta L \sim 10^{-19} \text{ m (Yikes !)}$
Interferometer in action
a closer look…
inside the vacuum chambers...
suspended test mass
LIGO observatories: LHO and LLO

2 or more sites provides coincident detection - a crucial feature
a short history of LIGO

- 1916: Einstein shows gravitational waves would result from General Relativity
- 1960’s: Kip Thorne (Caltech) and Rainer Weiss (MIT) predict that gravitational wave detection via laser interferometry is feasible
- 1972: Rainer Weiss (MIT) describes first realistic laser interferometer design
- 1975: Hulse and Taylor show that the decay in the orbit of a binary neutron star system is consistent with energy loss due to gravitational waves
- 1980-81: MIT and Caltech launch construction of first prototype detectors
- 1994: Ground breaking at the Hanford, WA site; 1995 at Livingston, LA
- 2002-2010: Data taking and development of the scientific program with initial detectors
- Sept 10, 2015: Advanced detectors begin data taking, observing run O1
- Sept 12, 2015: Observation of GW150914, merger of binary black holes
- Dec 26, 2015: Detection of GW151226, a lower mass binary black hole merger
- Dec 2016: Start of observing run O2
- Jan 4, 2017: Detection of GW170104, binary black hole merger
- Run O2 until end of Aug 2017; Virgo may join
Boom!

a merger of black holes

Black holes?

- The chirp function tells us we have 2 objects each of mass about 30 solar masses (30\(M_\odot\)).

- At merger, they are orbiting each other 75 times per second and their separation is about 350 km… And they are still missing each other!

- They are indeed black holes.
Is General Relativity the correct description?

- Predicts gravitational waves… ✔
- Waveforms from GR fit the data beautifully… ✔

A unique and important test of GR
Simulated Nearby View – slowed down 100X
GW150914 simulation II

-0.76s
Main GW150914 parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$36^{+5}<em>{-4} \text{ M}</em>\odot$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$29^{+4}<em>{-4} \text{ M}</em>\odot$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$62^{+4}<em>{-4} \text{ M}</em>\odot$</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410^{+160}_{-180} \text{ Mpc}$</td>
</tr>
<tr>
<td>Source redshift, $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>

- Energy radiated in GWs: $3.0^{+0.5}_{-0.5} \text{ M}_\odot c^2$
- Peak GW power: $3.6^{+0.5}_{-0.4} \times 10^{56} \text{ erg/s}$
GW150914 Parameters

<table>
<thead>
<tr>
<th>GW150914 Parameters</th>
<th>EOBNR</th>
<th>IMRPhenom</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector-frame total mass $M/M_\odot$</td>
<td>$70.3^{+5.3}_{-4.8}$</td>
<td>$70.7^{+3.8}_{-4.0}$</td>
<td>$70.5^{+4.6}_{-4.5} \pm 0.9$</td>
</tr>
<tr>
<td>Detector-frame chirp mass $M/M_\odot$</td>
<td>$30.2^{+2.5}_{-1.9}$</td>
<td>$30.5^{+1.7}_{-1.8}$</td>
<td>$30.3^{+2.1}_{-1.9} \pm 0.4$</td>
</tr>
<tr>
<td>Detector-frame primary mass $m_1/M_\odot$</td>
<td>$39.4^{+5.5}_{-4.9}$</td>
<td>$38.3^{+5.5}_{-3.5}$</td>
<td>$38.8^{+5.6}_{-4.1} \pm 0.3$</td>
</tr>
<tr>
<td>Detector-frame secondary mass $m_2/M_\odot$</td>
<td>$30.9^{+4.8}_{-4.4}$</td>
<td>$32.2^{+3.6}_{-5.0}$</td>
<td>$31.6^{+4.2}_{-4.9} \pm 0.6$</td>
</tr>
<tr>
<td>Detector-frame final mass $M_f/M_\odot$</td>
<td>$67.1^{+4.6}_{-4.4}$</td>
<td>$67.4^{+3.4}_{-3.6}$</td>
<td>$67.3^{+4.1}_{-4.0} \pm 0.9$</td>
</tr>
<tr>
<td>Source-frame total mass $M^{\text{source}}/M_\odot$</td>
<td>$65.0^{+5.0}_{-4.4}$</td>
<td>$64.6^{+4.1}_{-3.5}$</td>
<td>$64.8^{+4.6}_{-3.9} \pm 0.5$</td>
</tr>
<tr>
<td>Source-frame chirp mass $M^{\text{source}}/M_\odot$</td>
<td>$27.9^{+2.3}_{-1.8}$</td>
<td>$27.9^{+1.8}_{-1.6}$</td>
<td>$27.9^{+2.1}_{-1.7} \pm 0.2$</td>
</tr>
<tr>
<td>Source-frame primary mass $m_1^{\text{source}}/M_\odot$</td>
<td>$36.3^{+5.3}_{-4.5}$</td>
<td>$35.1^{+5.2}_{-3.3}$</td>
<td>$35.7^{+5.4}_{-3.8} \pm 0.0$</td>
</tr>
<tr>
<td>Source-frame secondary mass $m_2^{\text{source}}/M_\odot$</td>
<td>$28.6^{+4.4}_{-4.2}$</td>
<td>$29.5^{+3.3}_{-4.5}$</td>
<td>$29.1^{+3.8}_{-4.4} \pm 0.5$</td>
</tr>
<tr>
<td>Source-frame final mass $M_f^{\text{source}}/M_\odot$</td>
<td>$62.0^{+4.4}_{-4.0}$</td>
<td>$61.6^{+3.7}_{-3.1}$</td>
<td>$61.8^{+4.2}_{-3.5} \pm 0.4$</td>
</tr>
<tr>
<td>Mass ratio $q$</td>
<td>$0.79^{+0.18}_{-0.19}$</td>
<td>$0.84^{+0.14}_{-0.21}$</td>
<td>$0.82^{+0.16}_{-0.21} \pm 0.03$</td>
</tr>
<tr>
<td>Effective inspiral spin parameter $\chi_{\text{eff}}$</td>
<td>$-0.09^{+0.19}_{-0.17}$</td>
<td>$-0.03^{+0.14}_{-0.15}$</td>
<td>$-0.06^{+0.17}_{-0.18} \pm 0.07$</td>
</tr>
<tr>
<td>Dimensionless primary spin magnitude $a_1$</td>
<td>$0.32^{+0.45}_{-0.28}$</td>
<td>$0.31^{+0.51}_{-0.27}$</td>
<td>$0.31^{+0.48}_{-0.28} \pm 0.04$</td>
</tr>
<tr>
<td>Dimensionless secondary spin magnitude $a_2$</td>
<td>$0.57^{+0.40}_{-0.51}$</td>
<td>$0.39^{+0.50}_{-0.34}$</td>
<td>$0.46^{+0.48}_{-0.42} \pm 0.01$</td>
</tr>
<tr>
<td>Final spin $a_f$</td>
<td>$0.67^{+0.06}_{-0.08}$</td>
<td>$0.67^{+0.05}_{-0.05}$</td>
<td>$0.67^{+0.05}_{-0.07} \pm 0.03$</td>
</tr>
<tr>
<td>Luminosity distance $D_L/Mpc$</td>
<td>$390^{+170}_{-180}$</td>
<td>$440^{+140}_{-180}$</td>
<td>$410^{+160}_{-180} \pm 40$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.083^{+0.033}_{-0.036}$</td>
<td>$0.093^{+0.028}_{-0.036}$</td>
<td>$0.088^{+0.031}_{-0.038} \pm 0.004$</td>
</tr>
<tr>
<td>Upper bound on primary spin magnitude $a_1$</td>
<td>$0.65$</td>
<td>$0.71$</td>
<td>$0.69 \pm 0.05$</td>
</tr>
<tr>
<td>Upper bound on secondary spin magnitude $a_2$</td>
<td>$0.93$</td>
<td>$0.81$</td>
<td>$0.88 \pm 0.10$</td>
</tr>
<tr>
<td>Lower bound on mass ratio $q$</td>
<td>$0.64$</td>
<td>$0.67$</td>
<td>$0.65 \pm 0.03$</td>
</tr>
<tr>
<td>Log Bayes factor $\ln B_{s/n}$</td>
<td>$288.7 \pm 0.2$</td>
<td>$290.1 \pm 0.2$</td>
<td>—</td>
</tr>
</tbody>
</table>

R Frey QuarkNet June 26, 2017
GW150914 was the first observation of gravitational waves.
GW150914 was the first direct observation of a black hole.
Prior to GW150914, the astrophysical consensus was that there should not be \( \sim 30 \, M_\odot \) black holes – more on this later.
Actually, three BBHs Observed in First Run…

A detailed discussion of GW150914 is given in [16, 38, 43], which states that GW150914 was observed on September 14, 2015 at 09:50:45 UTC with a matched filter SNR of 23.7. The chirp mass of the binary is $\approx 4.1 \times 10^{-5} M_\odot$, and a likelihood of 84.7 in the GstLAL analysis. It is re-weighted with a re-weighted SNR in the PyCBC analysis of $\approx 12.7$.

The background contributed by GW150914 is so significant that the high significance background is dominated by its presence. GW150914 and GW151226 are the most significant events in the data, with GW151226 identified as the most significant event in the data. In both analyses, GW151226 is identified as the most significant event remaining in the data.

The performance of the GstLAL and PyCBC results is compared, with the GstLAL result on the right. The lower plots show results with GW150914 removed from both the foreground and background, with the PyCBC result on the left and the GstLAL result on the right. The significance obtained for LVT151012 is only marginally affected by including or removing GW150914 and GW151226.

The chirp mass of a binary is $\approx 4.1 \times 10^{-5} M_\odot$, and a likelihood of 84.7 in the GstLAL analysis. It is re-weighted with a re-weighted SNR in the PyCBC analysis of $\approx 12.7$. The third most significant event in the search, LVT151012, is identified with a significance of $\approx 3 \times 10^{-5}$.
Some properties of the 3 O1 BBH events

**FIG. 4.** Posterior probability densities of the masses, spins and distance to the three events GW150914, LVT151012 and GW151226. For the two dimensional distributions, the contours show 50% and 90% credible regions.

- Top left: Component masses $m_{\text{source}}^1$ and $m_{\text{source}}^2$ for the three events. We use the convention that $m_{\text{source}}^1 > m_{\text{source}}^2$, which produces the sharp cut in the two-dimensional distribution. For GW151226 and LVT151012, the contours follow lines of constant chirp mass ($M_{\text{source}} = 8.9 + 0.3$ $M_\odot$ and $M_{\text{source}} = 15.1 + 1.4$ $M_\odot$ respectively). In all three cases, both masses are consistent with being black holes.

- Top right: The mass and dimensionless spin magnitude of the final black holes.

- Bottom left: The effective spin and mass ratios of the binary components.

- Bottom right: The luminosity distance to the three events.

A greater impact upon the inspiral. We find that smaller spins are favored, and place 90% credible bounds on the primary spin $a_1 \ll 0.7$ for GW150914, $a_1 \ll 0.7$ for LVT151012, and $a_1 \ll 0.8$ for GW151226. In the case of GW151226, we infer that at least one of the components has a spin of $0.2$ at the 99% credible level.

While the individual component spins are poorly constrained, there are combinations that can be better inferred. The effective spin $c_{\text{eff}}$, as defined in Equation 6, is a mass-weighted combination of the spins parallel to the orbital angular momentum [71–73]. It is $+1$ when both the spins are maximal and parallel to the angular momentum, $-1$ when both spins are maximal and antiparallel to the angular momentum, and $0$ when there is no net mass-weighted aligned spin. Systems with positive $c_{\text{eff}}$ complete more cycles when inspiralling from a given orbital separation than those with negative $c_{\text{eff}}$[70, 110]. While $c_{\text{eff}}$ has a measurable effect on the inspiral, this is degenerate with that of the mass ratio as illustrated for the lower mass inspiral-dominated signals in Fig. 4.

Observations for all three events are consistent with small values of the effective spin: $|c_{\text{eff}}| \ll 0.17, 0.28$ and $0.35$ at 90% probability for GW150914, LVT151012 and GW151226 respectively. This indicates that large parallel spins aligned or antialigned with the orbital angular momentum are disfavored.

It may be possible to place tighter constraints on each component's spin by using waveforms that include the full effects of precession [39]. This will be investigated in future analyses.

All three events have final black holes with spins of $\ll 0.7$, as expected for mergers of similar-mass black holes [111, 112]. The final spin is dominated by the orbital angular momentum of the binary at merger. Consequently, it is more precisely constrained than the component spins and is broadly similar across the three events. The masses and spins of the final black holes are plotted in Fig. 4.
First event in O2: GW170104
Now we have 3.9 binary black hole mergers
LIGO’s Gravitational-Wave Detections

GW150914
Discovered: 14.09.2015
1.3 Billion Light Years Away
62 Solar Masses
360 Kilometres in Diameter

GW151226
Discovered: 26.12.2015
1.4 Billion Light Years Away
21 Solar Masses
120 Kilometres in Diameter

GW170104
Discovered: 04.01.2017
3 Billion Light Years Away
49 Solar Masses
270 Kilometres in Diameter

You are here

Did you know?
The solar mass is a standard unit of mass in astronomy. It is equal to the mass of the Sun equal to approximately $1.99 \times 10^{30}$ kg.

Data credit: LIGO Scientific Collaboration/OzGrav ARC Centre of Excellence
Black hole spins: a clue to their origin
Black hole spins for GW170104

aligned with L

anti-aligned with L

in-plane spin

no precession

max precession

Prior

Posterior
• Implies low metallicity and weak winds; Pop III stars?

• Rate may require dynamical formation
An explanation for the observations which also explains other mysteries

from the Beginning of Time

A hidden population of black holes born less than one second after the big bang could solve the mystery of dark matter

By Juan Garcia-Bellido and Sebastian Cline

Illustrated by Kevin Prevost, Marianne Kytola

COSMOLOGY

More than a billion years ago two black holes in the distant universe spiraled around each other in a deathly dance until they merged. This spiraling collision was so violent that it shook the fabric of spacetime, sending perturbations—gravitational waves—rippling outward through the cosmos at the speed of light. In September 2015, after traveling more than a billion light-years, those ripples washed over our planet, registering as a “chirp” in the sensors of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO).

This was the first direct detection of gravitational waves, and the observation confirmed Albert Einstein’s centuries-old prediction of their existence. Yet, the chirp revealed that each of the merger’s progenitor black holes was 50 times heavier than the sun. That is, their masses were two to three times larger than ordinary black holes born from supernovas explosions of massive stars. These black holes were as heavy it is hard to explain how they formed from stars at all. Furthermore, even if two such black holes did independently form from the deaths of two massive stars, they would have had to first each other and merge—an event with an exceedingly low
Primordial black holes

- Conjectured by Hawking in the 1970s
- Quantum fluctuations amplified by inflation
- Black hole masses from 1% of solar mass to 10,000 times solar mass
- Could explain:
  - Dark matter
  - LIGO enhanced rate of black holes
  - Lack of dwarf galaxies
  - Supermassive black holes

**Primordial Black Holes Form in Clusters**

Inflation—a proposed acceleration to the universe’s expansion less than a second after the big bang—would form PBHs by magnifying quantum fluctuations to immense scales. As inflation ended, these fluctuations would create density perturbations that then form PBHs. Larger, more powerful fluctuations would create more massive and numerous PBHs. The authors’ inflationary model predicts a broad peak of magnified fluctuations and a range of density perturbations, producing PBHs in clusters, with each PBH ranging from one 100th to 1,000 times the mass of our sun. Half a million years after the big bang, a cluster might span hundreds of light-years and contain millions of PBHs. As the PBHs within such clusters merged together, scattered apart, and fed on ordinary gas and dust, they would guide the growth of galaxies and galactic clusters.
Can we expect more LIGO BBH events?

- **Short Answer:** “Yes”
- **Longer Answer:**
  - The ~3 months of run O1 yielded 3 BBH events.
  - For O1, LIGO was at ~30% of its design sensitivity.
  - Expect improved sensitivity for O2, O3, … until 100% reached 2019-ish.
  - At design: 1 event/month → 1 event/day.
What else?

- population of BBH events; systems with hundreds of solar mass?
- stellar formation and evolution; cosmology
- Primordial black holes?

- GWs from NS-BH or NS-NS binary mergers
- associated with gamma-ray bursts (GRBs), EM afterglows
- cosmology (Hubble), neutron star EOS, …

- GWs from stellar collapse
- associated with Long GRBs, supernovae, afterglows, neutrinos

- GWs from (galactic) single neutron stars: magnetar x-ray flares, pulsars

- GWs from inflation, cosmic strings, ??
NS-NS mergers, NS equation of state, EM afterglows (kilonova), R-process elements

The analysis can be turned into an add-on for search and parameter-estimation pipelines.

Potential speed-up in offline GW searches following SGRB triggers:

- \( \sim 35\% \) of the parameter space is useful in following up an SGRB trigger
- \( \sim 57\% \) of the CBC templates cover the SGRB active region

Valeriu Predoi GRB call – September 04, 2014
Sky locations of O1 BBHs as seen from earth
The 2nd generation GW detector network

Advanced LIGO, 2015
GEO 2014
Virgo 2017
Kagra ~2019
LIGO-India ~2022

3 or more detectors: localization from ~100 square degrees to ~10 sq degrees
take home…

- Gravitational Waves discovered!
- General Relativity (still) looks good.
- A lot of science from the first few events
- The (really) exciting part:
  A new window on the Universe…
  The fun is just beginning!