Extracting Astrophysics from Gravitational Waves: GW170817 Case Study

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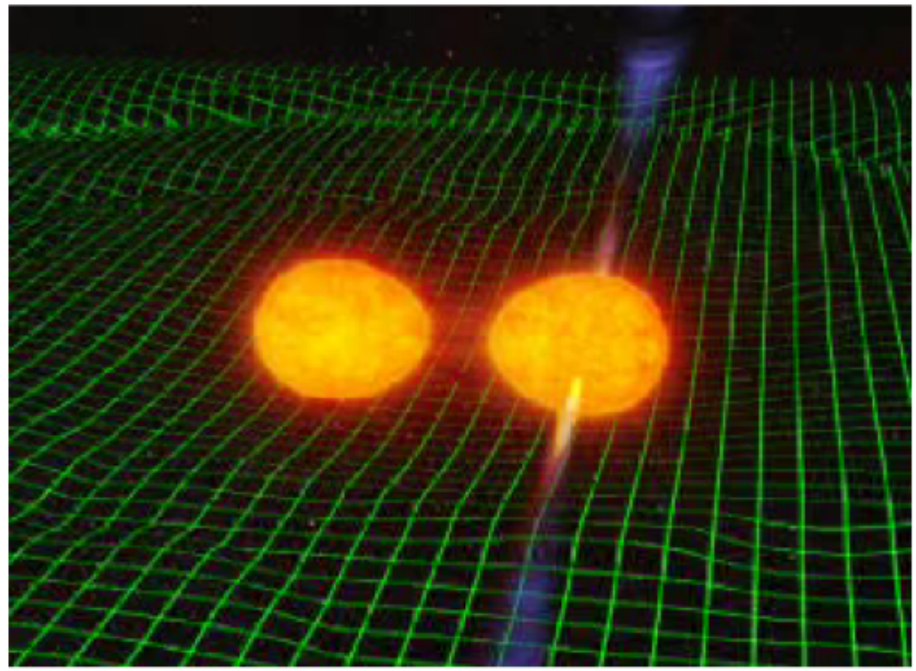
Link to Jupyter notebook to be presented here:

https://notebooks.azure.com/stuver/projects/AAPT-WM19

Gravitational Waves (GWs)

- Ripples on space-time
  - » A propagating change in the gravitational field
- Every mass acceleration creates a gravitational wave
  - » Much like an acceleration of charge creates an EM wave



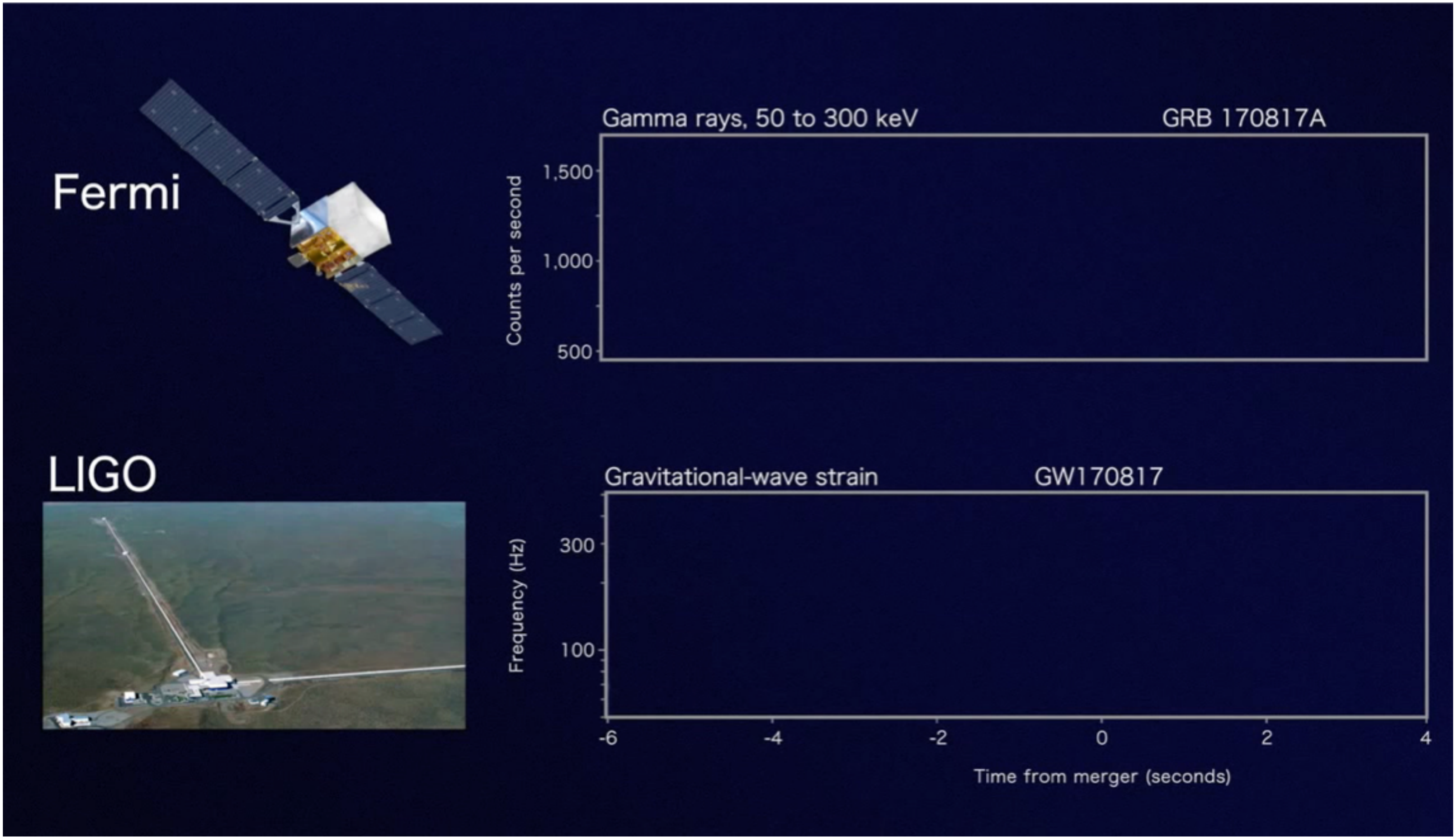
- Only extremely massive, energetic events will produce detectable gravitational waves
  - » The Big Bang, supernovae, compact binary merger, etc.

Video from: Jodrell Bank Observatory, 2003

GWs and Astronomy

- A gravitational wave is produced by the motion of mass, therefore bringing us information relating directly to this motion.
  - » This is something that light observations rarely do.
  - » This will also allow us to observe objects that do not produce EM radiation.
- Since the universe is essentially transparent to GW, nothing can block a GW from reaching Earth.

GW170817: 17 August 2017
The NS-NS Merger



LIGO

What Info Does a GW Carry?

[BLACK HOLE]

A BLACK HOLE IS ONE OF THE SIMPLEST OBJECTS IN THE UNIVERSE. IT HAS ONLY TWO CHARACTERISTICS: ITS MASS (WHICH DETERMINES ITS SIZE), AND ITS SPIN (HOW MUCH SPACETIME SWIRLS AROUND).

WHEN YOU HAVE TWO BLACK HOLES IN A BINARY SYSTEM, THINGS GET MORE COMPLICATED. WE NOW HAVE THE MASSES AND SPINS OF BOTH BLACK HOLES. THE SPINS STAY THE SAME SIZE DURING THE ORBIT, BUT THEIR DIRECTIONS WOBBLE AROUND IN A PROCESS CALLED PRECESSION. THE GRAVITATIONAL WAVES REACHING EARTH FROM THE BINARY ALSO DEPEND ON WHERE THE BINARY IS AND WHICH WAY IT IS ORIENTATED.

[SPIN]

AS THE BLACK HOLES ORBIT EACH OTHER, THEIR SPINS CHANGE DIRECTION. THIS ALSO CAUSES THE ORIENTATION OF THE ORBIT TO TOPPLE BACKWARDS AND FORWARDS A LITTLE. THIS PRECESSION LEAVES AN IMPRINT ON THE GRAVITATIONAL WAVES: THEY BECOME LOUDER AND QUIETER AS THE SPINS WOBBLE AROUND. THE PRECESSION DEPENDS ON DIRECTIONS OF THE TWO SPINS, COMPARED TO EACH OTHER AND COMPARED TO THAT OF THE ORBIT. THE SPIN OF THE MORE MASSIVE BLACK HOLE HAS A LARGER EFFECT THAN THAT OF THE SMALLER ONE.

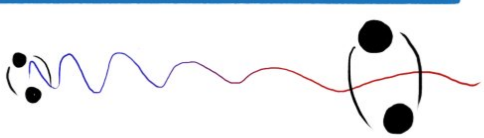
WE DON'T SEE MUCH SIGN OF PRECESSION IN GW150914. THIS MAY BE BECAUSE SPINS ARE SMALL, ITS INCLINATION MEANS THE WOBBLES AREN'T VISIBLE, OR A COMBINATION OF BOTH. SINCE THE INSPIRAL IS SHORT, WE WOULD NOT EXPECT TO SEE A LARGE EFFECT IN ANY CASE.

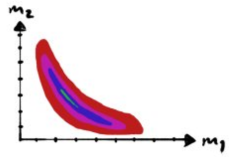
[REDSHIFT]

THE EXPANSION OF THE UNIVERSE AFFECTS GRAVITATIONAL WAVES IN A COUPLE OF WAYS. AS THE UNIVERSE EXPANDS, IT STRETCHES THE WAVES TRAVELLING THROUGH IT. THIS IS WELL KNOWN IN ASTRONOMY AND IS CALLED REDSHIFT, AS IT MAKES VISIBLE LIGHT MORE RED. TO HAVE A LARGE EFFECT, THE WAVES MUST HAVE TRAVELLED A LONG WAY.

THE FIRST EFFECT IS THAT THE FREQUENCY OF THE WAVE CHANGES. THIS HAS THE SAME IMPACT AS CHANGING THE MASSES: **THINGS FURTHER AWAY APPEAR MORE MASSIVE**. THE SECOND EFFECT IS TO CHANGE THE AMPLITUDE, WHICH IS THE SAME AS CHANGING THE DISTANCE: WE OFTEN TALK ABOUT THE LUMINOSITY DISTANCE, WHICH ABSORBS THIS EFFECT, BUT ISN'T THE SAME AS IF WE MEASURED THE DISTANCE TO THE SOURCE USING A TAPE MEASURE.

IF WE GET ENOUGH MEASUREMENTS OF HOW GRAVITATIONAL WAVES ARE REDSHIFTED, WE COULD POSSIBLY LEARN SOMETHING ABOUT HOW THE UNIVERSE IS EXPANDING.





[CHIRP MASS]

THE WAY THE SIGNAL CHANGES DURING THE INSPIRAL IS PRIMARILY FIXED BY A COMBINATION OF THE BLACK HOLE MASSES WE CALL THE CHIRP MASS. IF WE SEE LOTS OF CYCLES OF INSPIRAL, WE CAN MEASURE THE CHIRP MASS REALLY WELL (BETTER THAN A FRACTION OF A PERCENT). WHEN THINKING ABOUT WHAT WE CAN LEARN FROM GRAVITATIONAL WAVES, PEOPLE OFTEN FIRST THINK ABOUT THE CHIRP MASS.

[STAGES]

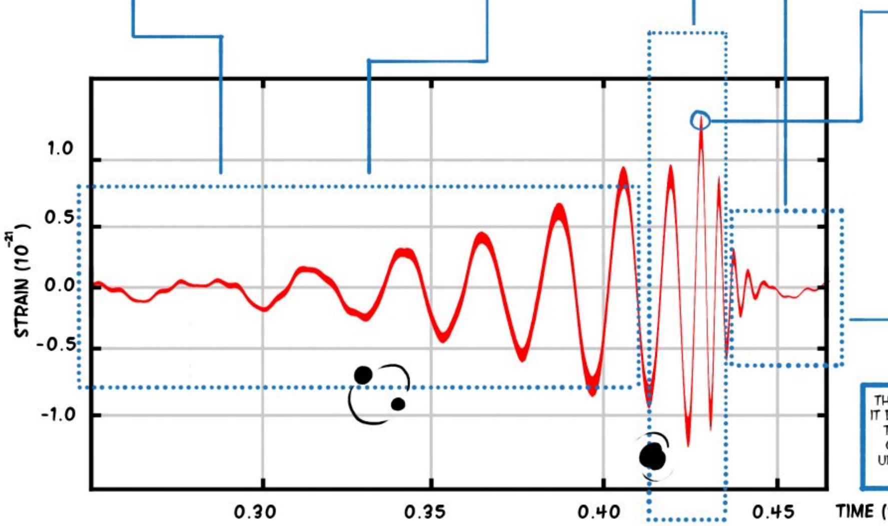
ONE OF THE REASONS WE DIVIDE UP THE GRAVITATIONAL WAVE SIGNAL IS BECAUSE DIFFERENT TECHNIQUES CAN BE USED TO CALCULATE THE WAVES AT DIFFERENT POINTS. THE EARLY **INSPIRAL** CAN BE CALCULATED USING POST-NEWTONIAN THEORY (THIS STARTS WITH NEWTON'S THEORY OF GRAVITY AND ADDS LITTLE EXTRA BITS TO ACCOUNT FOR HOW THINGS CHANGE IN GENERAL RELATIVITY). THE **RINGDOWN** CAN BE CALCULATED USING BLACK HOLE PERTURBATION THEORY (THIS STARTS WITH THE FINAL SHAPE OF THE BLACK HOLE, AND SEES HOW IT REACTS TO SMALL CHANGES). THE **MERGER** CAN ONLY BE CALCULATED USING NUMERICAL RELATIVITY (SIMULATIONS OF THE FULL EQUATIONS OF GENERAL RELATIVITY WHICH TAKE LOTS OF COMPUTING POWER); THIS HAS ONLY BEEN POSSIBLE IN THE LAST 10 YEARS, SO THE MERGER WAS THE LAST PART OF THE PUZZLE.

IF WE HAD A BINARY CONTAINING NEUTRON STARS INSTEAD OF BLACK HOLES, THE INSPIRAL WOULD BE MUCH THE SAME, BUT THERE WOULD NOT BE THE SAME MERGER AND RINGDOWN. THE SIGNAL WOULD BE MUCH MESSIER, POSSIBLY FEATURING NEUTRON STARS BEING RIPPED APART, BEFORE COLLIDING AND COLLAPSING TO A FINAL BLACK HOLE.

INSPIRAL

MERGER

RINGDOWN



[AMPLITUDE]

THE SIZE OF THE SIGNAL, ITS AMPLITUDE, DEPENDS ON HOW FAR AWAY THE BINARY IS. IF THE DISTANCE WERE TWICE AS BIG, THE AMPLITUDE WOULD BE HALF. THE QUIETER A SIGNAL IS, THE HARDER IT IS TO DETECT, AND THE LESS WE CAN LEARN ABOUT ITS PROPERTIES.

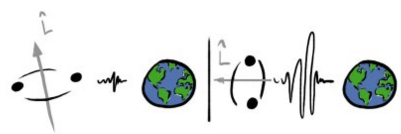
HEAVIER SYSTEMS PRODUCE LOUDER GRAVITATIONAL WAVES AS THERE IS MORE MASS MOVING AROUND TO CREATE THE WAVES.

THE SIGNAL AMPLITUDE DEPENDS UPON THE WAY THE BINARY IS FACING (ITS INCLINATION), AND ITS POSITION IN THE SKY: THE DETECTORS ARE NOT EQUALLY SENSITIVE TO GRAVITATIONAL WAVES FROM ALL DIRECTIONS (THE SIGNAL IS LOUDEST WHEN THE SOURCE IS DIRECTLY ABOVE OR BELOW A DETECTOR.

$$h(t) = \frac{G m v^2}{c^4 r}$$

[RINGDOWN]

THE RINGDOWN PART OF THE SIGNAL COMES FROM THE FINAL BLACK HOLE, SO IT DEPENDS UPON ITS MASS AND SPIN. THE FINAL MASS IS ALMOST THE SAME AS THE TOTAL MASS OF THE TWO INITIAL BLACK HOLES (SOME ENERGY IS LOST, CARRIED AWAY BY THE GRAVITATIONAL WAVES). THE FINAL SPIN DEPENDS UPON THE SPIN OF THE INITIAL BLACK HOLES AND HOW THEY WERE ORBITING AROUND EACH OTHER WHEN THEY MERGED.



[INCLINATION]

THE WAY THE BINARY IS FACING THE EARTH DETERMINES THE GRAVITATIONAL WAVES WE SEE. IF IT IS EDGE ON, THE SIGNAL IS QUIETER, BUT IT IS EASIER TO SPOT SMALL CHANGES CAUSED BY THE BLACK HOLES' SPINS. IF IT IS FACING US, THE SIGNAL IS LOUDER, BUT IT'S HARDER TO TELL IF THE ORBIT WOBBLES BECAUSE OF PRECESSION. WE HAVE A GREATER CHANCE OF DETECTING A FACE-ON BINARY BECAUSE THEY CAN BE DETECTED FROM FURTHER AWAY.

[TOTAL MASS]

THE TOTAL MASS OF THE SYSTEM DETERMINES HOW LONG IT TAKES FOR THINGS TO HAPPEN. HEAVY SYSTEMS ARE BIGGER, AND SO CHANGE MORE SLOWLY. THE GRAVITATIONAL WAVES ARE AT LOWER FREQUENCIES, WHICH MEANS THAT LIGO CAN ONLY SEE THE FINAL PARTS. LIGHTER SYSTEMS PRODUCE GRAVITATIONAL WAVES AT HIGHER FREQUENCIES, SO WE CAN MEASURE MORE OF THE INSPIRAL.

THE TOTAL MASS OF THE SYSTEM SETS WHICH PARAMETERS ARE MOST EASILY MEASURED. FOR REALLY MASSIVE SYSTEMS WE MEASURE THE TOTAL MASS BEST (AS WE ONLY SEE THE MERGER AND RINGDOWN), BUT FOR LIGHT SYSTEMS, LIKE BINARY NEUTRON STARS, WE MEASURE THE CHIRP MASS BEST (AS WE ONLY SEE THE INSPIRAL). GW150914 IS SOMEWHERE IN THE MIDDLE.

[SKY]

WITH MULTIPLE DETECTORS, WE CAN WORK OUT WHICH DIRECTION THE GRAVITATIONAL WAVES CAME FROM BY LOOKING AT THE TIMES WHEN THE SIGNALS ARRIVED AT EACH DETECTOR. THIS IS SIMILAR TO HOW YOU CAN LOCATE THE SOURCE OF A SOUND USING YOUR EARS.

WE CAN GET SOME EXTRA INFORMATION ABOUT THE DIRECTION FROM HOW LOUD EACH SIGNAL IS (SINCE EACH OF THE DETECTORS HAS ITS BEST SENSITIVITY IN A DIFFERENT DIRECTION), AND WHERE THE WAVE IS IN ITS CYCLE.

Theory Tools

- In this case study, we will be decoding information about its source from the inspiral portion of the signal.
- We will be making use of Kepler's 3rd law:

$$P_{orb}^2 = R^3 \left(\frac{4\pi^2}{G(m_1 + m_2)} \right)$$

- And the chirp mass: a quantity that appears frequently in gravitational wave physics and is needed to determine how the period of an inspiral signal changes over time:

$$M_c = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}} = \frac{c^3}{G}\left[\left(\frac{5}{96}\right)^3 \pi^{-8} f^{-11} \dot{f}^3\right]^{\frac{1}{5}}$$

LIGO

Programming Exercise

- I have written a Jupyter notebook detailing an exercise to establish a hypothesis of the source types, and extract chirp mass, component masses (with some assumptions), orbital separation, and orbital velocity.
- You will be able to have students come to the same conclusions scientists have! It is within their reach!
- The notebook can be found here:

  https://notebooks.azure.com/stuver/projects/AAPT-WM19

Useful References

also listed at bottom of my notebook!

- L. Rubbo, S. Larson, M. Larson, D. Ingram, "Hands-on gravitational wave astronomy: Extracting astrophysical information from simulated signals", American Journal of Physics 75, 597 (2007); https://doi.org/10.1119/1.2721587. (Accompanying activity here: http://cgwp.gravity.psu.edu/outreach/activities/handson_activity/
- L. Burko, "Gravitational Wave Detection in the Introductory Lab", The Physics Teacher 55, 288 (2017); https://doi.org/10.1119/1.4981036.
- LIGO Scientific and Virgo Collaborations, "The basic physics of the binary black hole merger GW150914", Annalen der Physik, 529, No. 1-2, 1600209 (2017); https://doi.org/10.1002/andp.201600209
- H. Mathur, K. Brown, A. Lowenstein, "An analysis of the LIGO discovery based on introductory physics", American Journal of Physics 85, 676 (2017); https://doi.org/10.1119/1.4985727.
- B. Farr, G. Schelbert, L. Trouille, "Gravitational wave science in the high school classroom", American Journal of Physics, 80, 898 (2012); https://doi.org/10.1119/1.4738365.

Abstract

A new era of multi-messenger astronomy began with the coincident detection of gravitational waves by LIGO (an event labeled GW170817) and electromagnetic waves by over 70 observatories across and orbiting Earth. Part of the light observed came in the form of a short gamma-ray burst; the source of this class of GRB has been a longstanding mystery. The observation of associated gravitational waves finally proved that the merger of a neutron star binary system is a source of these bursts. This talk will focus on how information about a gravitational wave source is extracted from the recorded signal and the contributions this makes to a fuller understanding of our universe. Classroom connections with references to the GW170817 detection will be discussed.