LIGO

Exploring Gravitational Waves in the Classroom

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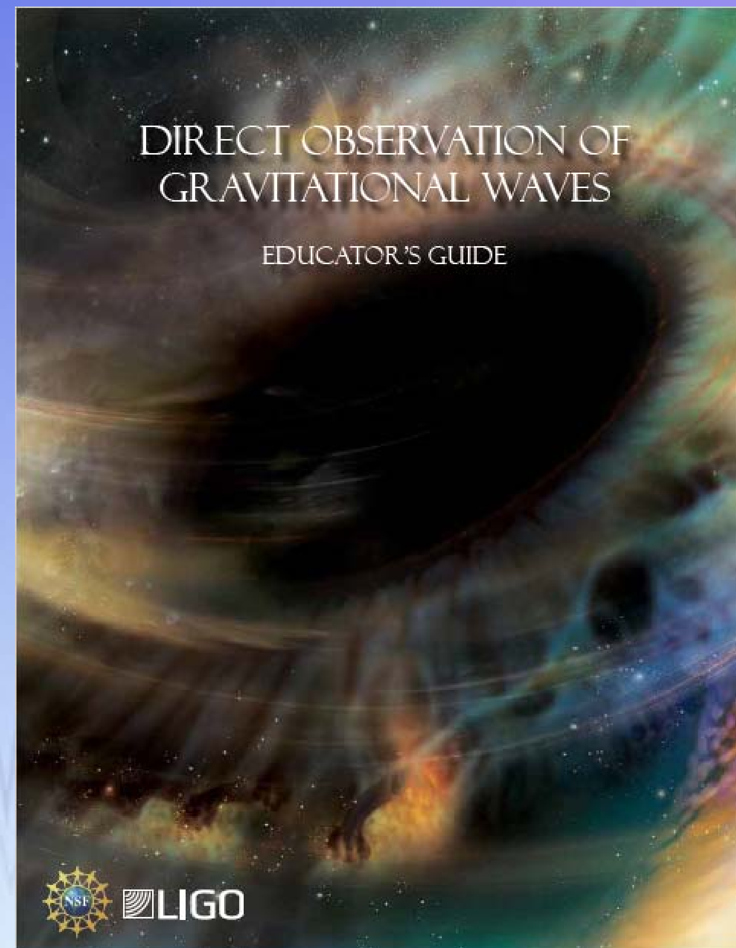
KITP 2017

Outline

- LIGO Educator Guide for GW150914
  - Background information
  - Classroom demonstrations
- Online courses
  - Big Ideas in Cosmology (Great River Learning)
  - LIGO: Waves and Gravity (Summer 2015)
  - LIGO: Detecting Gravitational Waves (Summer 2016)
  - Testing GR with Gravitational Waves (in progress for 2017)
- Contemporary Physics Education Project
  - New section: Gravitation and new poster!

About a year ago…. (2/11/16)



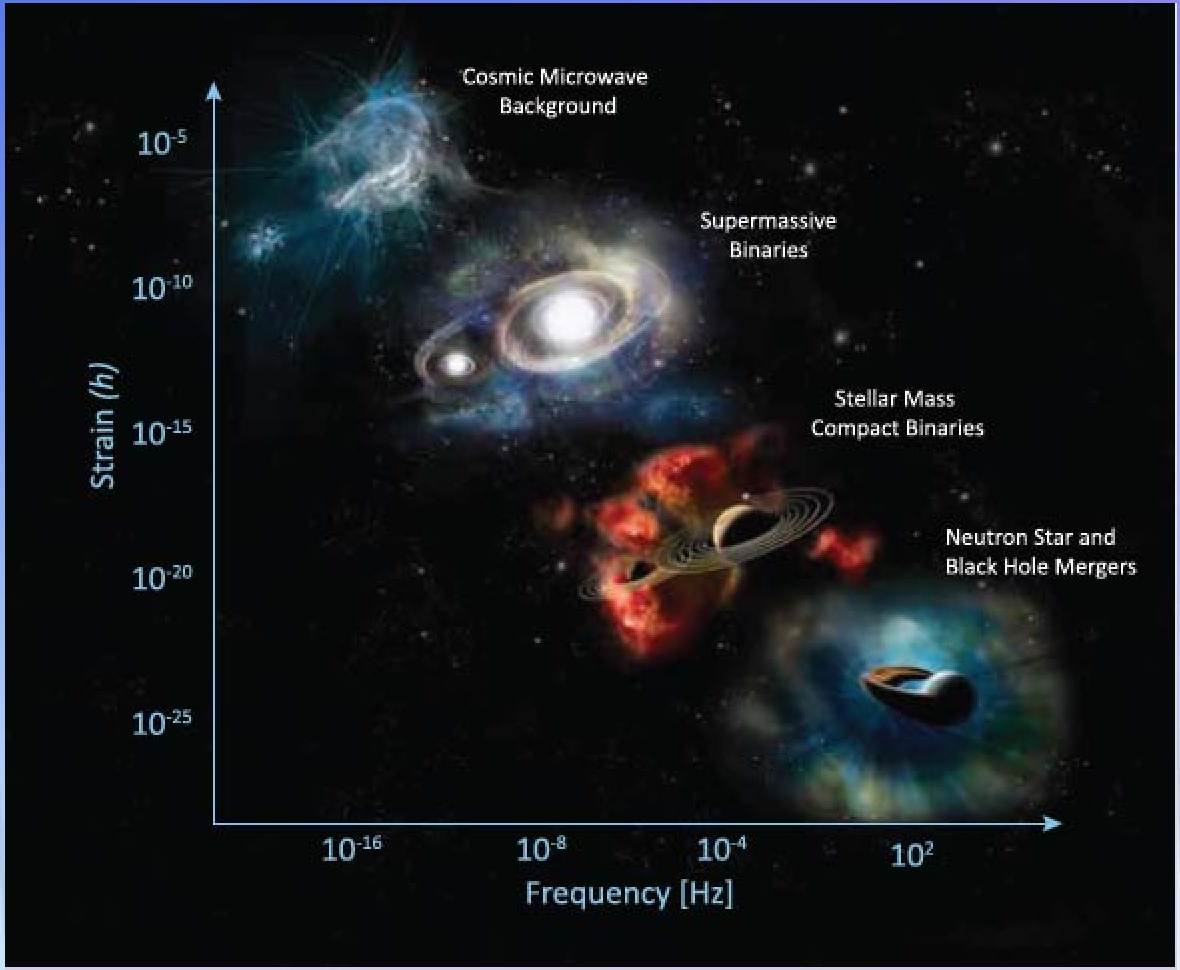
LIGO GW150914 Educator Guide

- Quick project commissioned by NSF to accompany press packet for press conference on 2/11/16 that announced GW discovery
- Adapted background material from “Big Ideas in Cosmology” (Great River Learning)
- Adapted classroom activities that have been used for pulsars and black holes for Fermi and other NASA missions

Background Material

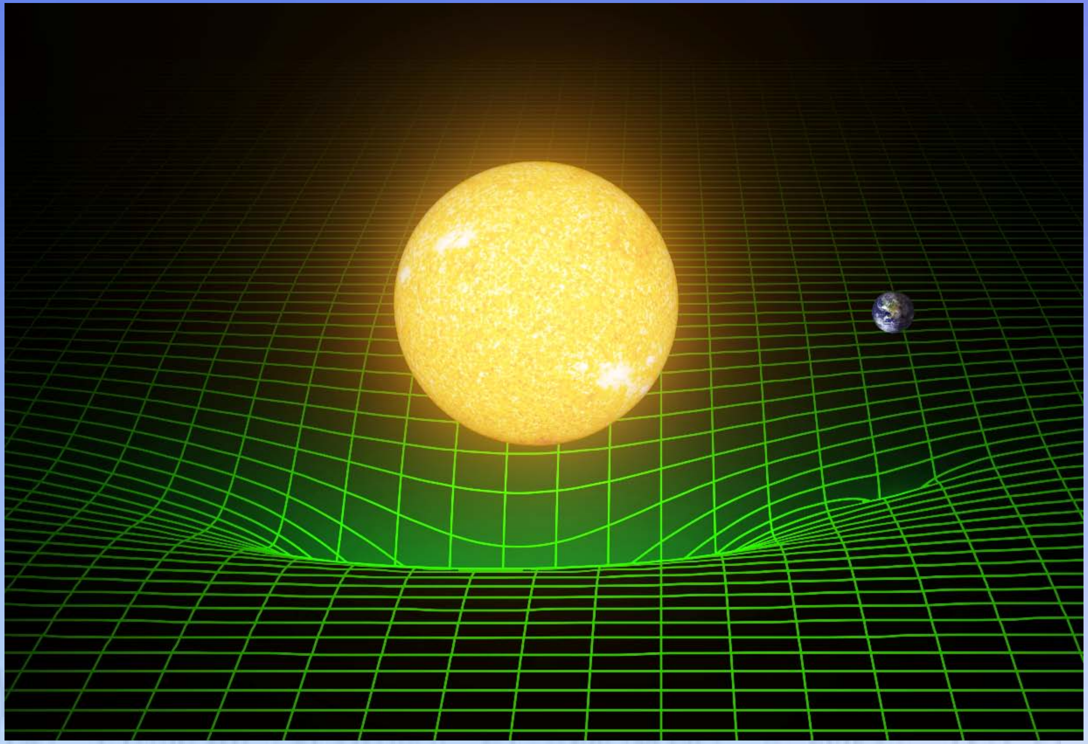
- Gravitational Waves as Signals from the Universe
- Gravity from Newton to Einstein
- Gravitational Waves
- The Direct Observation of Gravitational Waves by LIGO
- Black Holes

New visualizations

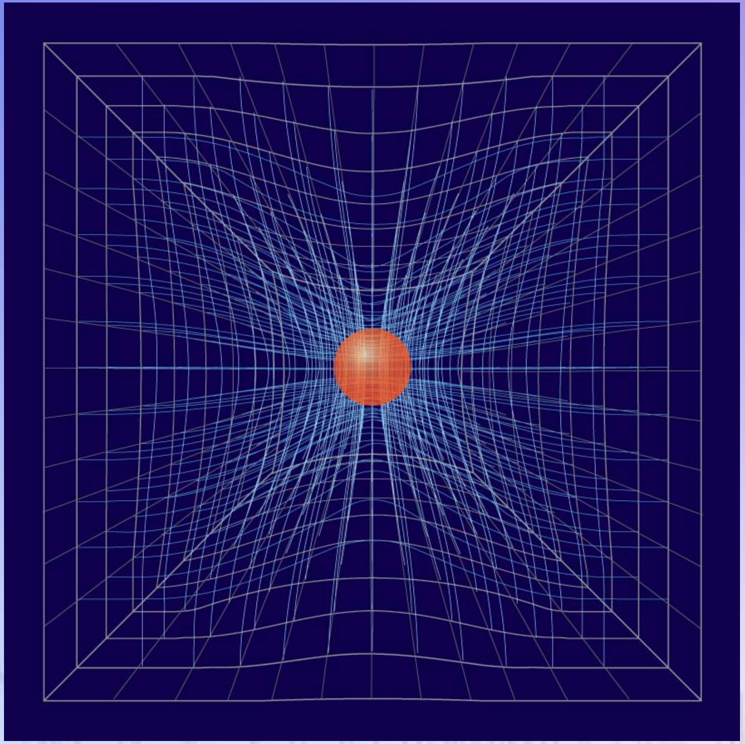


Credit:SSU/A. Simonnet

Addressing misconceptions



Credit:LIGO/T. Pyle



Credit:SSU/A. Simonnet

Classroom Activities

Activity 1 – Coalescing Black Holes

Brief overview:

Students interact with a demonstration of orbiting spheres that have an increasing orbital frequency as they coalesce.

Science Concepts:

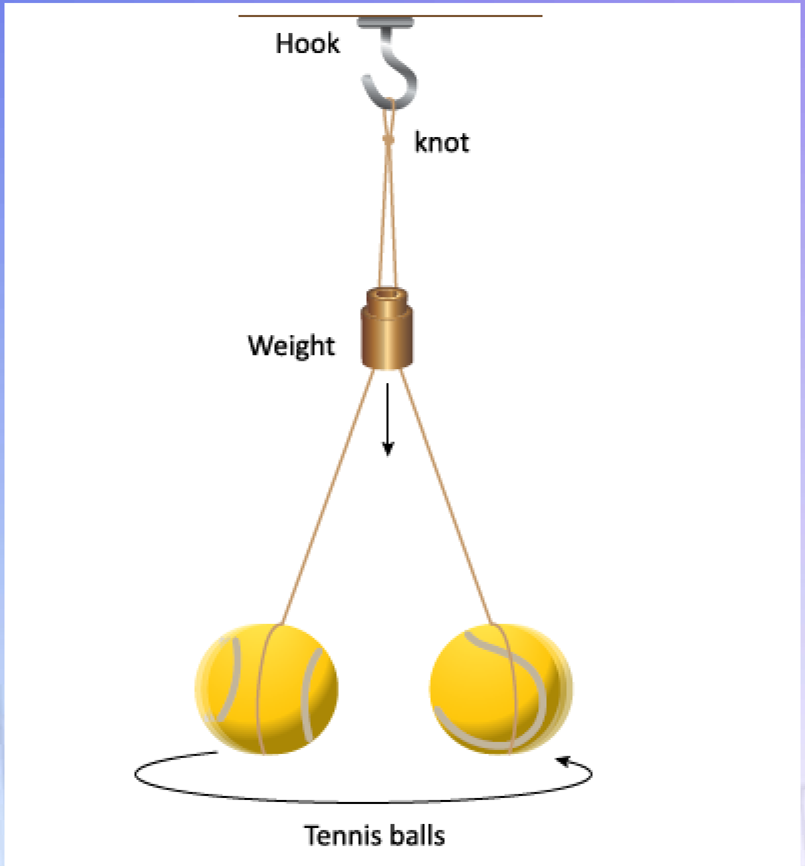
Gravitational waves are ripples in spacetime produced by some of the most violent events in the cosmos, such as the collisions and mergers of massive compact stars or black holes. These ripples travel at the speed of light through the Universe, carrying with them information about their origins.

Duration: 30 min

Essential Question:

What happens when two black holes spiral in towards each other?

Grades: 5 – 12



Classroom Activities

Activity 2 – Warping of Spacetime

Brief overview:

Students explore the behavior of two orbiting spheres in spacetime.

Science Concepts:

A pair of orbiting black holes will produce gravitational waves, which are ripples in the fabric of spacetime. Gravitational waves will carry energy away from the pair, causing their orbit distance to shrink and their orbital period to decrease. Eventually the black holes will coalesce. LIGO's detectors can measure the gravitational waves produced by the system during the coalescence.

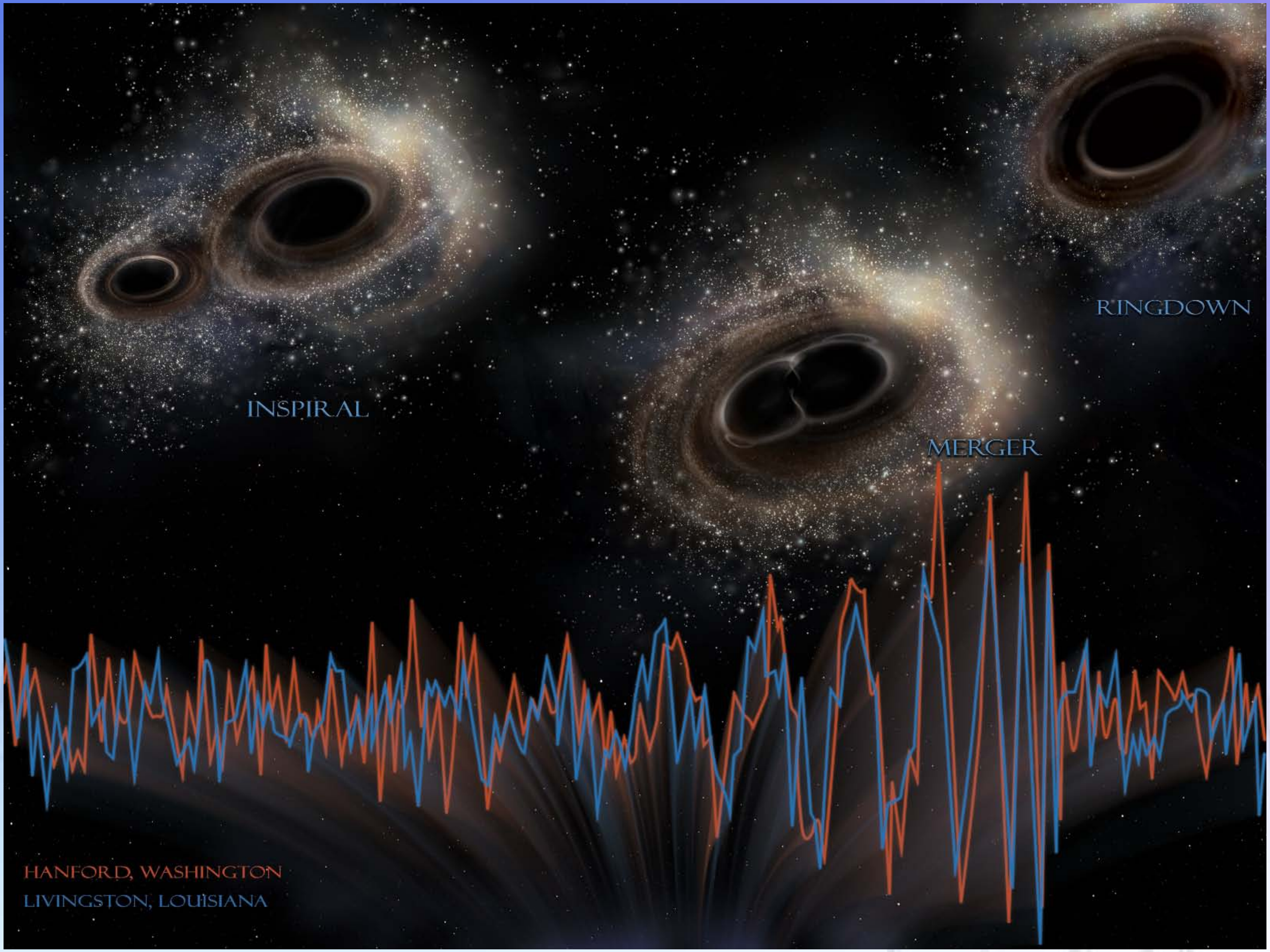
Duration: 30 min

Essential Question:

How do binary black holes warp spacetime?

Grades: 5 – 12

APOD 2/11/16


INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

Kim COBLE
Kevin MCLIN
Janelle M. BAILEY
Anne J. METEVIER
Carolyn C. PERUTA
Lynn COMINSKY

BIG IDEAS in COSMOLOGY

A Digital First Curriculum for College Students

Why Online?

- Interactive and engaging
- Scalable
- Flexible and easy to update as scientific thinking evolves
- Use online, hybrid or traditional pedagogies

Key features

- Informed by peer-reviewed education research into preconceptions
- Interactive format which uses **real data**
- Engages students in higher levels of understanding, analysis and synthesis
- Has been tested in hybrid and online learning environments

Chapters

- Review of Mathematics
- Chapter 1: Size and Scope
- * Chapter 2: Light
- Chapter 3: Telescopes
- Chapter 4: Moving through Space
- Chapter 5: Moving through Time
- * Chapter 6: Measuring Cosmic Distances
- Chapter 7: Classical Physics: Gravity and Energy
- Chapter 8: Dark Matter
- * Chapter 9: Special Relativity
- * Chapter 10: General Relativity
- Chapter 11: Black Holes
- Chapter 12: Gravitational Lensing
- Chapter 13: The Expansion of the Universe
- Chapter 14: The Growth of Structure
- Chapter 15: The Cosmic Microwave Background
- Chapter 16: The Early Universe
- Chapter 17: Dark Energy and the Fate of the Universe

- Adopting authors can select any combination of chapters
- Assessment results from both online and hybrid classes
- * chapters used in 2015 LIGO course

Chapter 10 – General Relativity

- The force of gravity is a natural consequence of curved spacetime due to the presence of mass and energy.
- Properties of curved spacetime include time dilation, gravitational redshifts, and gravitational lensing.
- Build a mathematical construct for describing curvature and apply it to two- and three-dimensional models.

Chapter 10 – General Relativity

- 10.1 – Equivalence Principle
- 10.2 – Gravity and Curvature
  - 10.2.1 Gravity Curves Space
  - 10.2.2 Gravity Curves Time
- 10.3 – What is Curvature?
  - 10.3.1 Distances and Curvature in 2D Space
  - 10.3.2 Distances and Curvature Extended to 3 Dimensions
  - 10.3.3 Curvature in Spacetime

Chapter 10 – General Relativity

- 10.4 – Tests of General Relativity
  - 10.4.1 The Orbit of Mercury
  - 10.4.2 Light Bends Around the Sun
  - 10.4.3 Gravitational Redshift
  - 10.4.4 Dragging of Reference Frames by Moving Objects
  - 10.4.5 Gravitational Radiation (LIGO is here!)
- 10.5 The Source of Gravity
- Wrapping it up: Curved Spacetime Around a Star

Pedagogical Implementation

- Learning Objectives are defined for each chapter section and/or subsection
- Each chapter starts with a video to set the stage
- Each subsection starts with a student dialogue to elicit pre-conceptions
- Conceptual and numerical problems are interwoven throughout the text
- Interactive activities explore the phenomena under discussion
- Wrapping it up activity to synthesize all LOs

Chapter 10 Intro Video

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Floating in Space

Lena, Max, and Noah are building rockets to take to the next AeroPac launch in the desert. Lena looks outside at a bird flying past the window.

Lena: "What would happen if that bird tried to fly inside my rocket? Like if I could build a really big rocket and launch it with a bird inside?"

Max: "The bird would be weightless while the rocket is launching. I've seen videos of the astronauts in space, and they just float around while they are up there."

Noah: "The bird would weigh more while the rocket is launching. It would only float around weightless if it was in orbit. And our rockets that we are building can't get into orbit. They just go up and come back down again."

Lena: "Well I think the bird could still fly around inside the rocket as long as there was some air in there. I don't think it would even notice it was being launched as long as it was flying."

Do you agree with any or all of these students, and if so, whom?

Curved Spacetime around a Star

LIGO: Waves and Gravity

- Offered for academic or continuing education credit during July-August 2015
- Pre- and post-surveys done by WestEd
- We surveyed the teachers background and how they taught E&M and Special Relativity before taking our class
- Also required “Final Reflections” on how the material could be used in their class(es)

Course content

- Seven units of material
  - Light (chapter 2 from Big Ideas)
  - Learning More about Light (new, following MIT/B&B)
  - Classical Physics: Gravity and Energy (ch. 7)
  - Special Relativity (ch. 9, following Moore)
  - General Relativity (ch. 10)
  - Geometry and Gravity for Weak Fields (new)
  - Astrophysical Sources of Gravitational Waves (new)
- Plus Resources (lots of links and references)
- All the newly created material is available online through: http://epo.sonoma.edu/ligo

Some comments

- “a renewed awareness for what my students must go through when they are tackling new and/or difficult topics”
- “given me some new ideas about using technology to a greater degree in my courses”
- “as much as I love discussing entropy or the conservation of angular momentum, people are more likely to ask about black holes, gravitational waves, etc.”
- “FYI, your documents are the first docs I have ever read that made this material understandable. I have tried several texts, and they are SO mathematical early on that I could never see the physics behind the mathematical thicket.”

LIGO: Detecting Gravitational Waves

- Offered for academic or continuing education credit during July-August 2016
- Pre- and post-surveys done by WestEd
- We surveyed the teachers background and if/how they taught relativity before taking our class
- Also required “Final Reflections” on how the material could be used in their class(es)

Course content

- Five units of material
  - Introduction and Background
  - Direct Observations
  - LIGO: The Basic Idea (includes new video)
  - Sources of Noise
  - Signal Extraction (includes LIGO Open Science Center tutorials)
- Plus Resources (lots of links and references)
- All the material is available online through: http://epo.sonoma.edu/ligo

New realistic LIGO video

Credit: Over the Sun, LLC

LIGO Open Science Center

- https://losc.ligo.org
- Currently offers access to data prior to “Advanced LIGO” – S5 and S6 data sets
- PLUS DATA AROUND GW150914,GW151226 and a third “almost” event LVT151012
- Uses iPython and specialized viewing tools
- Tutorials included!
- Examples of student and citizen scientist projects: https://losc.ligo.org/projects/

Some comments

- “The problems were cleverly chosen in a way that gave me a deeper appreciation for the steps needed to design and execute an experiment that help to confirm a cornerstone of general relativity.”
- “The variety of ways that the material was presented was impressive and I look forward to using several of the materials presented in my own calculus (and algebra-based) physics class.”
- “It was so refreshing to be able to take a real honest-to-goodness physics course for a change.”
- “I believe that LIGO and its discoveries have provided a unique opportunity for contemporary physics to be integrated into the introductory course.”

Testing GR with LIGO's GWs

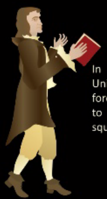
- To be offered for academic or continuing education credit during July-August 2017
- May reuse some of the earlier material on SR and GR
- Background material on classical tests of GR
- New material on using LIGO's observations with numerical relativity models to test GR
- Registration for the course is now open!
- http://www.ssuexed.com/course.php?id=2839&sem=2&year=2017

Contemporary Physics Education Project (CPEP)

- Non-profit group that created the famous particle physics poster (and more!)
- New section on Gravitation – please join!
- LIGO online materials have been linked to CPEP website – more are welcomed!
- New poster now for sale through the website http://CPEPphysics.org (links to Amazon) but you can each take one home for free!

GRAVITATION: FROM NEWTON TO EINSTEIN

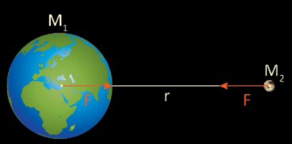
The Newtonian View of Gravity



In 1687, Isaac Newton published his Law of Universal Gravitation. In this law, the gravitational force between two point-masses is proportional to the product of their masses divided by the square of their separation.

$$F = \frac{GM_1M_2}{r^2}$$

In this equation, the two objects have masses M_1 and M_2 and the distance between them is r. The proportionality constant G is called the *Universal Gravitational Constant*. An attractive force pulls the masses toward each other along a straight line that passes through them.



Newton's great insight was to realize that the same influence that makes objects fall toward the ground on Earth also keeps the planets and other celestial bodies in their orbits.

The Newtonian View of Black Holes

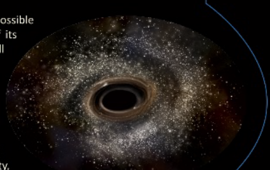
In 1783, the English philosopher John Michell first proposed the idea that there were such things as "dark stars," an idea which arose from Newtonian gravity. The escape velocity (v_{esc}) is the minimum speed required for a test particle to escape the gravitational pull of an object with mass M:

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

Notice that the escape velocity increases as the square root of the object's mass increases, and decreases if the test particle starts farther from the object's center (at a distance r).

If the escape velocity is set equal to the speed of light, c, then we can find the physical size (R_{Sch}) of Michell's dark star:

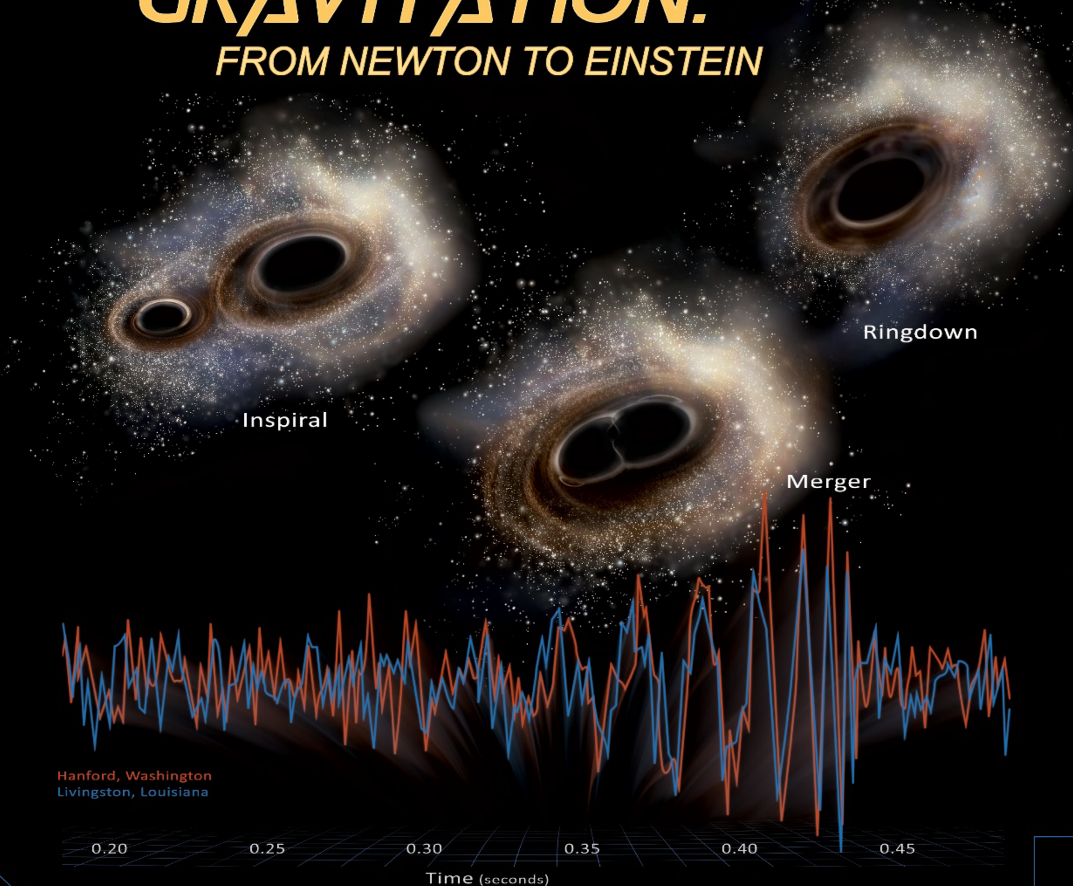
$$R_{Sch} = \frac{2GM}{c^2}$$



Since c is the maximum possible speed, an object with all of its mass within this radius will have such strong gravity that not even light can escape; it will thus be "black."

The same relation can be derived using Einstein's General Theory of Relativity, but the calculation is much more complicated. Karl Schwarzschild used General Relativity to solve for this "radius of no return" for non-spinning black holes: it is called the Schwarzschild radius, R_{Sch}, in his honor. It is just a coincidence that the size of black holes in Newtonian gravity and General Relativity are the same; at the point of forming a black hole, Newtonian gravitational theory is no longer valid, and General Relativity must be used.

We gratefully acknowledge support from the National Science Foundation for some of the work done to create this poster.



Direct Detection of Gravitational Waves

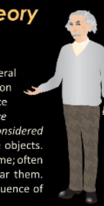
Gravitational waves were directly detected for the first time on September 14, 2015 by the LIGO (Laser Interferometer Gravitational-wave Observatory) scientific collaboration and the Virgo collaboration. The illustration above depicts the signals detected by the twin LIGO detectors from a system with two in-spiraling black holes. The red and blue lines show the amplitude of the gravitational wave signals received at the LIGO detectors in Hanford, Washington and Livingston, Louisiana, respectively. After traveling for billions of years, the signal arrived first at Livingston, and then 7 ms later, at Hanford.

Note the correspondence between the two signals. Both match closely to the theoretical model computed using General Relativity for an inspiralling black hole binary system. In this system, the black holes weigh in at 36 and 29 times the mass of our Sun, respectively. At the point of merger, the gravitational wave emission abruptly dies away, in an event called the ringdown, as the newly formed 62 solar mass black hole settles into its equilibrium state. The merger process emits the equivalent of 3 solar masses of energy as gravitational waves.

The artwork above the waveform shows a visualization of the binary black hole system at various times during the event. The inspiral phase lasts for millions to billions of years prior to the merger. The data show about the last 0.15 seconds of the inspiral phase, prior to the merger. The strongest gravitational waves are emitted during the black hole merger, which occurs from around t = 0.35 to t=0.44 seconds on this plot. The final, brief, ringdown phase starts at about t = 0.44 seconds.

Due to the small value of the Universal Gravitational Constant, gravity is considered the weakest of the four fundamental forces of physics. However, because extremely massive objects are usually involved, gravitational forces can generate considerable amounts of energy. The peak gravitational-wave power radiated during the final moments of this black hole merger was more than ten times greater than the power from the light emitted by all the stars and galaxies in the observable Universe.

Einstein's General Theory of Relativity



In 1915, Albert Einstein published his General Theory of Relativity. In this theory, gravitation is not a force at all, but a property of space and time (*spacetime – a union of space and time in which the two cannot be considered independently*) in the presence of massive objects. Such objects distort and stretch the spacetime; often we say that they *curve* the spacetime near them. What we experience as gravity is a consequence of objects moving in that curved spacetime.

Einstein expressed the gravitational effects of spacetime through an equation, called the Einstein Equation.

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

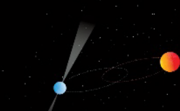
The Einstein Equation can be explained using the famous quote by John Archibald Wheeler:

"Spacetime tells matter how to move; matter tells spacetime how to curve."

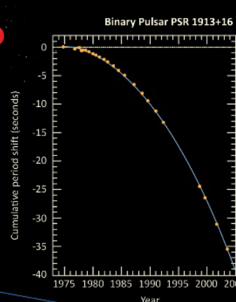
In Einstein's equation, $G_{\mu\nu}$ describes the curvature of spacetime while $T_{\mu\nu}$ describes the distribution and form of mass and energy. These two four-dimensional mathematical quantities are related through constants including the speed of light, c, and the Universal Gravitational Constant, G. Einstein's equation simplifies to Newton's Law of Gravitation in most cases.

Gravitational Waves

Einstein's General Theory of Relativity predicts that two stars in a binary orbit will generate gravitational waves as the stars orbit each other. These waves carry away energy. As a result, the two stars will slowly spiral in toward one another and will eventually merge. If one of the stars emits regular pulses (like a pulsar), the pulse period will appear to shift as the orbit shrinks. This phenomenon was first confirmed in a binary system discovered in 1974 by Russell Hulse and Joseph Taylor. In this system (known as the Hulse-Taylor binary pulsar or PSR 1913+16), both of the stars are collapsed objects called neutron stars. One of them is a pulsar that emits regular pulses which are used to measure the period shift of the shrinking orbit. The diagrams below shows an artist's illustration of the binary pulsar system and a plot of the changing period with time.



The figure to the right shows almost 30 years of data illustrating the changing orbit of the Hulse-Taylor binary pulsar. The measured points (orange dots) are plotted along with the theoretical prediction from Einstein's theory (blue line). Derived by J. M. Weisberg and J. H. Taylor.



CPEPphysics.org

Summary

- We have created a variety of materials that might be useful to classes
- Big Ideas in Cosmology
  http://greatriverlearning.com/Cosmology

  Or contact me for examination access
- All NSF-funded materials available through http://epo.sonoma.edu/ligo
- New CPEP poster at: http://CPEPphysics.org

Now let's get busy!

- Build your own pulsars and watch them inspiral
- Play with the black hole spacetime hoop
- Explore the LIGO Open Science Center https://losc.ligo.org using tools in 2016 LIGO course or go directly there using https://notebooks.azure.com/library/y5LSf4Z1s7k