Expanding our view of the universe through gravitational-wave astronomy

Marissa Walker for the LIGO Scientific Collaboration
Postdoctoral Associate
California State University, Fullerton
Theory
The Theory of General Relativity is Einstein’s theory of gravity.

More accurate than Newton’s view of gravity as a force, especially for strong gravity and high velocity.

Key idea is that gravity is an effect of the curvature of space and time.

Credit: The Library of Congress
Curved spacetime

“Matter tells spacetime how to curve and space-time tells matter how to move.”
- John Wheeler
Black holes and Neutron Stars

Fullerton region

Neutron star

Black hole

- Mass = 1.5 ☀
- Radius = 4.5 km

- Mass = 1.5 ☀
- Radius = 9-15 km

About 15 km
SXS Collaboration: “Calculation of warped spacetime consistent with GW170104 (zoomed)"

https://www.youtube.com/watch?v=AGLMflnzac
Effects of gravitational waves

• Cause the distance between objects to change $h(t) \sim \Delta L(t)/L$

• Fractional change shown 10% ($h \sim 10^{-1}$)

• Fractional change from gravitational waves arriving at Earth…

0.000000000000000001% ($h \sim 10^{-21}$) over a distance of 4 km, that’s $10^{-18}$ m!
Detectors
LIGO

Laser Interferometer Gravitational-Wave Observatory

Livingston, Louisiana

Hanford, Washington

Credit: LIGO
The second generation of gravitational-wave observatories

Inspired by TJ Massinger
Movie courtesy Kai Staats, www.overthesun.com
from: “LIGO Detection” https://www.newscientist.com/round-up/ligodetection/
Observations
Observation of Gravitational Waves from a Binary Black Hole Merger

September 14, 2015 at 02:50:45 PDT

PRL 116, 061102 (2016)
Supercomputer calculation of gravitational waves from merging black holes
How could we be confident this wasn’t terrestrial?

- H1-L1 Correlation, waveform consistency
- No environmental noises could have created this signal
- Thousands of instrumental channels, all consistent with gravitational-wave signal
- Waveform is consistent with general relativity and inconsistent with instrument noise
The dawn of gravitational-wave astronomy
Binary black hole discovery

• First direct detection of gravitational waves
• Tests and agrees with Einstein’s predictions
• First observation of black holes of this size (30 \( \odot \))
• First observation of two black holes merging to form one final black hole
• Opens a new field: gravitational-wave astronomy
Movie by CSUF undergraduate student Teresita Ramirez
GW170817: a neutron star merger

August 17, 2017 12:41:04 UTC

No significant signal in Virgo, but that's actually very helpful!
A glitch in LIGO-Livingston
LIGO and VIRGO have announced our first Binary Neutron Star gravitational-wave event! Look for a special surprise when classifying on workflow Neutron Star Merger and above. Facts about the event can be found here: http://www.ligo.org/detections/GW170817.php and papers about the discovery can be found here: https://www.ligo.caltech.edu/page/detection-companion-papers
Neutron-star merger
The Dawn of Multi-messenger Gravitational-wave Astronomy
LIGO+Virgo map the origin of the gravitational waves

Credit: LIGO/Virgo/NASA/Leo Singer
A gamma ray burst (GRB170817A)

1.7 seconds later, gamma rays!

- **Solved**: Neutron star mergers cause GRBs!
- Gravitational waves and light traveled 130 Million years, arrived 2 seconds apart
- **Measured**: speed of gravity equals speed of light (to part in $10^{15}$)

Gravitational waves and gamma rays arrived 2 seconds apart after traveling for 130 Million years.

Measured: the speed of gravity matches the speed of light (to one part in $10^{15}$).
GW170817 electromagnetic observations

LIGO and Virgo told the astronomy community:
- where to look in the sky,
- the distance, and
- expect fireworks from a neutron star merger

Full spectrum observations

Over the following days, weeks, and months, observed:

- X-ray
- Gamma ray
- UV
- Optical
- Infrared
- Radio
- Neutrino
Binary Neutron Star Discovery

• First joint gravitational-wave and light-wave observation
• Multi-messenger astronomy allowed us to pinpoint the host galaxy: NGC 4993 — 130 million light years away
• Convincingly ties neutron star mergers as cause of mysterious (short) gamma ray bursts
• Probes matter in its densest state - rules out some models of neutron star matter
• A new (independent) way to measure the expansion of the universe (the Hubble constant)
• Measures that gravity travels at speed of light
What’s next?
**O3:**

Third observing run

- Improved detector sensitivities in LIGO and Virgo

https://www.gw-openscience.org/detector_status/
Third observing run

- Improved detector sensitivities in LIGO and Virgo
- Open public alerts

https://gracedb.ligo.org/latest/
LIGO/Virgo S190426c: Update on Source Classification

The LIGO Scientific Collaboration and Virgo Collaboration report:

Based on posterior support from preliminary parameter estimation [1,2], under the assumption that the candidate S190426c is astrophysical in origin, the relative probabilities amongst the signal categories NSBH : MassGap : BNS : BBH are revised to be approximately 12 : 5 : 3 : 0.

https://gcn.gsfc.nasa.gov/selected.html
O3:
Third observing run

- Improved detector sensitivities in LIGO and Virgo
- Open public alerts
- Predicted rate of detections around 1/week
A parallel with Galileo’s Telescope

Second generation, *just barely sensitive enough to detect gravitational waves*, will provide:

- Hundreds of black holes mergers to 6 Gly
- Tens of neutron star mergers to 1 Gly
- Completely new way of measuring cosmological parameters

What could we do with dramatically better detectors?
Cosmic Explorer

- 40km-long, on surface
- 320kg Silicon optics at 123K
- 2 Million Watt infrared laser
- 14cm wide laser beams
- R&D progress needed in optical coatings, quantum noise, thermal compensation
- ~ year 2030 and ~ 1B USD

Abbot et al., arXiv:1607.08697

Artwork: E. Hall, Background: A. Simmonet
What might humans discover with these detectors?

- Waves from black holes and neutron stars… But way clearer!
- Every merger in the whole universe
  - How do city-sized atomic nuclei behave?
  - Gravity in extreme and turbulent conditions
- Primordial stars formed at the beginning of time?
- The history of the universe
- The unknown?!
Gravitational Wave frequency (Hz)

- Cosmic Microwave Background: $10^{-16}$ (today)
- Pulsar timing: $10^{-8}$ (~cycle/year)
- Space-based interferometers: $10^{-4}$ (~cycle/hour)
- Ground-based interferometers: $10^2$ (audio)

Gravitational Wave detection techniques:
- IPTA
- LISA ~2034
- LIGO
- Virgo
- KAGRA