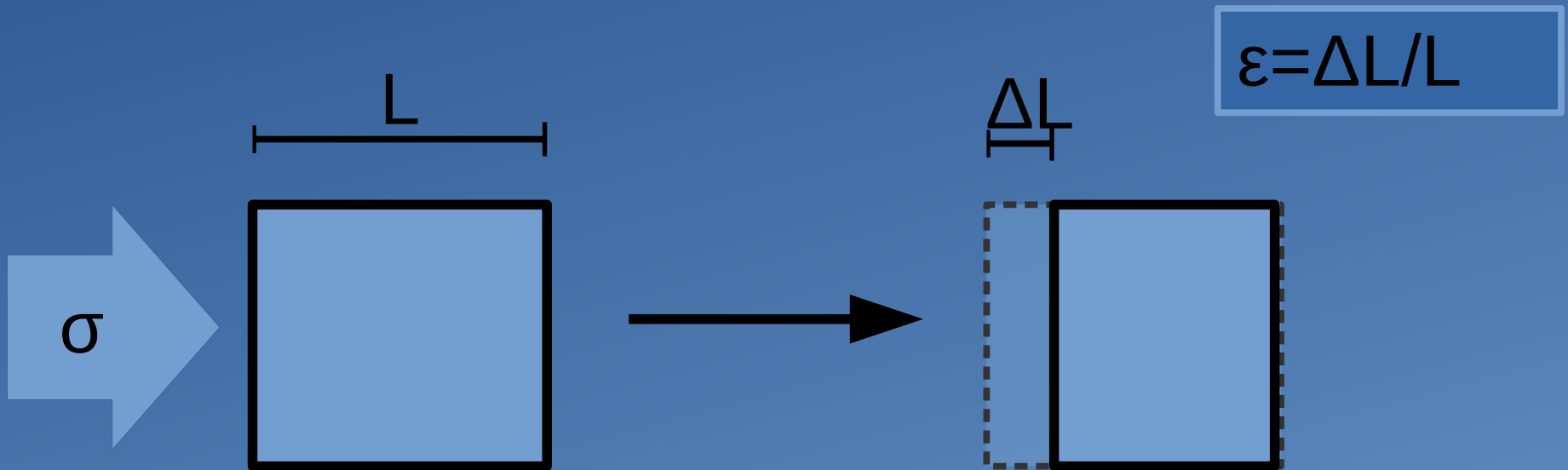


# What are gravitational waves?

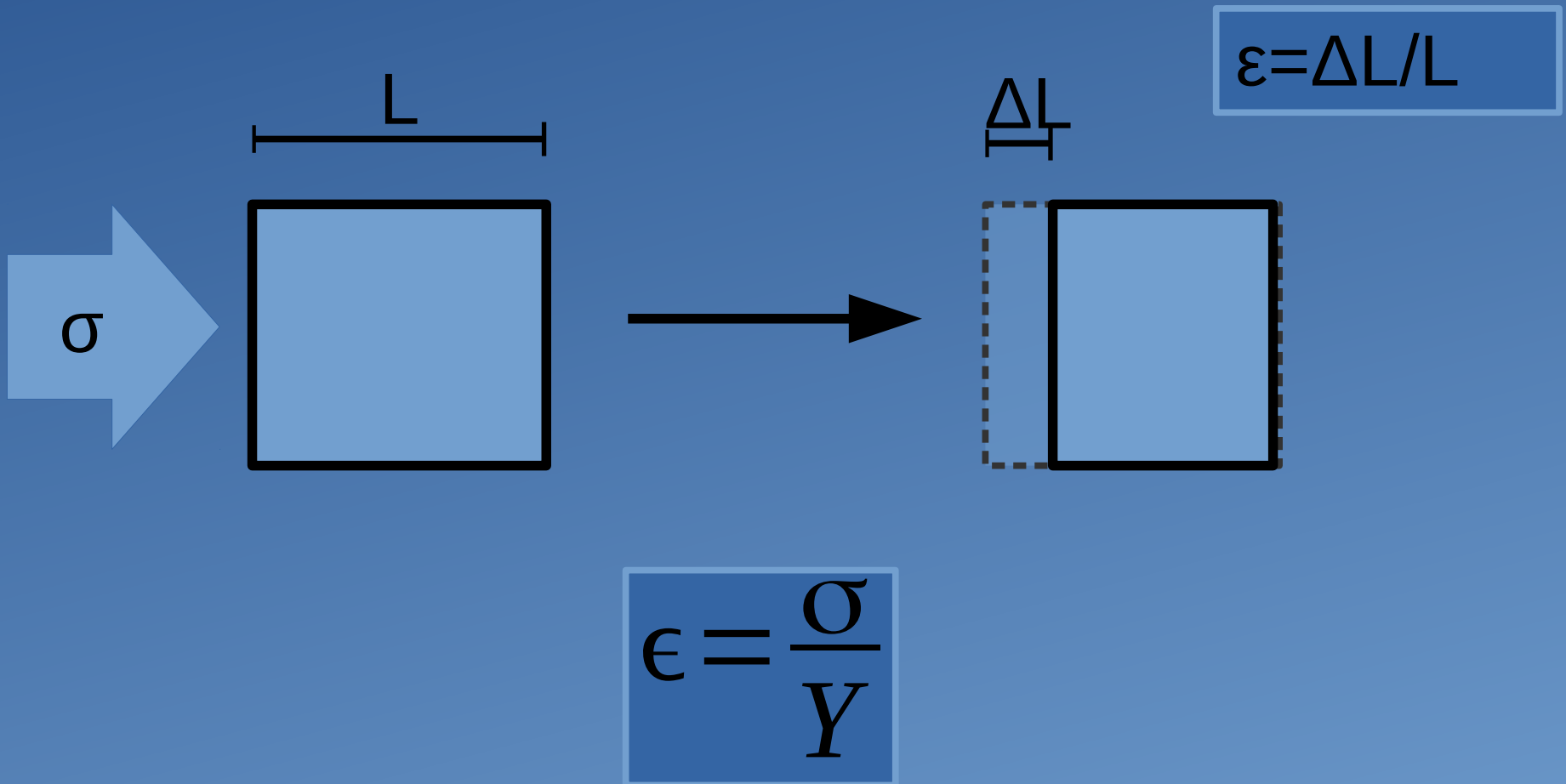
# What are gravitational waves?

## Strains in space

# Stress and Strain

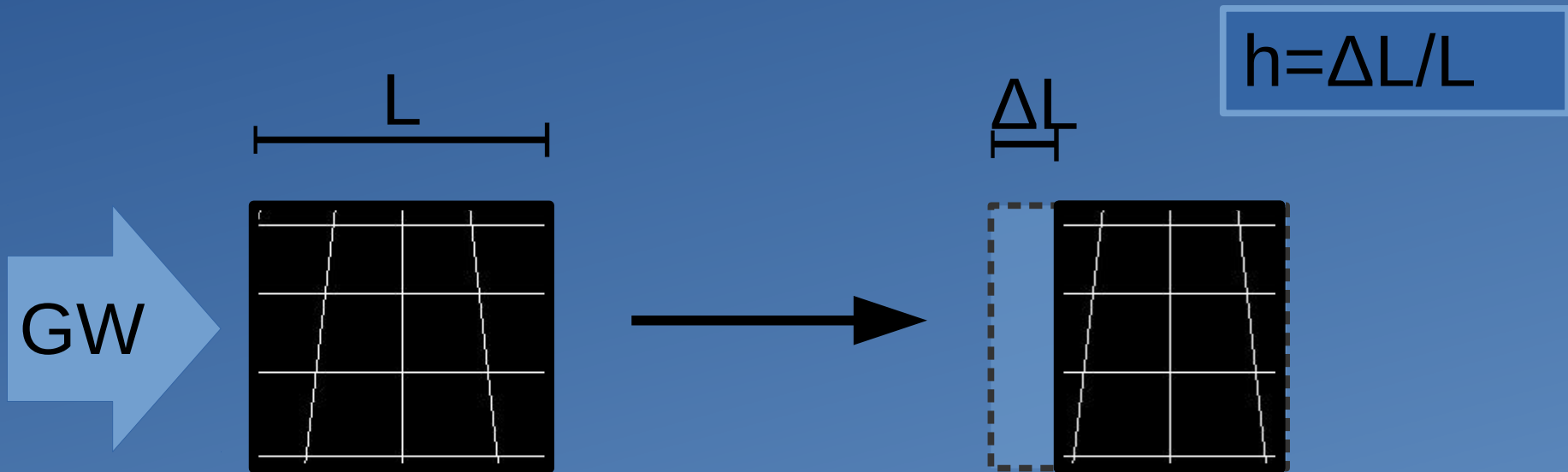


# Stress and Strain





# Stress and Strain



$$h = \frac{2G}{r} \frac{1}{c^4} \frac{\partial^2}{\partial t^2} \left[ D_{[jk]} \left( t - R/c \right) \right]^{TT}$$

# Stiffness of Space

$$\epsilon = \frac{\sigma}{Y}$$

$$h = \frac{2G}{r c^4} \frac{\partial^2}{\partial t^2} \left[ D_{[jk]}(t - R/c) \right]^{TT}$$

# Stiffness of Space

Typical Material:  
 $Y \sim 10^{10}$

$$\epsilon = \frac{\sigma}{Y}$$

$$h = \frac{2G}{r c^4} \frac{\partial^2}{\partial t^2} \left[ D_{[jk]}(t - R/c) \right]^{TT}$$

# Stiffness of Space

Typical Material:  
 $Y \sim 10^{10}$

$$\epsilon = \frac{\sigma}{Y}$$

Space:  
 $c^4/G \sim 10^{44}$

$$h = \frac{2G}{rc^4} \frac{\partial^2}{\partial t^2} \left[ D_{[jk]}(t - R/c) \right]^{TT}$$

# Stiffness of Space

Typical Material:  
 $Y \sim 10^{10}$

$$\epsilon = \frac{\sigma}{Y}$$

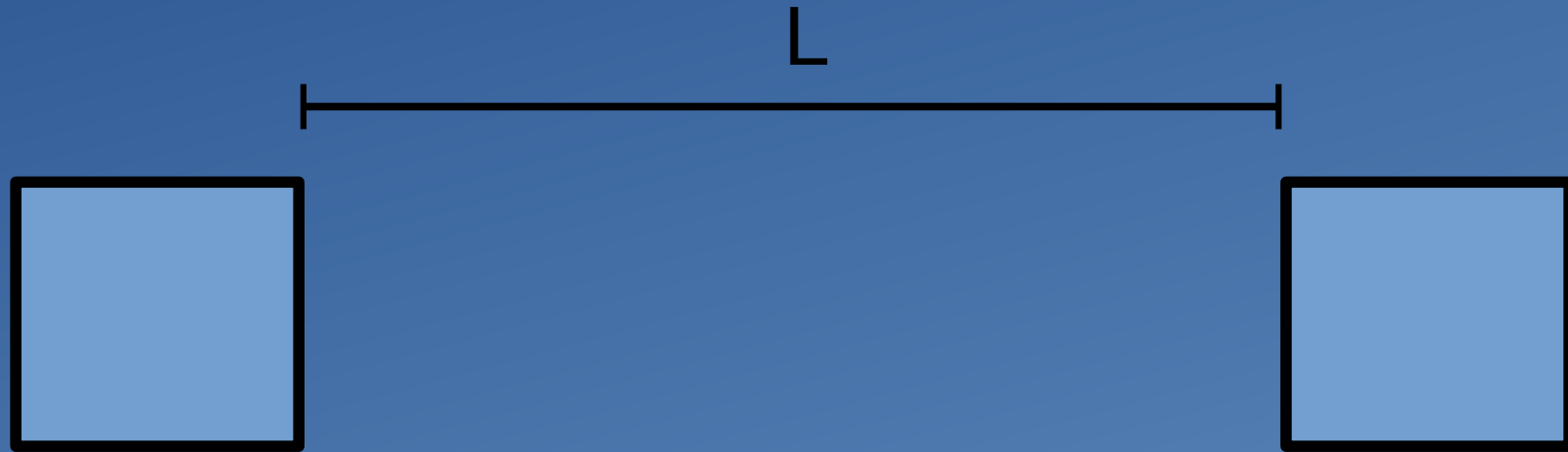
Space:  
 $c^4/G \sim 10^{44}$

Space is stiff!

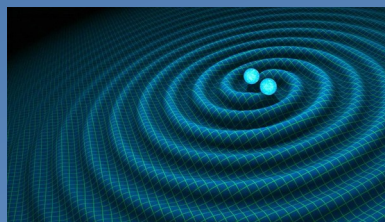
Gravitational waves are tiny!

$$h = \frac{2G}{rc^4} \frac{\partial^2}{\partial t^2} [D_{[jk]}(t - R/c)]_{TT}$$

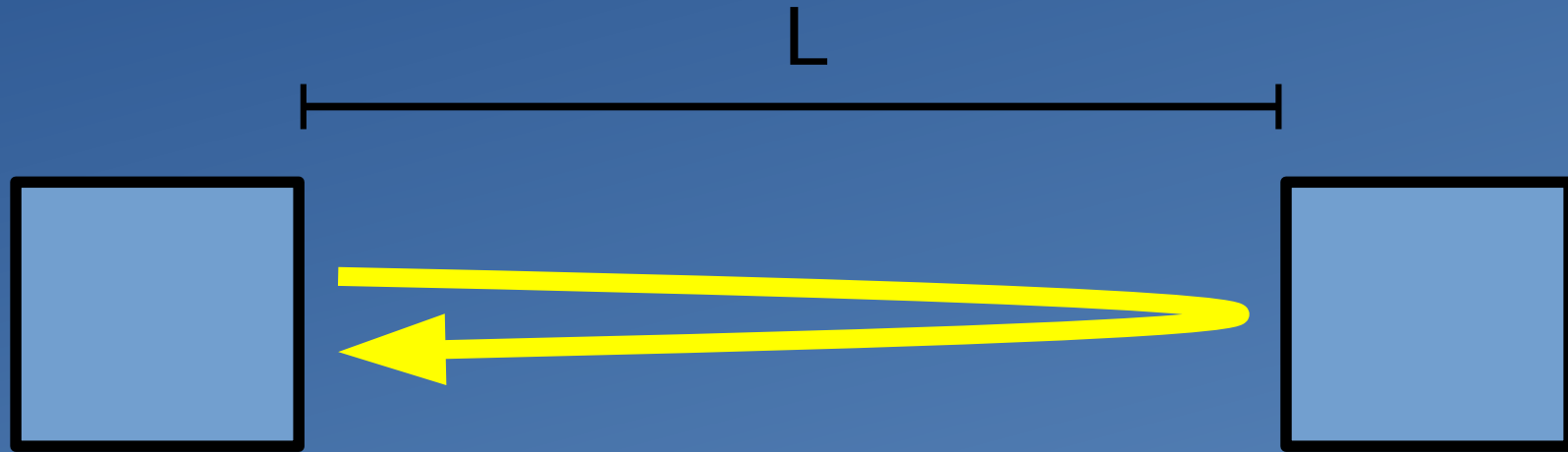
# Gravitational Wave Effects



# Gravitational Wave Effects

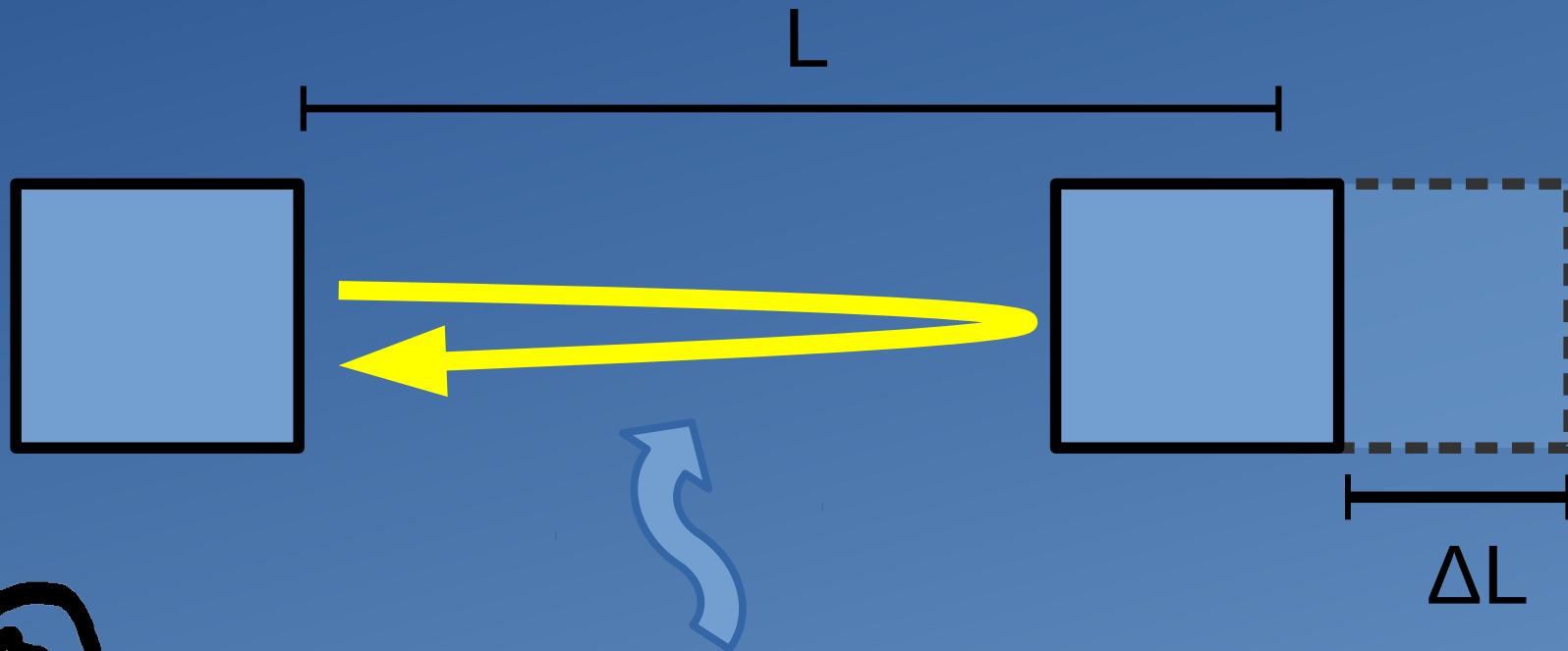


# Gravitational Wave Effects

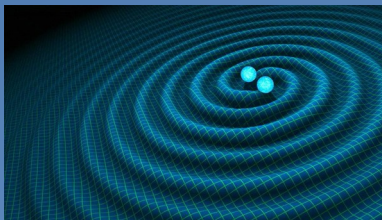




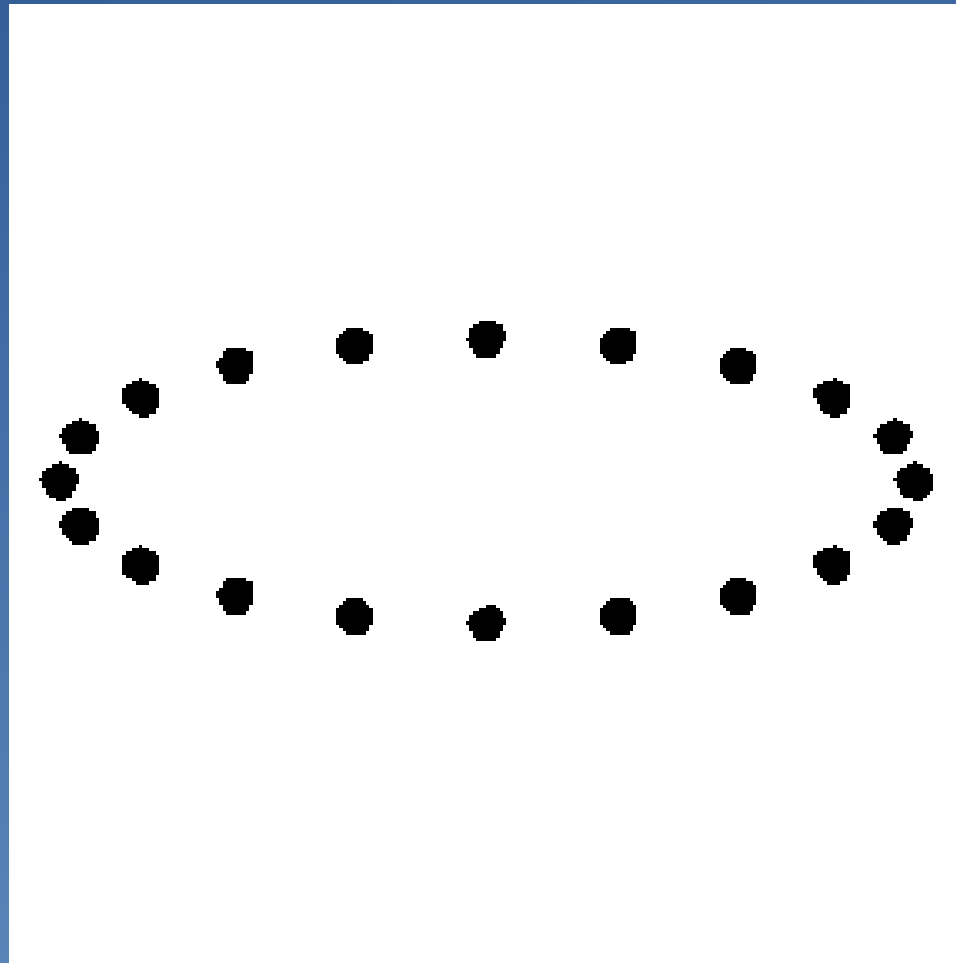
# Gravitational Wave Effects



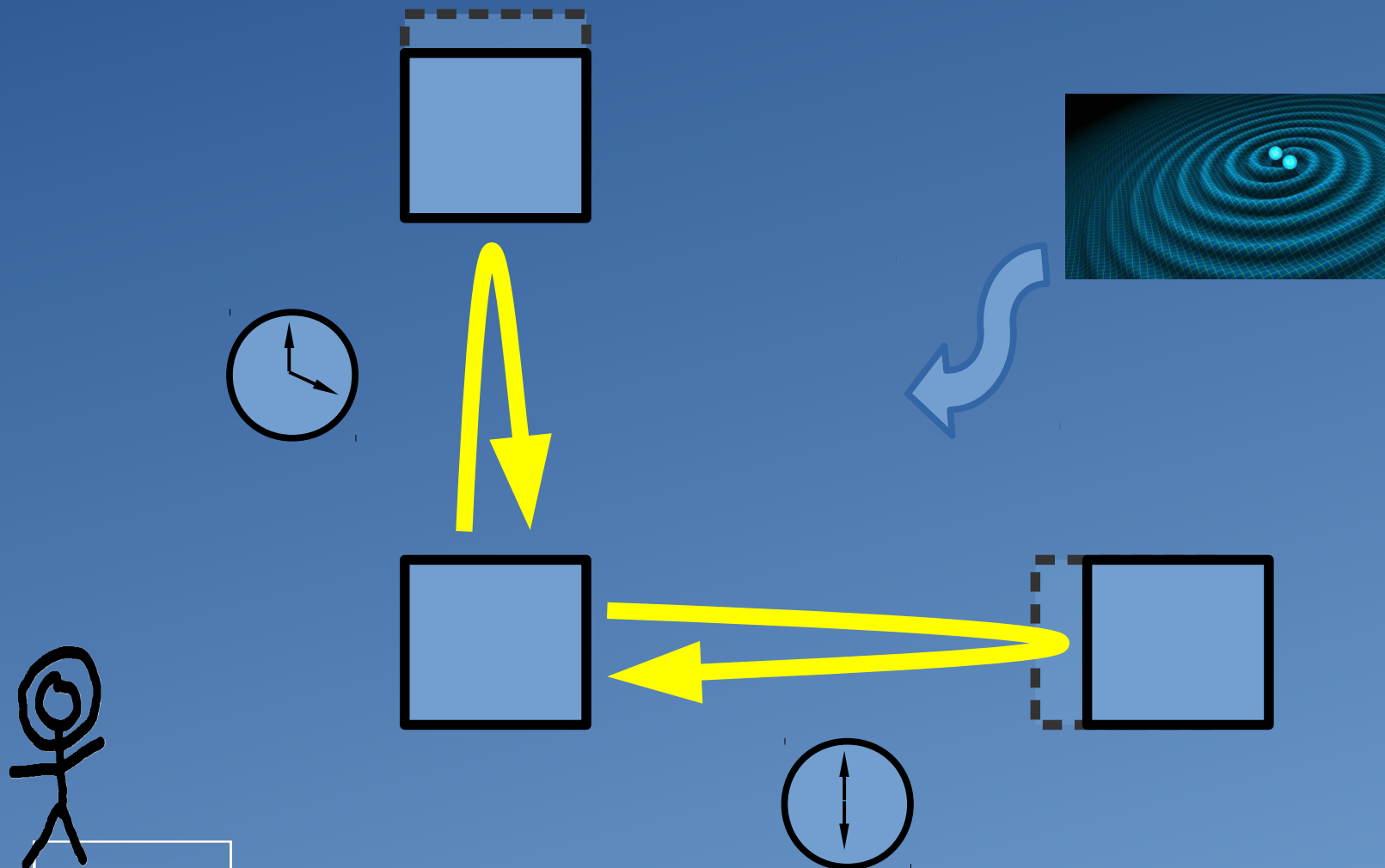
$$\Delta L = c\Delta t$$



# Gravitational Wave Effects



# Gravitational Wave Effects

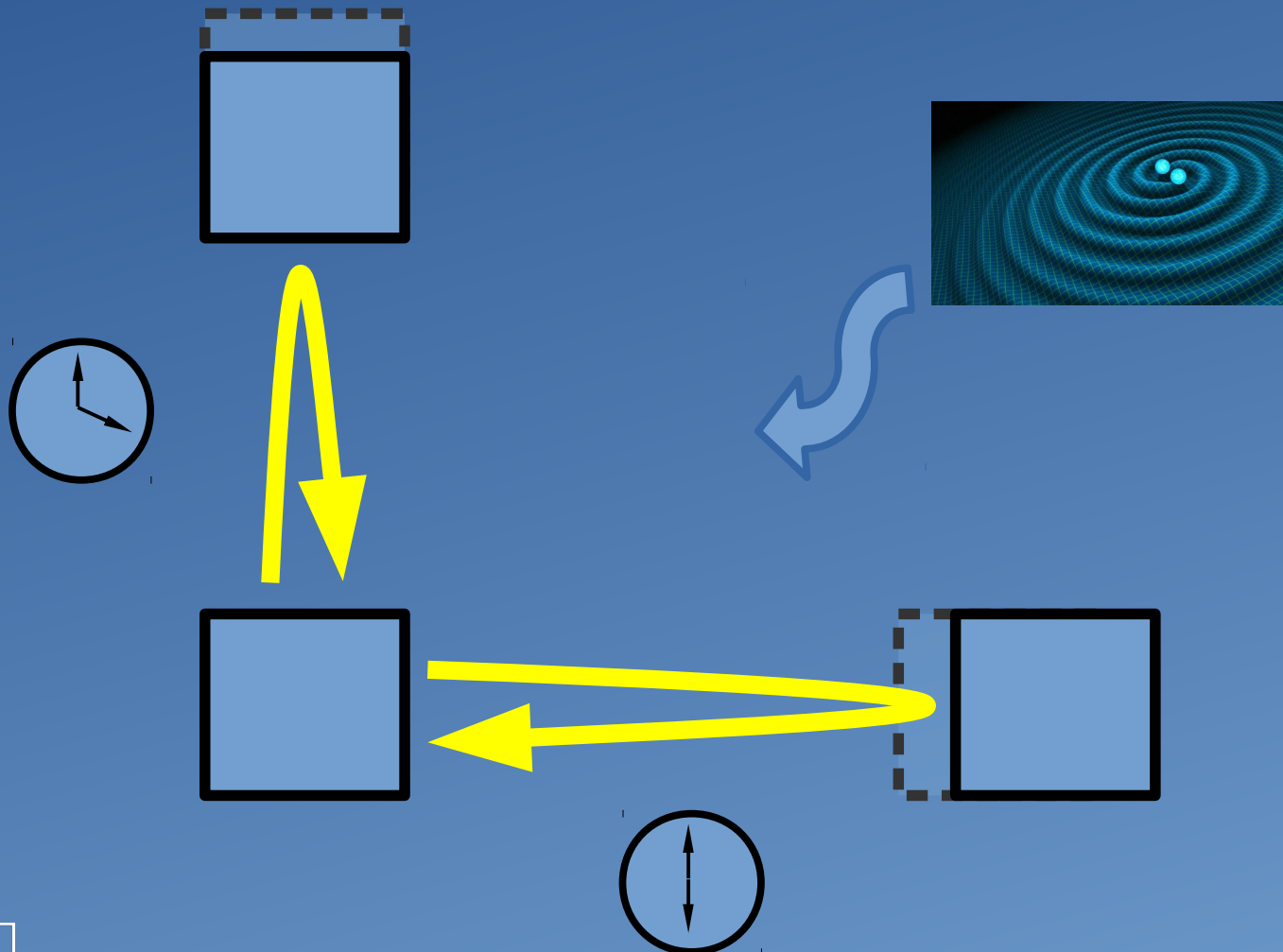


# How are gravitational waves really detected?

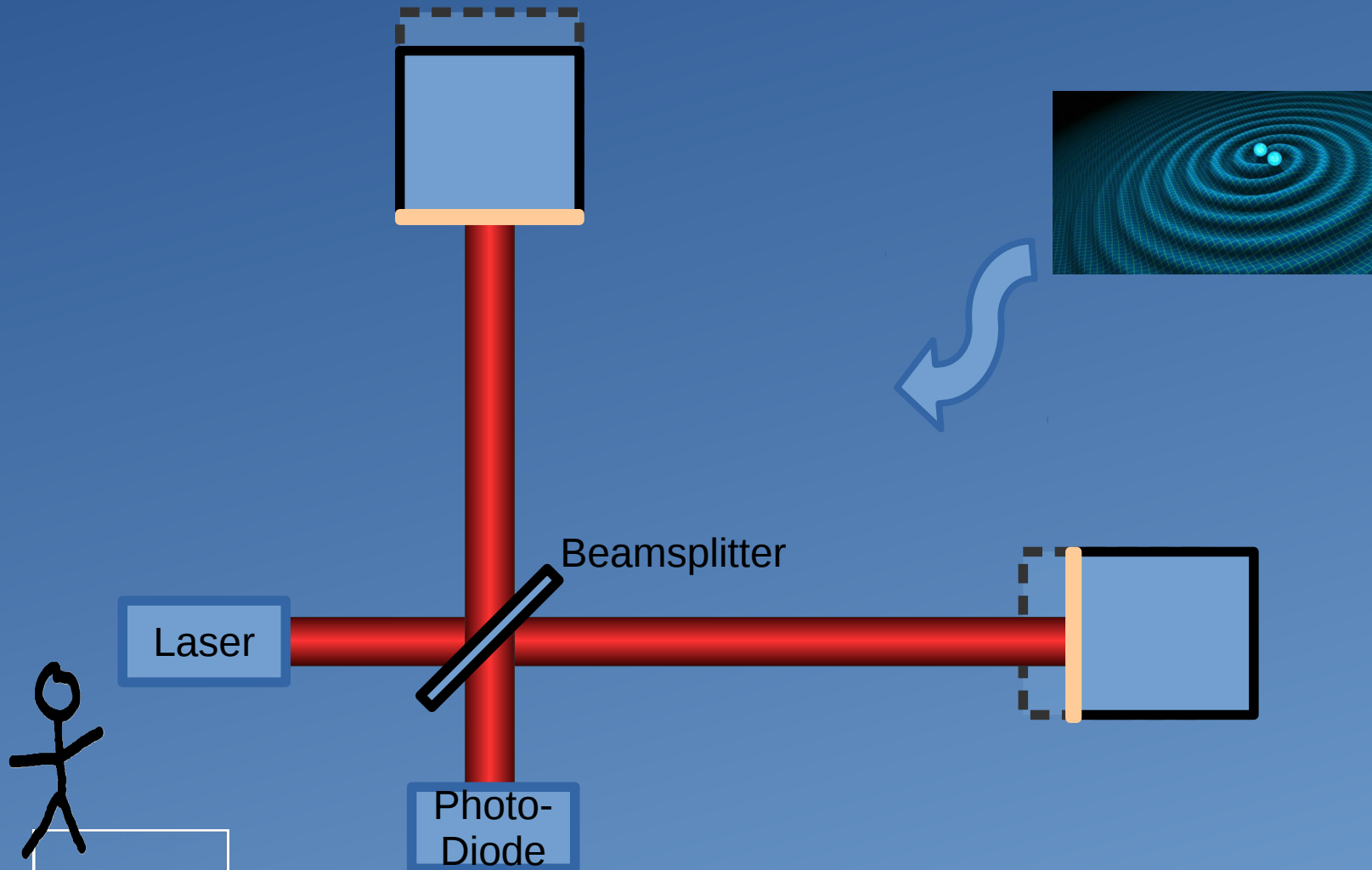
How are gravitational waves  
really detected?

Interferometers

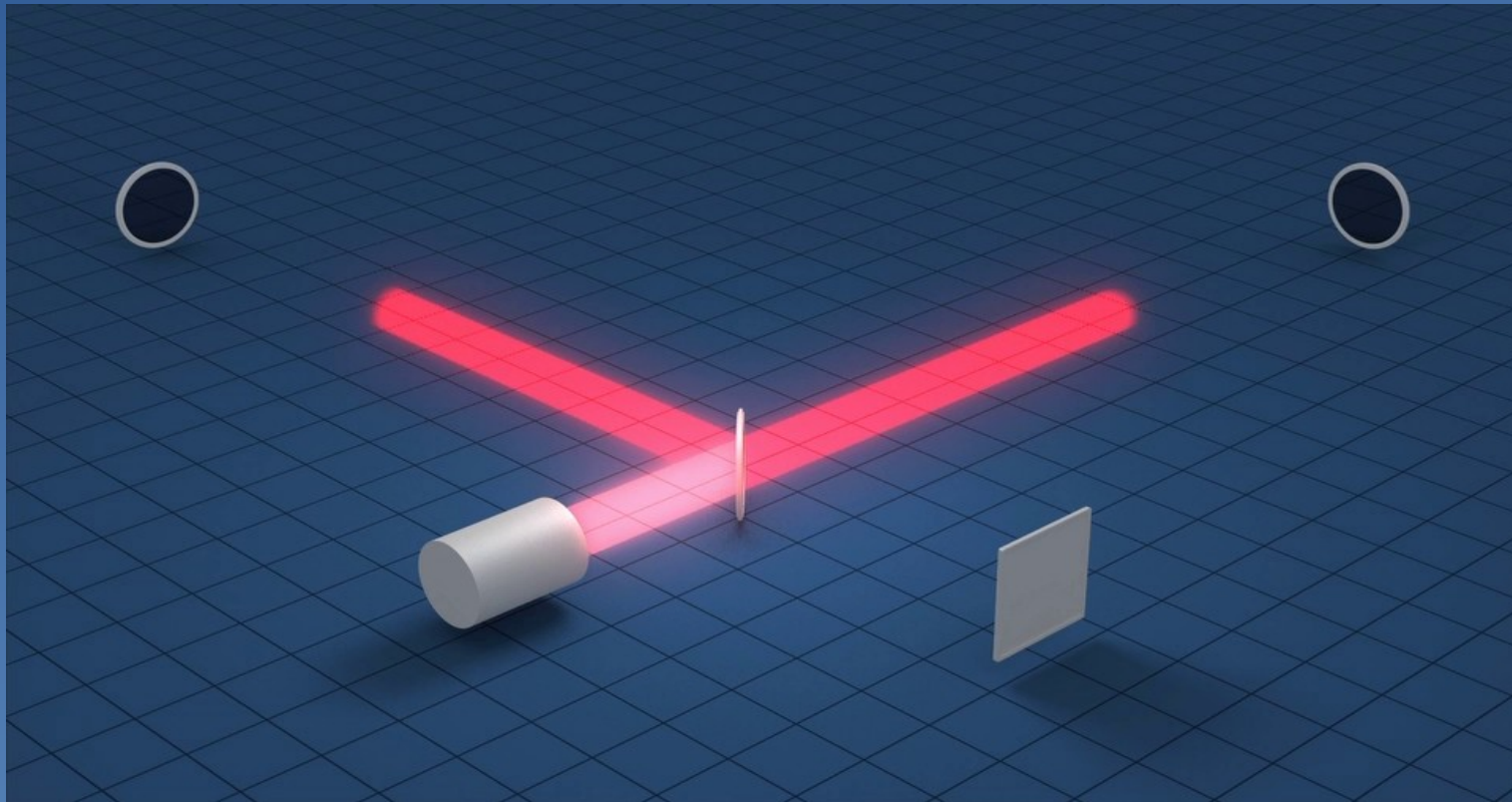
# Gravitational Wave Detection



# Gravitational Wave Detection

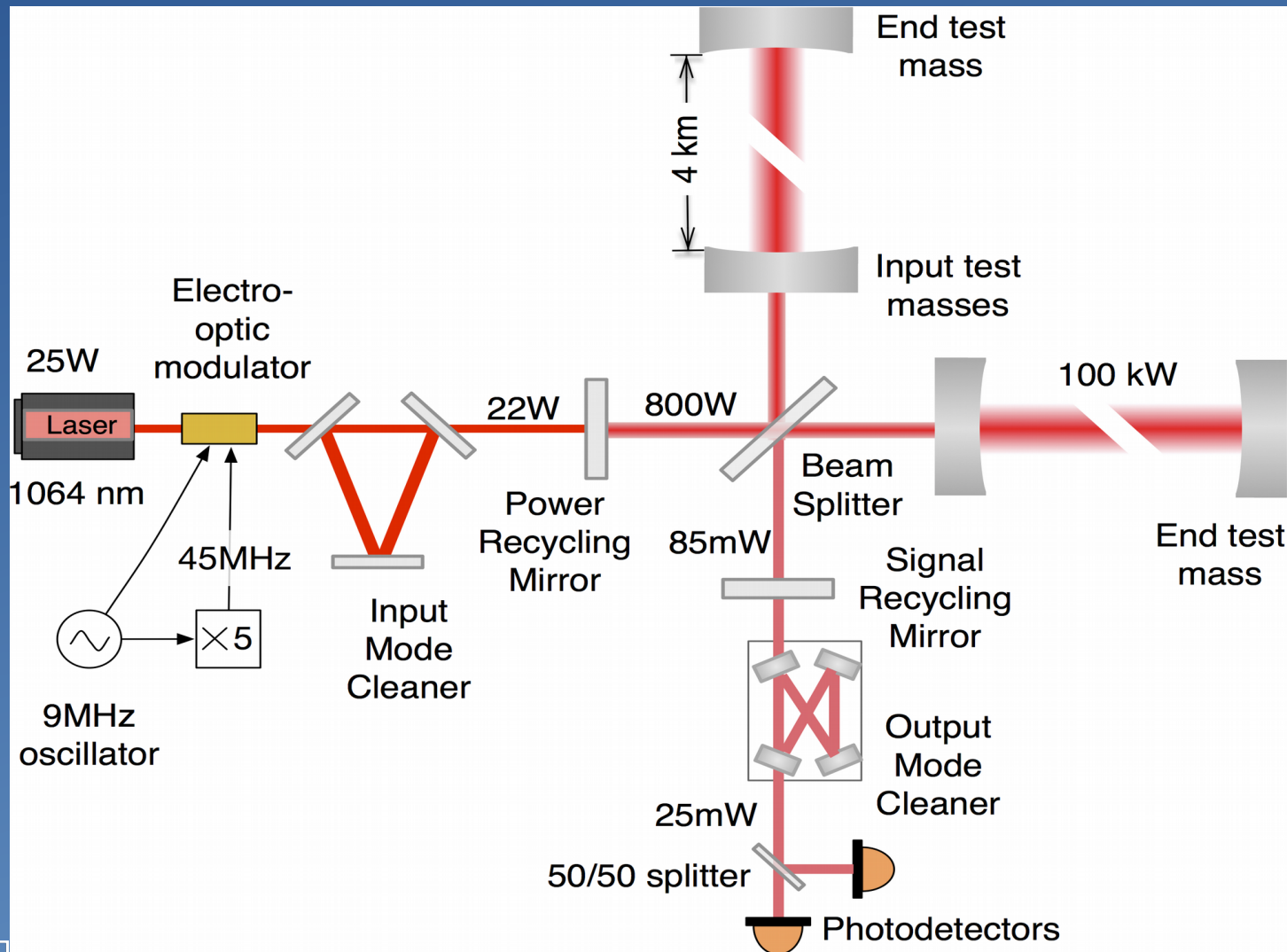


# Gravitational Wave Detection

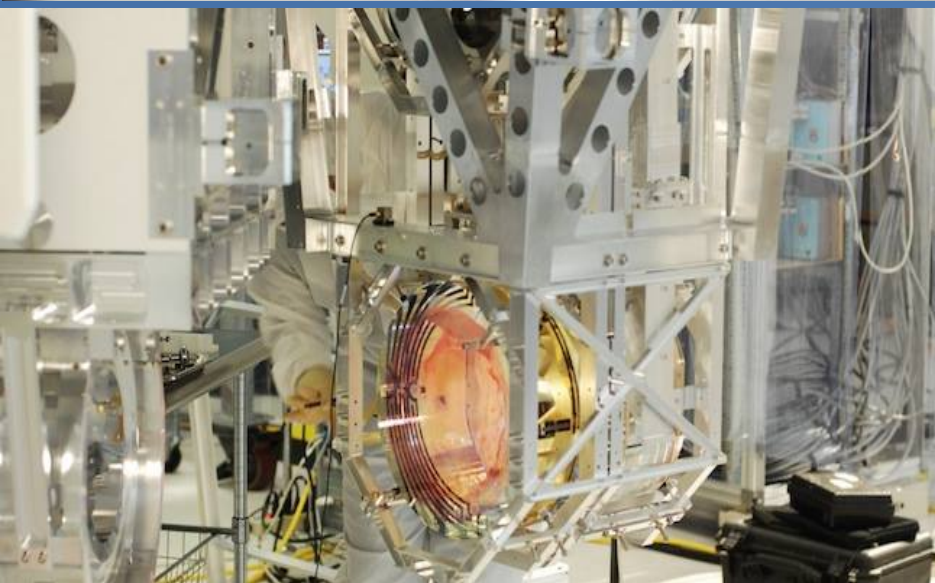
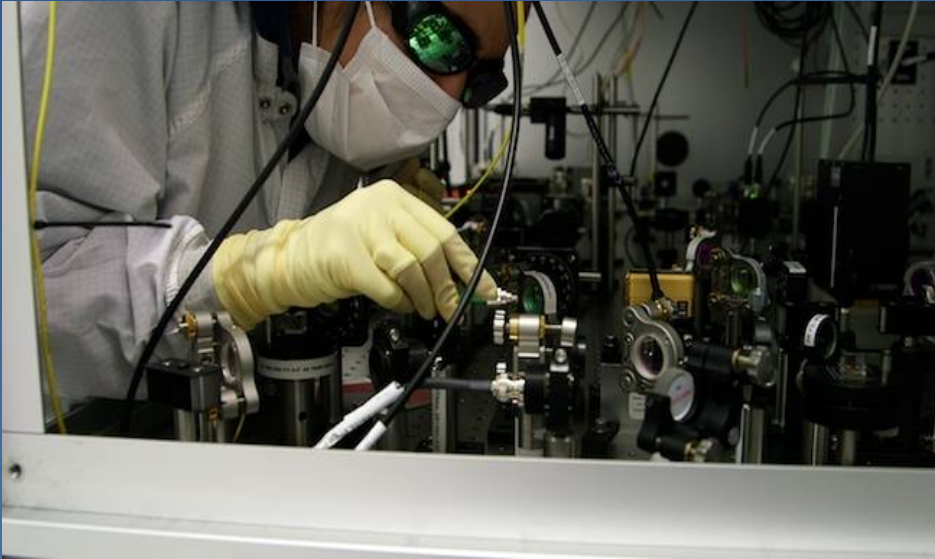




# Gravitational Wave Detection

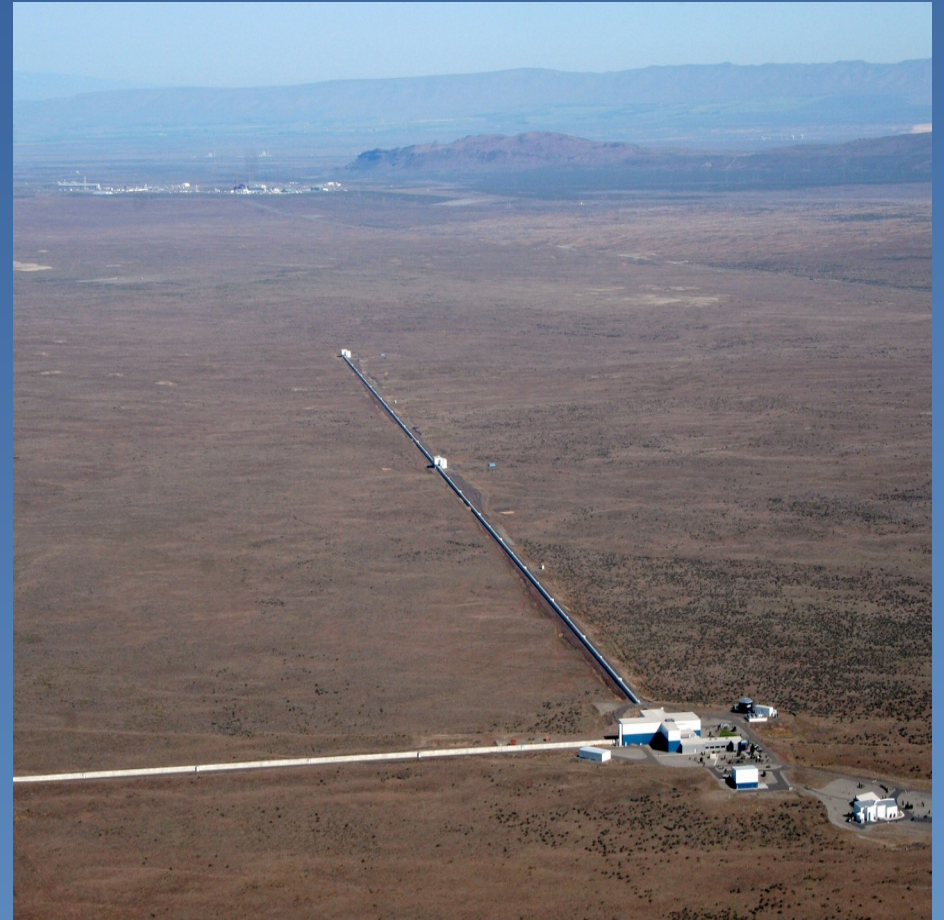


# Gravitational Wave Detection





# Gravitational Wave Detection





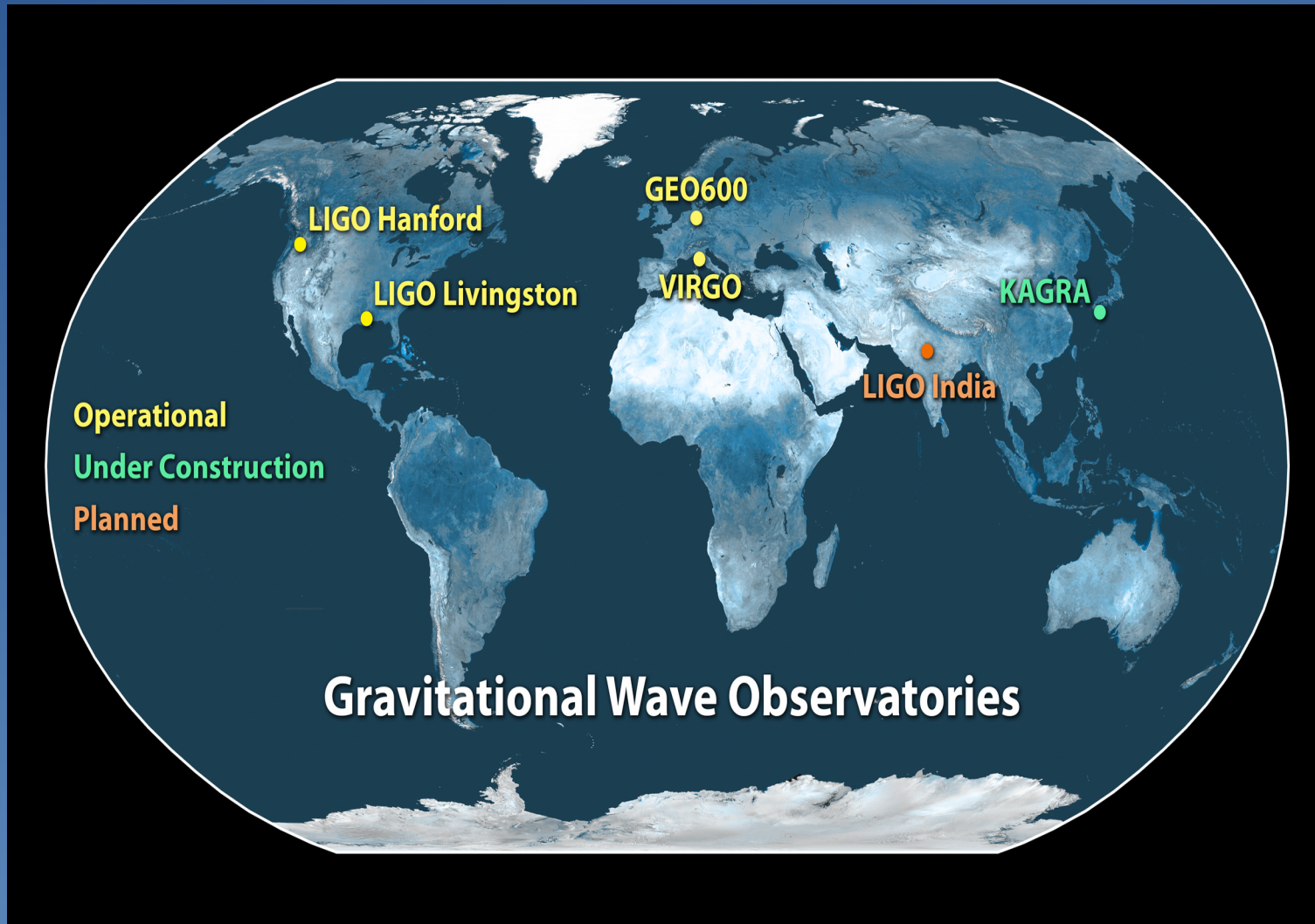


# LIGO Scientific Collaboration

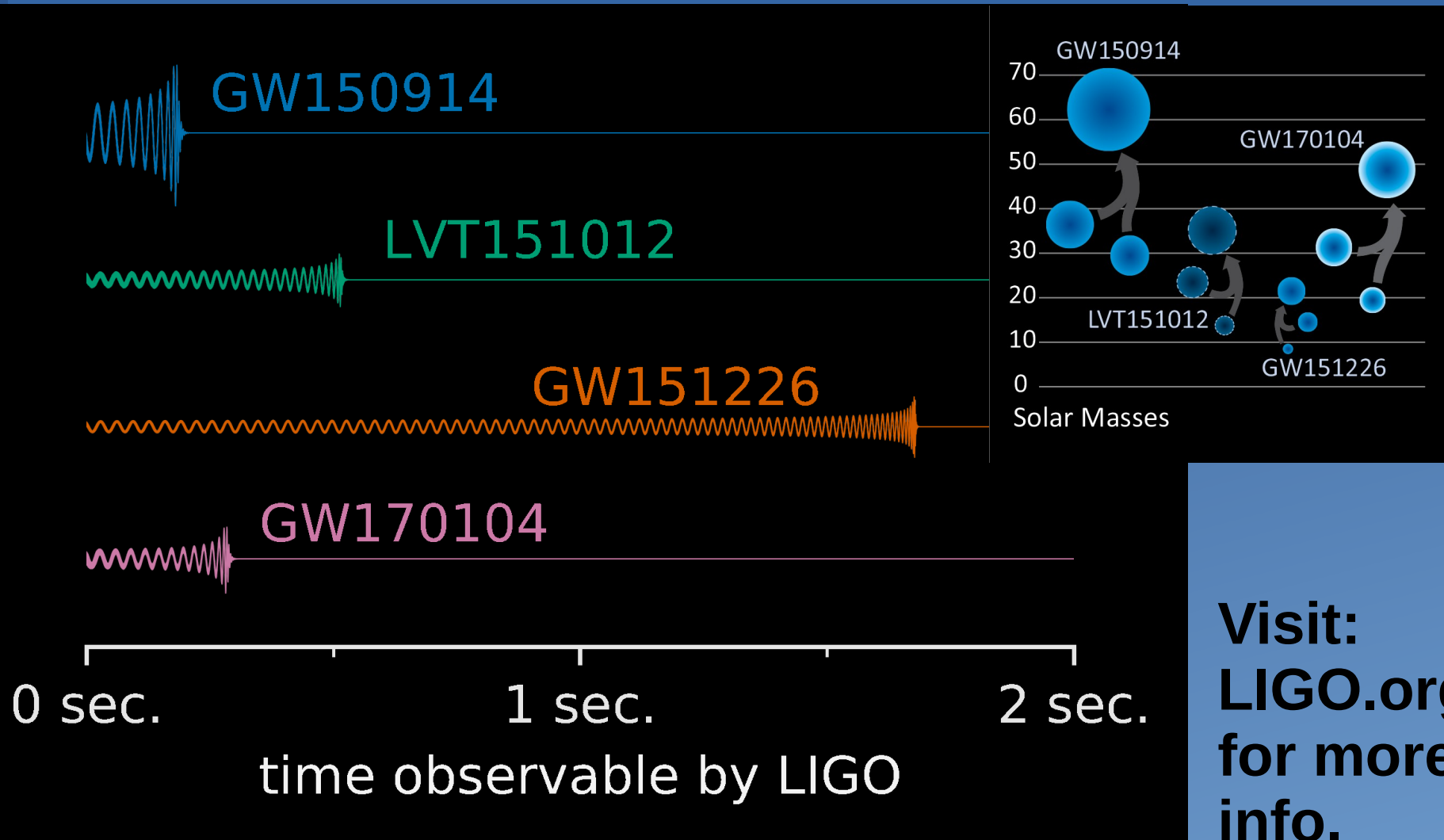




# LIGO Scientific Collaboration



# It Works!



Visit:  
**LIGO.org**  
for more  
info.

# ligo.org

LSC's main global communication tool.

## Key products:

- updates on LSC news/events.
- “detection” pages (links to publications, press releases, related multimedia).
- science summaries.
- collecting/curating resources of the EPO group.
- general info about the LSC.

LIGO Scientific Collaboration

Detections News About LIGO science Educational resources Multimedia For researchers LIGO Lab site

## LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Lightcurve from *Fermi*/GBM (50 – 300 keV)

Gravitational-wave time-frequency map

NEWS

- Mar 21, 2018 Read the March 2018 issue of LIGO Magazine
- Nov 15, 2017 LIGO and Virgo announce black hole merger detected in June 2017
- Oct 16, 2017 LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

PRESS RELEASES

- Oct 16, 2017 LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars
- Sep 27, 2017 Gravitational waves from a binary black hole merger observed by LIGO and Virgo
- Jun 1, 2017 LIGO Detects Gravitational Waves for Third Time

2017 Nobel Prize in Physics

LIGO Scientific Collaboration

Detections News About LIGO science Educational resources Multimedia For researchers LIGO Lab site

## DETECTIONS

Information about gravitational-wave detections made by LIGO to date.

Jump to a separate page for a specific event (listed in reverse-chronological order), or see the [General Detection Resources](#) section below for further information on LIGO detections.

- [GW170908](#)
- [GW170817](#) (First binary neutron star detection; first electromagnetic counterpart)
- [GW170104](#)
- [GW151226](#)
- [GW150914](#) (First detection)

## GENERAL DETECTION RESOURCES

### DOCUMENTS, WEBSITES, & MULTIMEDIA

- Full list of [LSC Publications](#). (See Runs O1 and higher for papers following the first detection.)
- [Science Summaries](#)
- [LIGO Open Science Center \(LOSC\)](#): Download LIGO data or explore tutorials on LIGO data analysis. See also their [data release page](#) for links to audio of LIGO events.
- [Timeline](#) and [brief history](#) of the LIGO project.
- The [Caltech Media Assets page](#) for [GW150914](#) contains a wealth of useful documents, graphics, and video.
- [Sounds of Spacetime](#): A website that explains LIGO detections and gravitational-wave physics via the analogy between gravitational waves and audio signals. (Montclair State University)
- [Black Hole Bubble Diagram](#): Interactive graphics showing known stellar-mass black holes from gravitational-wave candidates and X-ray binaries. (Cardiff University School of Physics and Astronomy)
- [LIGO Gravoscope](#): An interactive tool that lets you compare visions of the Universe in a range of wavelengths. Also shows locations of detected gravitational-wave signals. (Cardiff University Astronomy and Astronomy Instrumentation Groups)
- [Gravily Spy](#): a citizen-science project to help LIGO search for gravitational waves by improving glitch classification.
- [Einstein@Home](#): use your computer's idle processing time to help search for pulsars using gravitational wave, radio, and gamma-ray data.
- [Educator's Guide](#): Contains background material on gravitational waves and classroom activities that align with K-12 science standards. (Sonoma State University)
- [Image gallery](#) hosted at the LIGO Lab site.
- [LSC Youtube Channel](#), [Facebook page](#), and [Twitter page](#)
- "Chirp" ringtones from the first two LIGO detections. ([Instructions](#)). [GW150914](#) [[m4r file](#) (iPhone) | [mp3 file](#) (Android)]; [GW151226](#) [[m4r file](#) (iPhone) | [mp3 file](#) (Android)]

## AT A GLANCE

GW150914 signal observed by the two LIGO observatories at Livingston, Louisiana, and Hanford, Washington. The signals came from two merging black holes each weighing less than the mass of our sun, lying 1.3 billion light-years away. The top two plots show data from Livingston and Hanford, along with the predicted shapes for the waveform. These predicted waveforms show what two merging black holes should look like according to the equations of Albert Einstein's general theory of relativity, along with the instrument's event-present noise. Time is plotted on the X-axis and strain on the Y-axis.

## Black Holes of Known Mass

New Population of Binary Black Holes. LIGO and Virgo have discovered a new population of black holes with masses that are larger than what had been seen before with X-ray studies alone. The three previously confirmed detections by LIGO (GW150914, GW151226, GW170104) plus one low-confidence detection (GW170723), are shown along with the fourth confirmed detection (GW190521), the latter was observed by Virgo and both LIGO observatories. These point to a population of stellar-mass binary black holes that, since merged, are larger than 20 solar masses—larger than what was known before. (Image credit: LIGO/Caltech/Sonoma State (Aurore Simonnet))



# Science summaries

- one of our key EPO products.
- web page summaries of published papers; also pdf “flyer” versions for handouts at booths/ events.
- produced by members of paper writing teams and further edited by EPO.
- translations (~5 languages) for detection summaries.
- **More than 80 summaries since 2011**
- Now core part of PWT responsibilities, assisted by EPO group



The screenshot shows the LIGO Scientific Collaboration website. The header includes the LSC logo and navigation links for Detectors, News, About, LIGO science, Educational resources, Multimedia, For researchers, and LIGO Lab site. The main content area is titled 'SUMMARIES OF LSC SCIENTIFIC PUBLICATIONS' and features a section for 'DETECTION PAPERS'. It lists two papers: GW170805 (Nov 15, 2017) titled 'LIGO's Lightest Black-Hole Binary?' and GW170817 (Oct 15, 2017) titled 'Observation of Gravitational Waves from a Binary Neutron Star Inspiral'. The GW170817 entry includes a list of companion papers and translations. On the right, there is a section titled 'LOOKING DOWN A DETECTOR ARM' with an image of two people looking at a large detector arm.



## THE DAWN OF MULTI-MESSENGER ASTROPHYSICS: OBSERVATIONS OF A BINARY NEUTRON STAR MERGER

On August 17, 2017, astronomers around the world were alerted to gravitational waves observed by the *Advanced LIGO* and *Advanced Virgo* detectors. This gravitational wave event, now known as GW170817, appeared to be the result of the merger of two neutron stars. Less than two seconds after the GW170817 signal, NASA's Fermi satellite observed a gamma-ray burst, now known as GRB170817A, and within minutes of these initial detections telescopes around the world began an extensive observing campaign. The Swope telescope in Chile was the first to report a bright optical source (SSS17a) in the galaxy NGC 4993 and several other teams independently detected the same transient over the next minutes and hours. For the next several weeks astronomers observed this location with instruments sensitive across the electromagnetic spectrum; these observations provide a comprehensive view of this cataclysmic event starting 100 seconds before merger until several weeks after. The observations support the hypothesis that two neutron stars merged in NGC 4993 - producing gravitational waves, a short-duration gamma-ray burst, and a kilonova. GW170817 marks a new era of multi-messenger astronomy, where the same event is observed by both gravitational waves and electromagnetic waves.

### INTRODUCTION

The idea of a *neutron star* (NS) was first presented over eighty years ago in 1934, but it was another 33 years before they were observed. In 1967 X-ray emission from *Scorpius X-1* was determined to be from a NS, and later the same year the first *radio pulsar* was discovered. Since then several binary neutron star (BNS) systems have been discovered, including the *Hulse-Taylor binary*, a BNS where one of the NSs is a pulsar. BNS have provided strong observational tests of *General Relativity* including the first firm evidence for the existence of *gravitational waves* (GWs). Since the early days of LIGO, BNS mergers have been considered a primary target for gravitational wave observations.

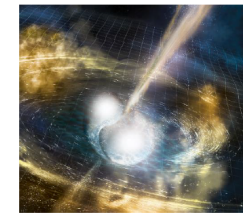
In the mid-1960s *gamma-ray bursts* (GRBs) were discovered by the Vela satellites, and later established to be of cosmic origin. Determining the sources of GRBs has been one of the key challenges in high-energy astrophysics ever since. The idea that GRBs might be related to BNS mergers had been put forward early on and in 2005 the field experienced a breakthrough, when a short-duration gamma-ray burst (sGRB) was localized to a host galaxy, and multi-wavelength (X-ray, optical, radio) afterglows could be observed. These multi-wavelength observations provided evidence that sGRBs might be associated with BNS mergers or the merger of a NS with a black hole.

### A MULTI-MESSENGER DISCOVERY

On August 17, 2017 NASA's *Fermi* satellite and its *Gamma-ray Burst Monitor* (GBM) instrument sent an automatic alert about GRB170817A. It took about 6 minutes for automated LIGO data analysis to find that a candidate GW transient (later designated GW170817) had been detected at almost the same time at the LIGO-Hanford observatory. The GW was consistent with a BNS merger occurring less than 2 seconds before GRB170817A and the LIGO-Virgo rapid-response team manually inspected the data and issued an alert, reporting that a highly significant GW candidate was associated with the time of the GRB. Initial analysis of the data identified the area of the sky most likely to be the source of the GRB170817A and GW170817 signals, shown in Figure 1.

This event marked the first GW multi-messenger discovery; it was observed by both GWs and electromagnetic (EM) waves. With the area of the sky identified from the GW and gamma-ray signal, telescopes around the world focused their effort to make further observations associated with this source. There was a plethora of key observations that occurred at different electromagnetic wavelengths, as well as neutrino fluence measurements, and Figure 2 shows a timeline of the observations. The multi-wavelength observations were critical to the richness of this scientific discovery.

At the time of the alert for GW170817, the location of the source in the sky had set in Australia, but it was still well placed for observing by telescopes in South Africa and Chile. In the first few hours of Chilean darkness, the *Swope telescope* identified an optical transient (SSS17a) in the galaxy NGC 4993. Over the next two weeks, a network of ground-based telescopes and space-based observations followed up the initial detections, examine the



Artist's illustration of two merging neutron stars. The narrow beams represent the gamma-ray burst while the rippling spacetime grid indicates the isotropic gravitational waves that characterize the merger. Swirling clouds of material ejected from the merging stars are a possible source of the light that was seen at lower energies. Credit: National Science Foundation/LIGO/Sonoma State University/A. Simonet.

### FIGURES FROM THE PUBLICATION

For more information on these figures, see the full publication [here](#).

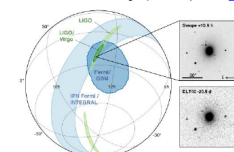
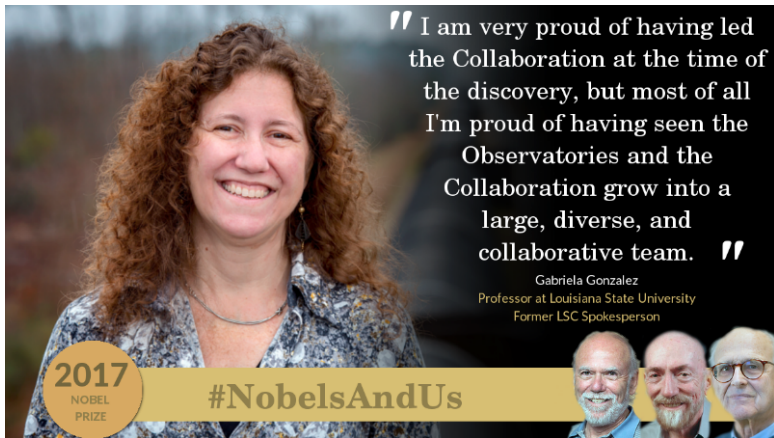
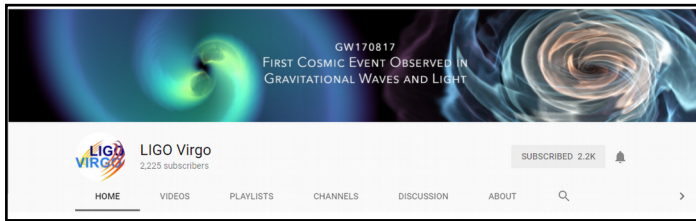


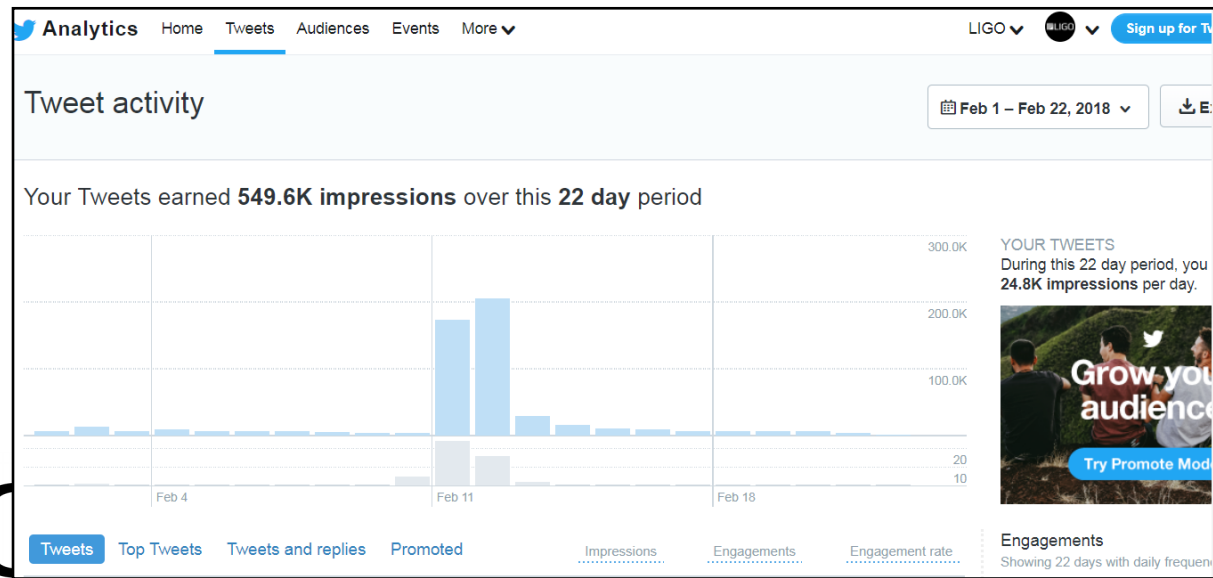
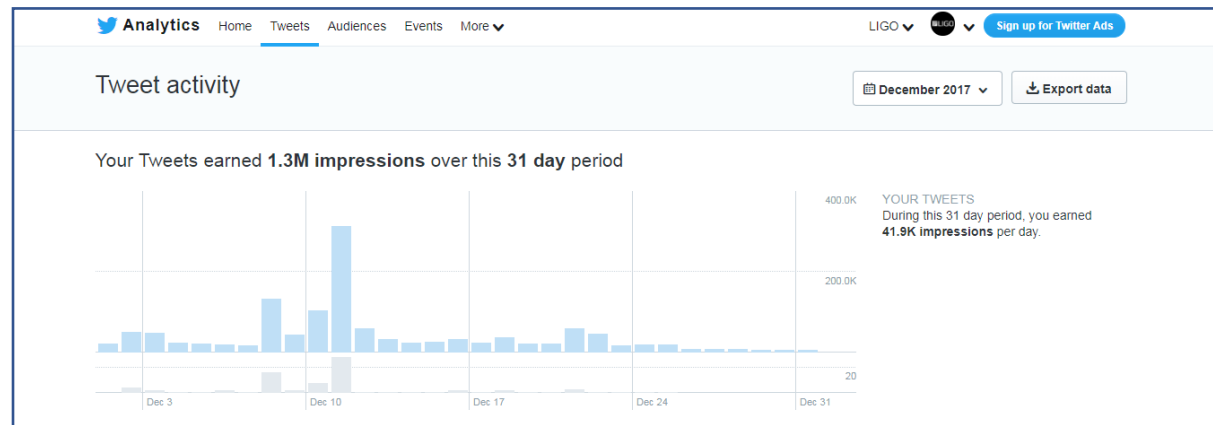
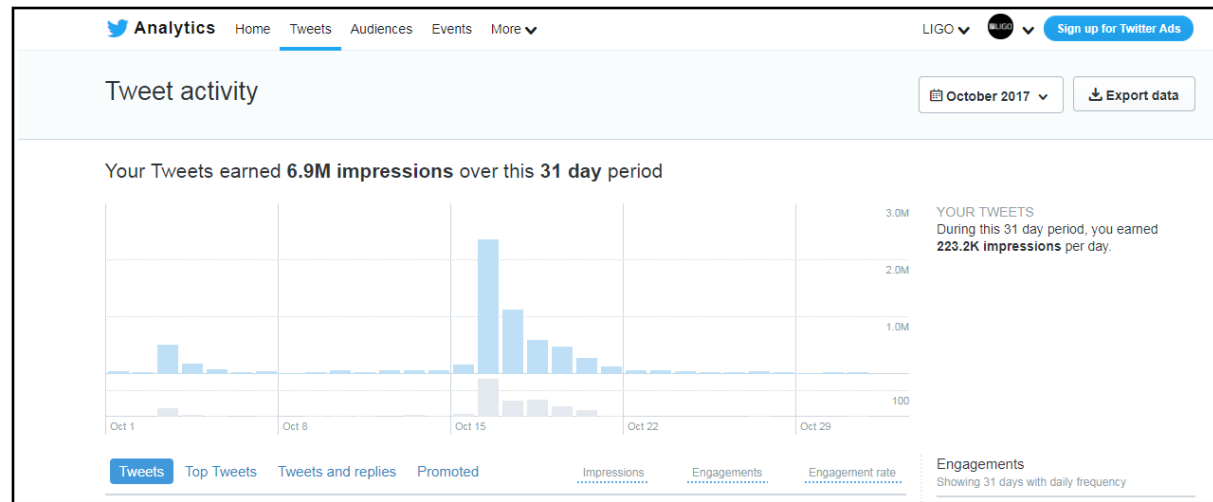
Figure 1 Localization of the gravitational-wave source and initial detections.

# EPO Social Media:



Aiming to improve social media coordination with laboratories, institutions, consortia and other GW projects.

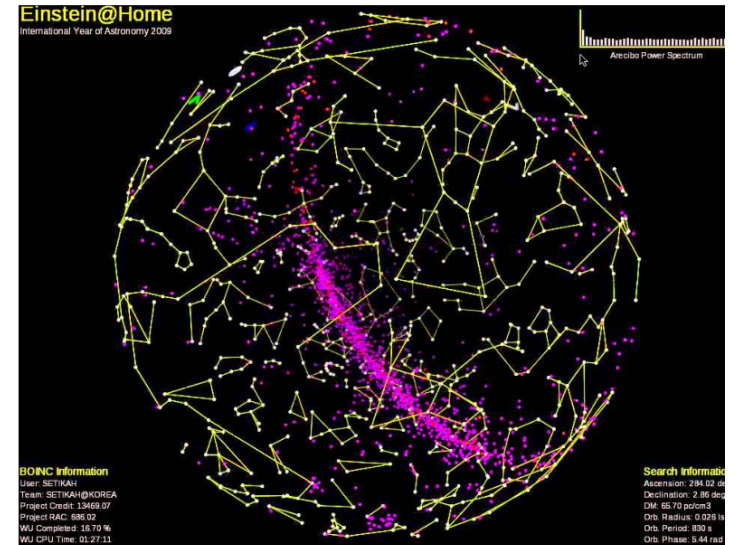
Thinking hard about how best to support O3 public alerts



# Citizen science: Einstein@home



- distributed computing project; analyzes data during your computer's idle time.
- search for continuous GWs from spinning neutron stars. Also look for new pulsars in radio or gamma-ray data.
- Key recent results:
  - 13 new gamma-ray pulsars (Jan. 2017).
  - most massive double neutron star system (Nov. 2016).
  - measurement of braking index of new gamma-ray pulsar (Nov. 2016).
  - 13 new radio pulsars discovered (Aug. 2016).
  - limits on GW amplitude and ellipticity from spinning neutron stars (Sep. 2016).



(einsteinathome.org)



# Citizen science: GravitySpy.org

- volunteers help classify LIGO glitches; train machine learning algorithm and identify new glitch classes.
- ~9000 volunteers, ~2.2 million glitches classified. (Aug 2017)
- currently using O2 data.

The screenshot shows the GravitySpy.org website interface. At the top is a navigation bar with the logo and links for ABOUT, CLASSIFY, TALK, COLLECT, and BLOG. Below the navigation bar is a blue banner with the text: "LIGO has announced its third gravitational-wave event! Look for a special surprise when classifying on workflow Neutron Star Merger and above." The main content area features a background image of the LIGO detector with the text: "Help scientists at LIGO search for gravitational waves, the elusive ripples of spacetime." Below this text are two buttons: "Learn more" and "Get started". At the bottom of the page, there are three spectrograms showing frequency (Hz) on the y-axis (ranging from 16 to 1024) and normalized energy on the x-axis. The first spectrogram shows a prominent peak at approximately 350 Hz. The second spectrogram shows a smaller peak at a similar frequency. The third spectrogram shows a horizontal band of energy at the bottom of the frequency range. To the right of the spectrograms, there is a social media widget that says "6 people are talking about Gravity Spy right now." and a "Join in" button.

# LIGO Open Science Center (LOSC)

Main public portal  
for LIGO data:

<https://losc.ligo.org/>

**key products:**

- h(t) data segments near detected events.
- past (S5, S6) and future data releases for science/observing runs.
- some data from publication figures.
- documentation and software tools for using data.
- python-based tutorials: play with data to extract detected signals.
- ~100 users/day



The screenshot shows the LIGO Open Science Center (LOSC) website. At the top, there is a blue header with the LIGO logo and the text "LIGO Open Science Center". Below the header, there is a navigation menu on the left with links for "Getting Started", "Tutorials", "Data", "Events", "Bulk Data", "Timelines", "My Sources", "Software", and "GPS ↔ UTC". On the right side, there is a "Welcome to the LIGO Open Science Center" message. Below this, there is a section titled "Discoveries from the LIGO detectors!" with a sub-section "released 2017 June 1: Event of January 4, 2017: GW170104: total mass 50".

**Open F2F workshop in March 2018**