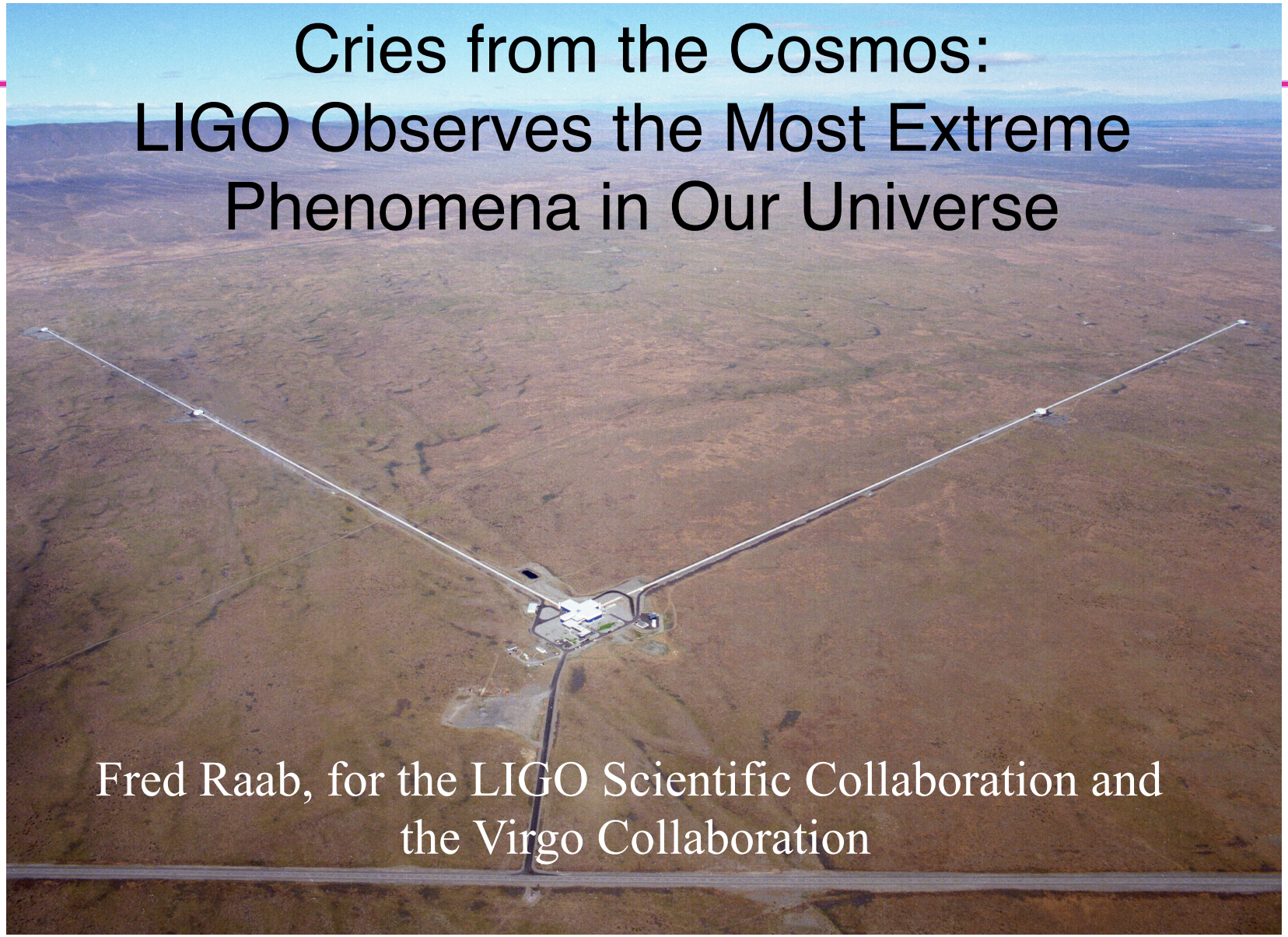
Cries from the Cosmos: LIGO Observes the Most Extreme Phenomena in Our Universe

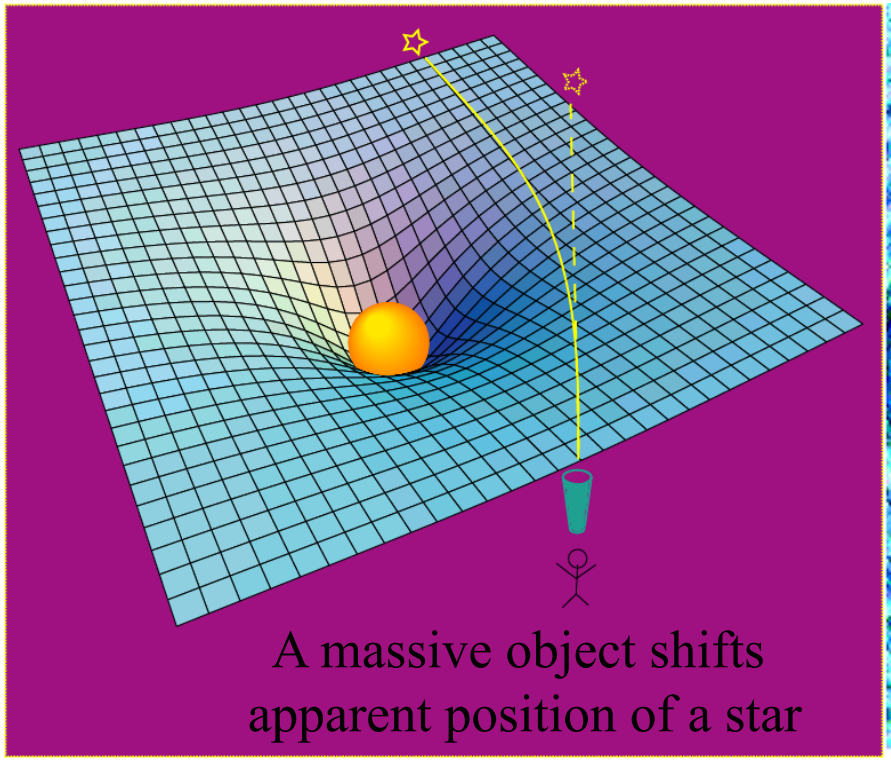


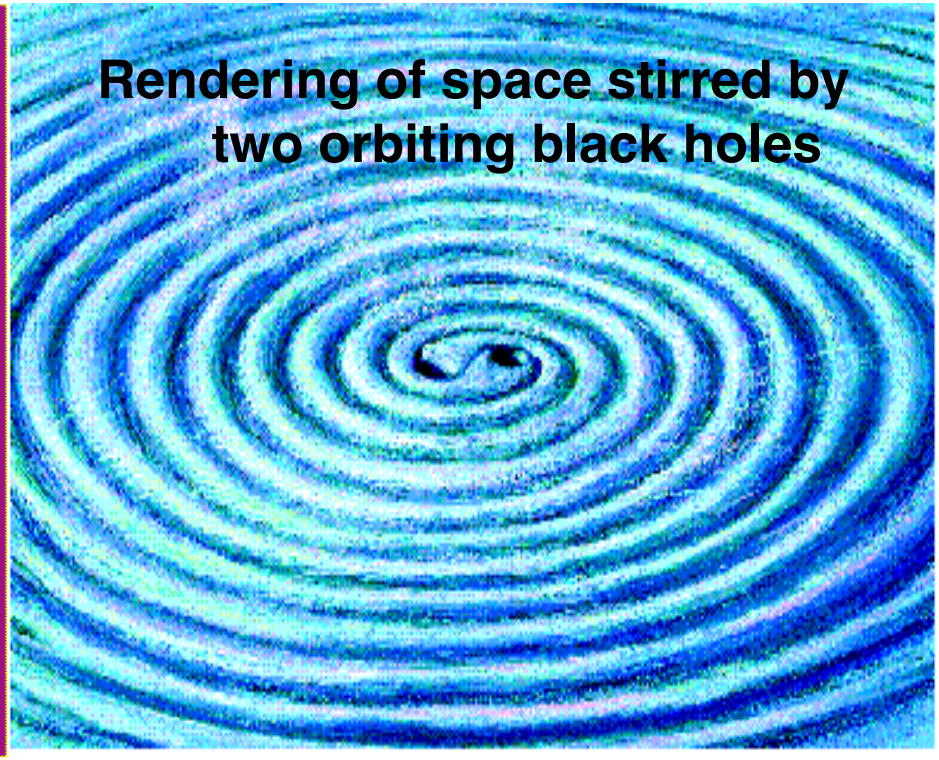
Fred Raab, for the LIGO Scientific Collaboration and the Virgo Collaboration

This is a story of discovery, written in the "spacequakes" created by the births and deaths of black holes. It is a story predicted a century ago. Learning how to read this story took half a century. The story was read first by a village of scientists spanning the globe, who then shared it with the rest of the world.

The stage for this story is space and time.

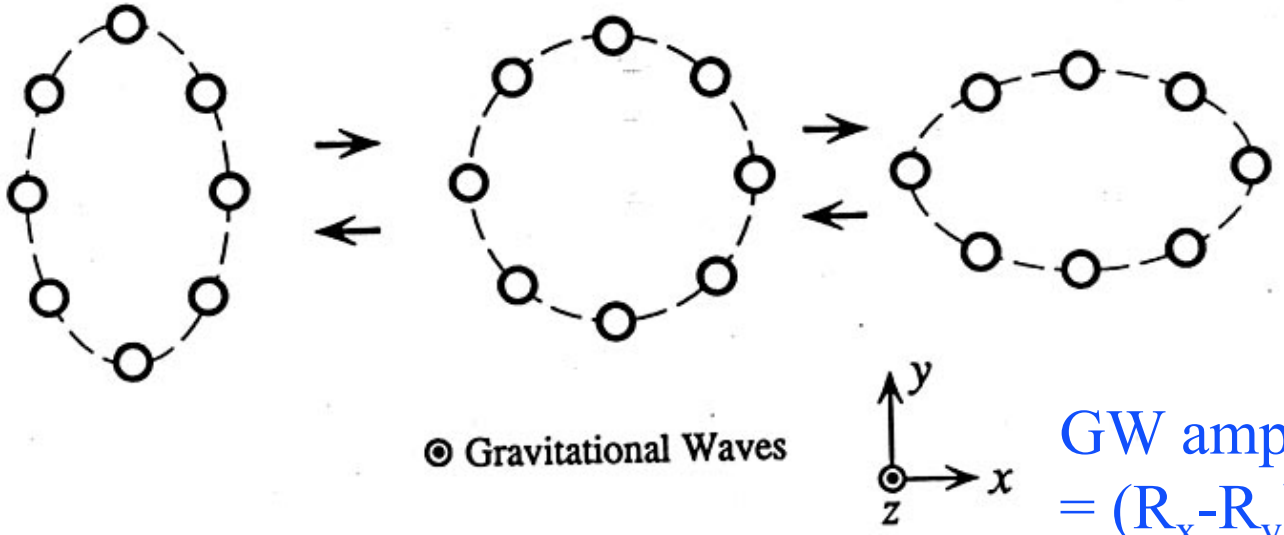
Einstein's General Relativity re-wrote the rules of space and time



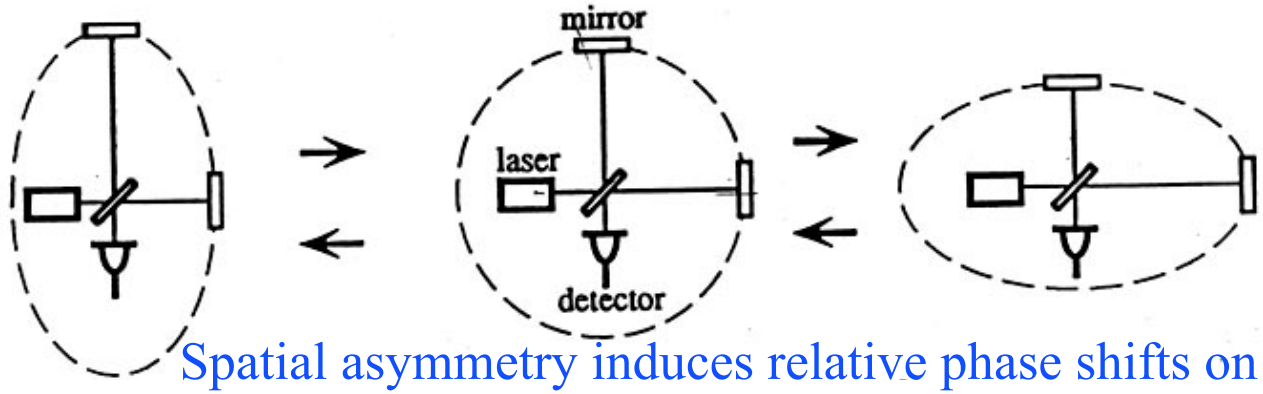


Empty space and time are things, with real physical properties. Space has a shape, a stiffness and a maximum speed for information transfer.

Basic idea is simple



GW amplitude h
$= (R_x - R_y)/R$



Spatial asymmetry induces relative phase shifts on light in arms

The Laser Interferometer Gravitational-Wave Observatory

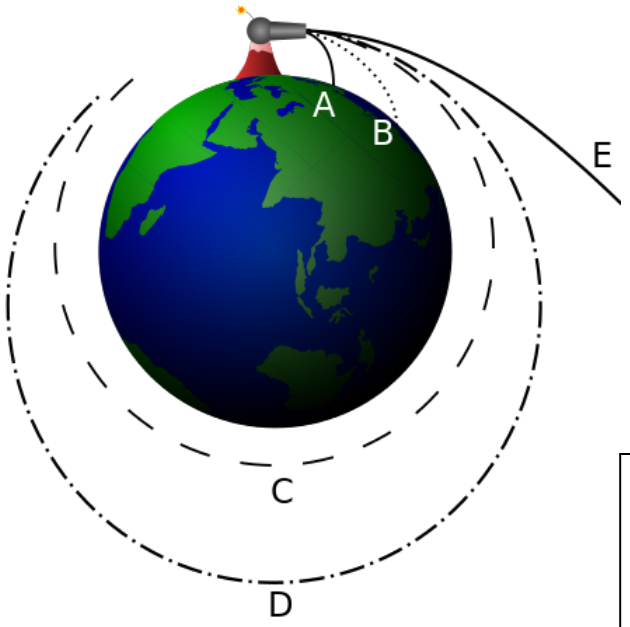
LIGO (Washington)

LIGO (Louisiana)

Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 1000 LIGO Scientific Collaboration members worldwide.

The actors are monster objects called “black holes” which became locked in a death spiral and died in an event of unimaginable violence.

Schwarzschild Black Hole



Newton's Cannonball
Credit: Brian Brondel

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

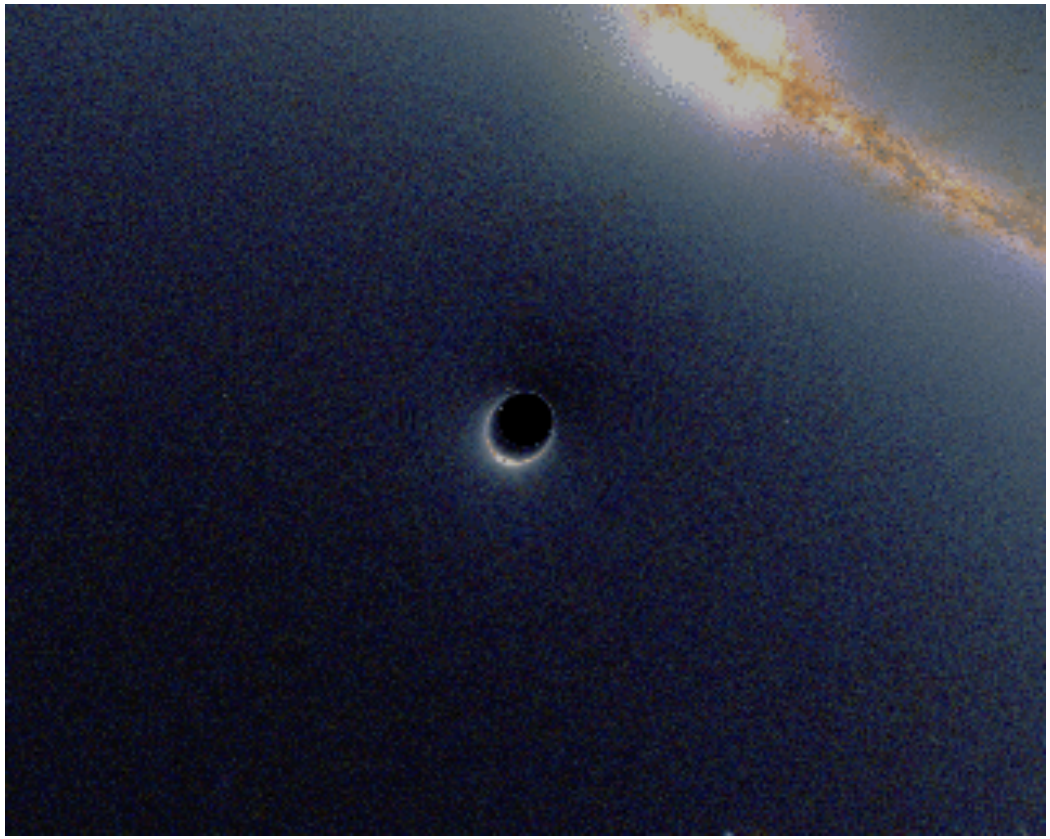
Schwarzschild Radius $$R_s = \frac{2GM}{c^2}$$

Object	Schwarzschild Radius
Earth	1 cm (size of marble)
Sun	3 km (2 miles)

Karl Schwarzschild

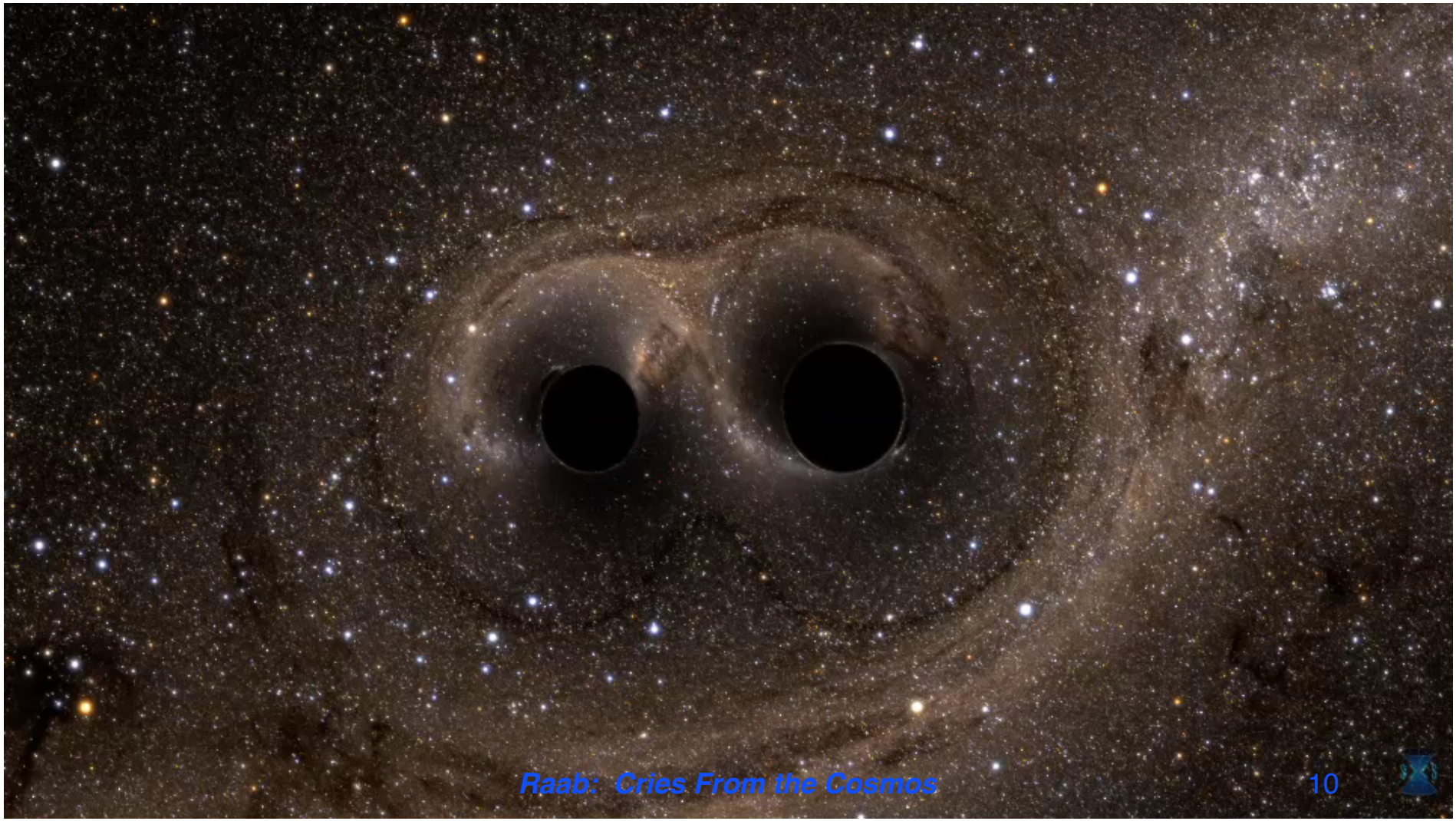
Diameter of a 60 solar-mass black hole is equivalent to the distance between Yakima and Walla Walla.

Illustration of How a Black Hole Distorts Background Light

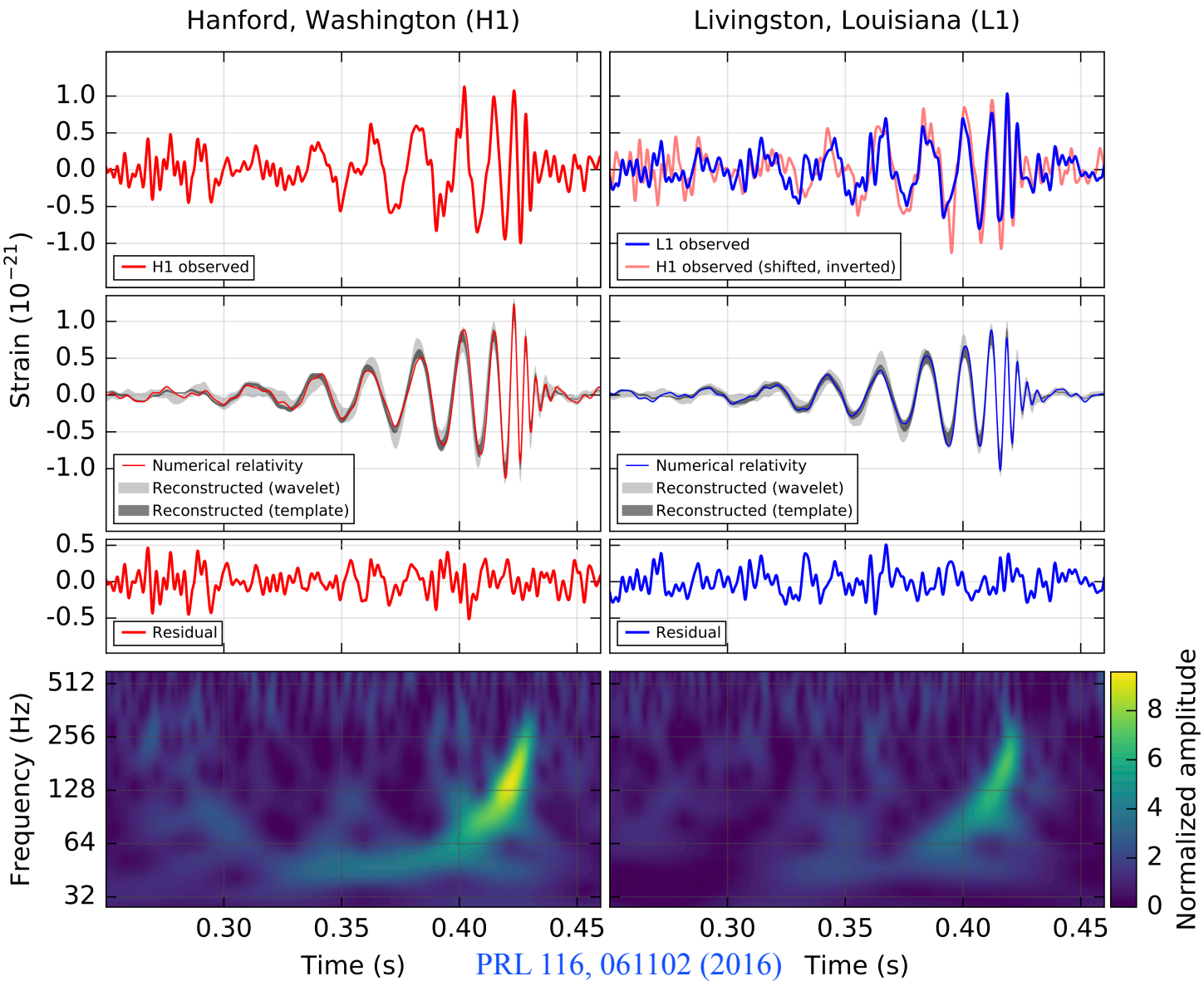


https://en.wikipedia.org/wiki/File:BlackHole_Lensing.gif

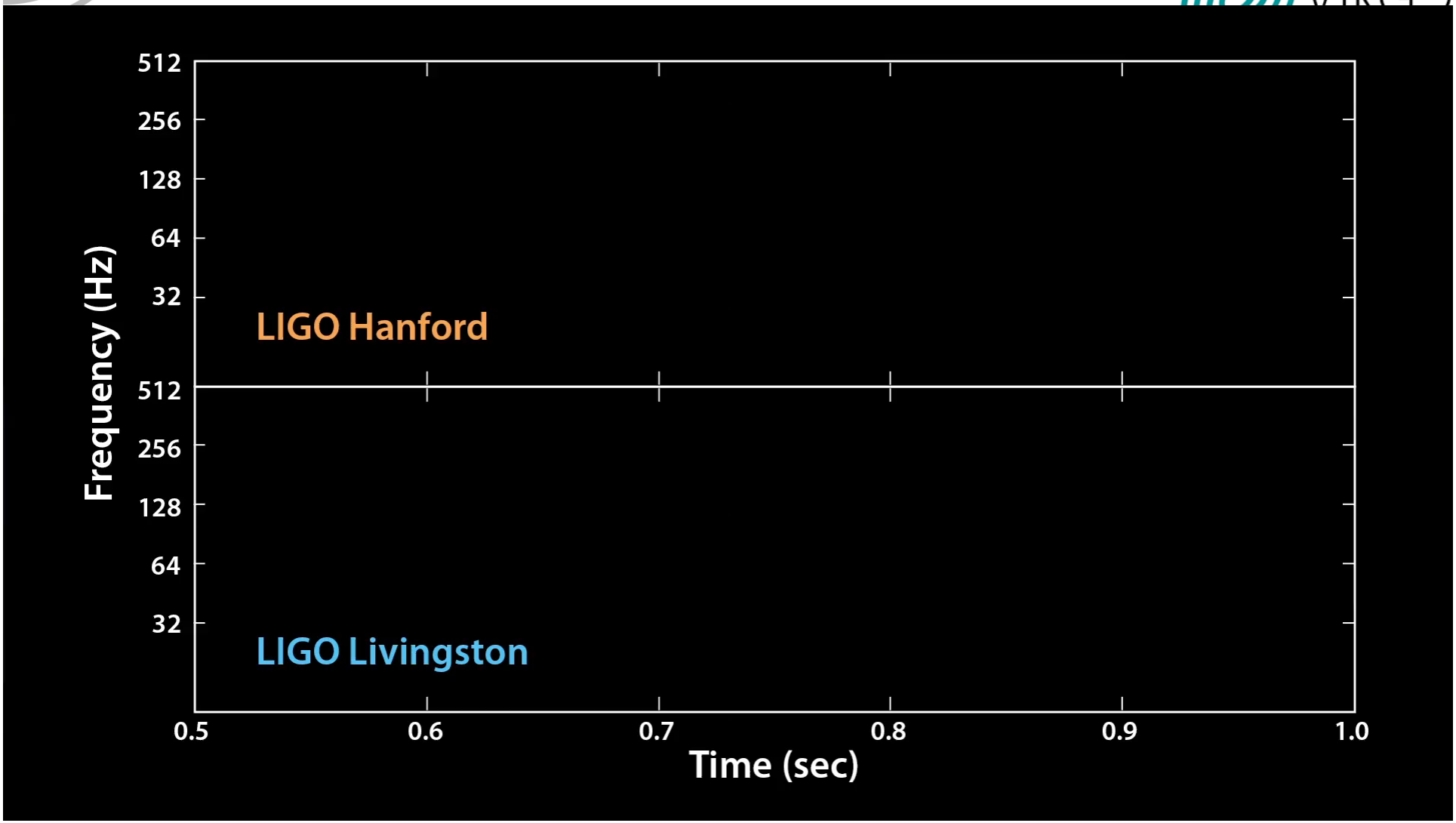
The story starts a long time ago in a part of our universe far, far away…



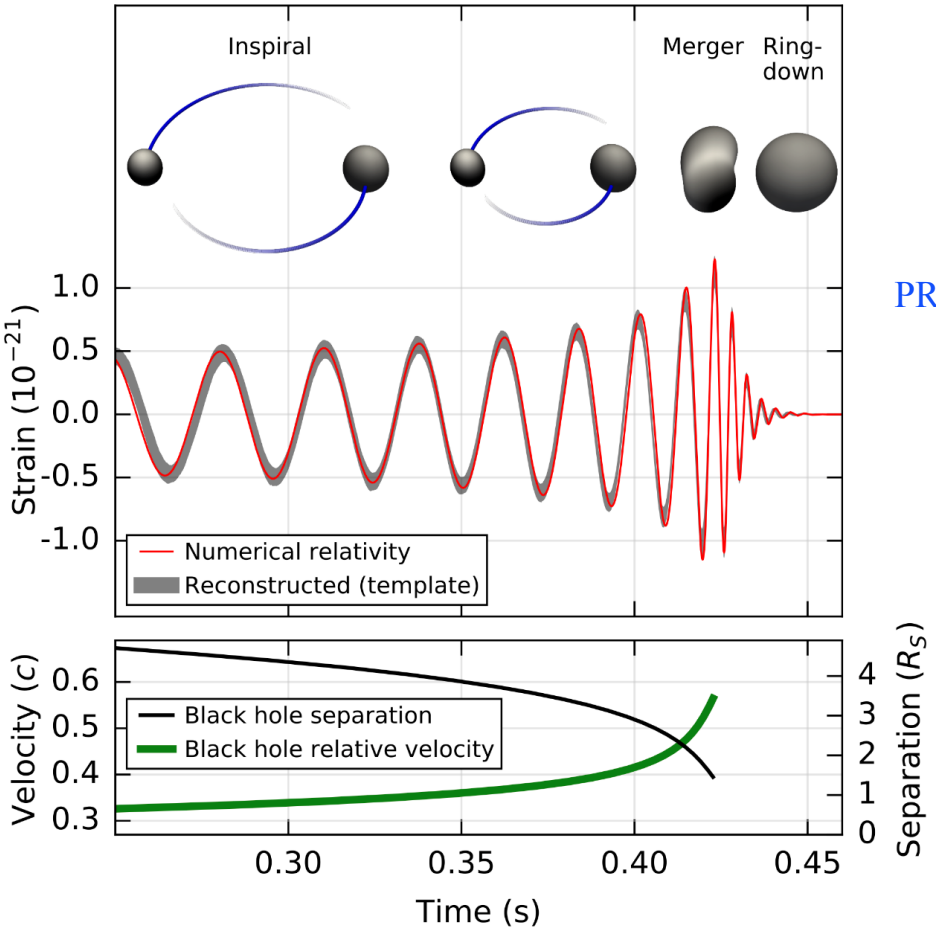
LIGO Observed on Sep 14, 2015



PRL 116, 061102 (2016)


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

A signal from a binary black hole merger



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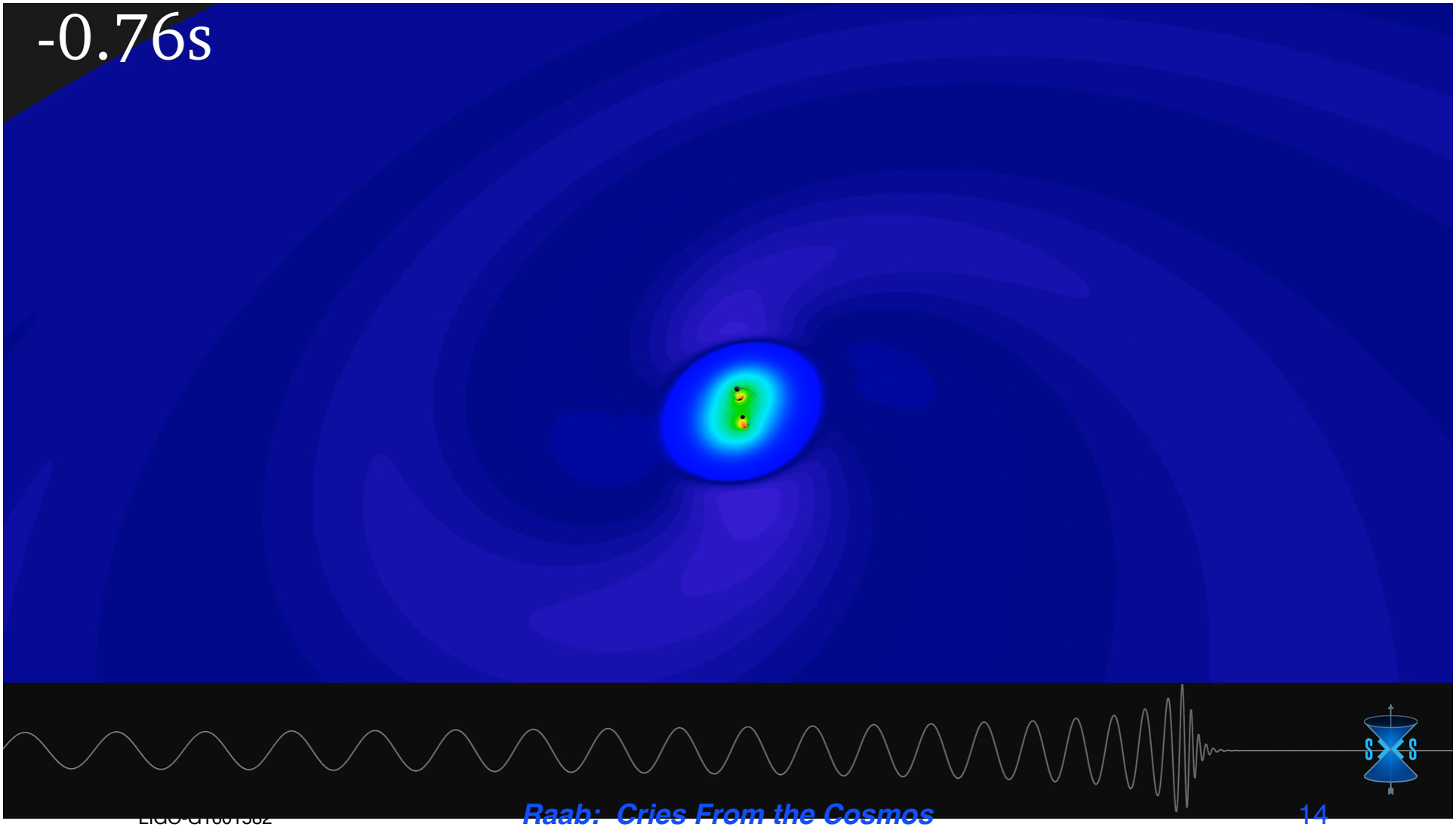


Long, long ago? Far, far away?

- This event occurred more than a billion years ago and the “spacequake”, known as a gravitational wave traveled at the speed of light for all that time.
- At that time, life on Earth consisted of only single-cell creatures.
- We can explore distances using light, which travels at a speed of one foot per nanosecond.
- Since we are exploring the night sky later tonight, let’s use some of the things we see in the day or night-time sky.

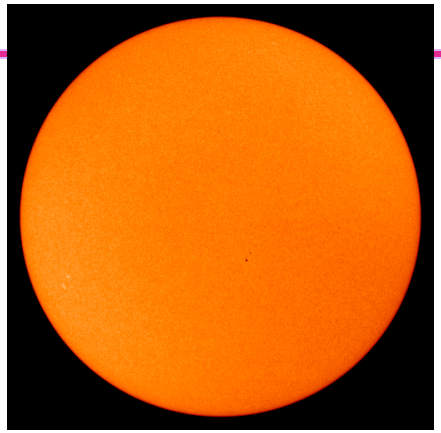
Astronomical distances

Astronomical distances are inconveniently large to measure in meters, so we often give distance as the length of time it takes light to cross that distance.

David & Fred Raab

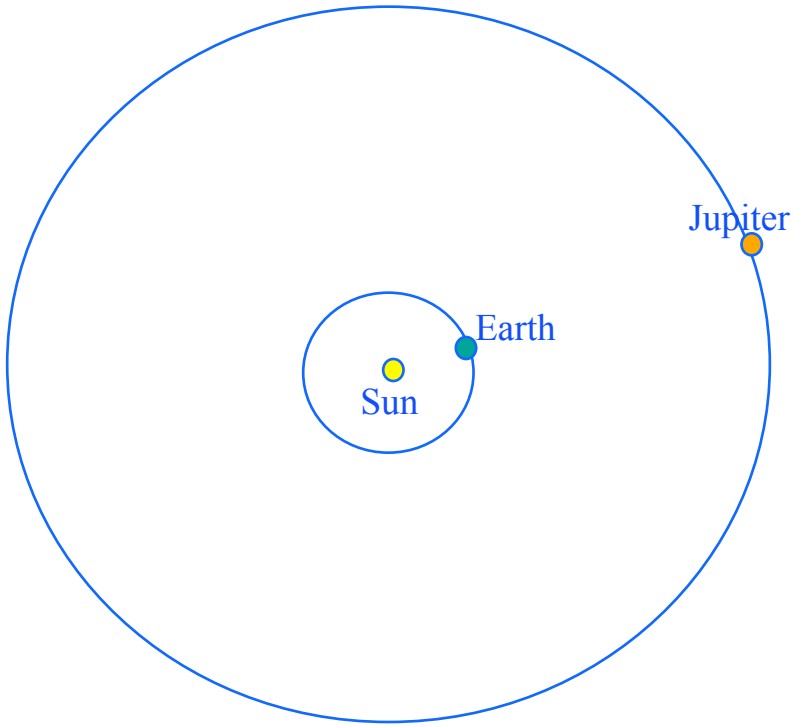
For example, it takes light about 1.3 seconds to travel the distance from Earth to Moon, so we say the Moon is 1.3 light-sec from Earth.

Distance to the Sun



The Sun is 8.3 light-minutes away; first estimated by the Danish mathematician and astronomer Olaf Roemer 1675.

Roemer realized that errors between Cassini's estimates of eclipses of Jupiter's moons and observations were caused by time it takes light to cross Earth's orbit.



Jupiter is 35-52 light-minutes from Earth.

Distances to stars visible to naked eye…

- Vega is 25 light-years away; light you see tonight left Vega during Earth year 1991
  - » The Dow Jones Industrial Average closes above 3,000 for the first time ever, at 3,004.46.
  - » The Cold War ends as President of the Soviet Union, Mikhail Gorbachev, resigns and the Soviet Union dissolves.
  - » The LIGO Construction proposal does not get funded. (It got funded the following year.
- Double-Double is 160 light-years away; light you see tonight left in Earth year 1856
  - » Russia signs Peace of Paris, ending the Crimean War.
  - » Republican Party opens its 1st national convention in Philadelphia.
  - » James Buchanan becomes 15th U.S. President.

Globular Clusters are even farther away, but still in our own Milky Way galaxy

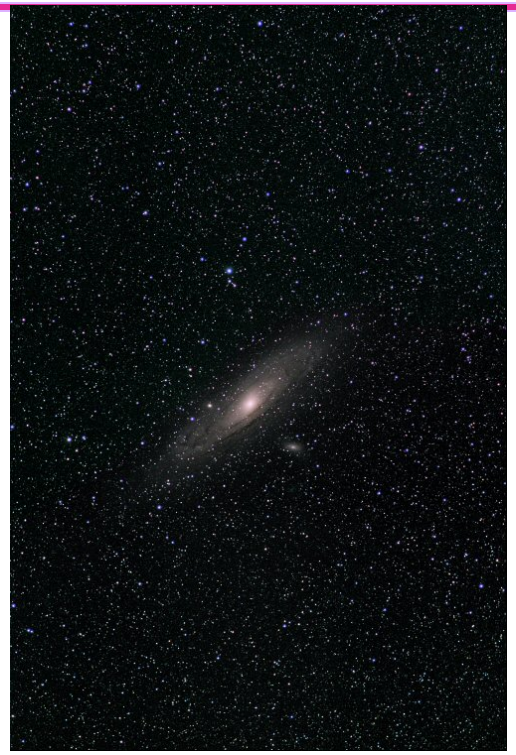
Globular cluster M13 is 21,000 light years away; light you see tonight has been traveling since a time on Earth that giant sloth, dire wolves and sabertooths were drowning in the LaBrea tar pits.

M13 from utahskies.org

Globular clusters are dense, spherical collections of stars in the spherical halo surrounding our galaxy, outside the main disk containing most stars and nebulae. Typical globular clusters contain hundreds of thousands to millions of stars and are tens of thousands of light-years from our solar system.

Galaxies are much further away…

You should be just barely able to see M31, the Andromeda Galaxy, with your naked eye tonight; it is the furthest object that the naked eye can detect at 2.3 million light-years from Earth. With hundreds of billions of stars it puts out enough light to be seen in dark skies at such great distance.

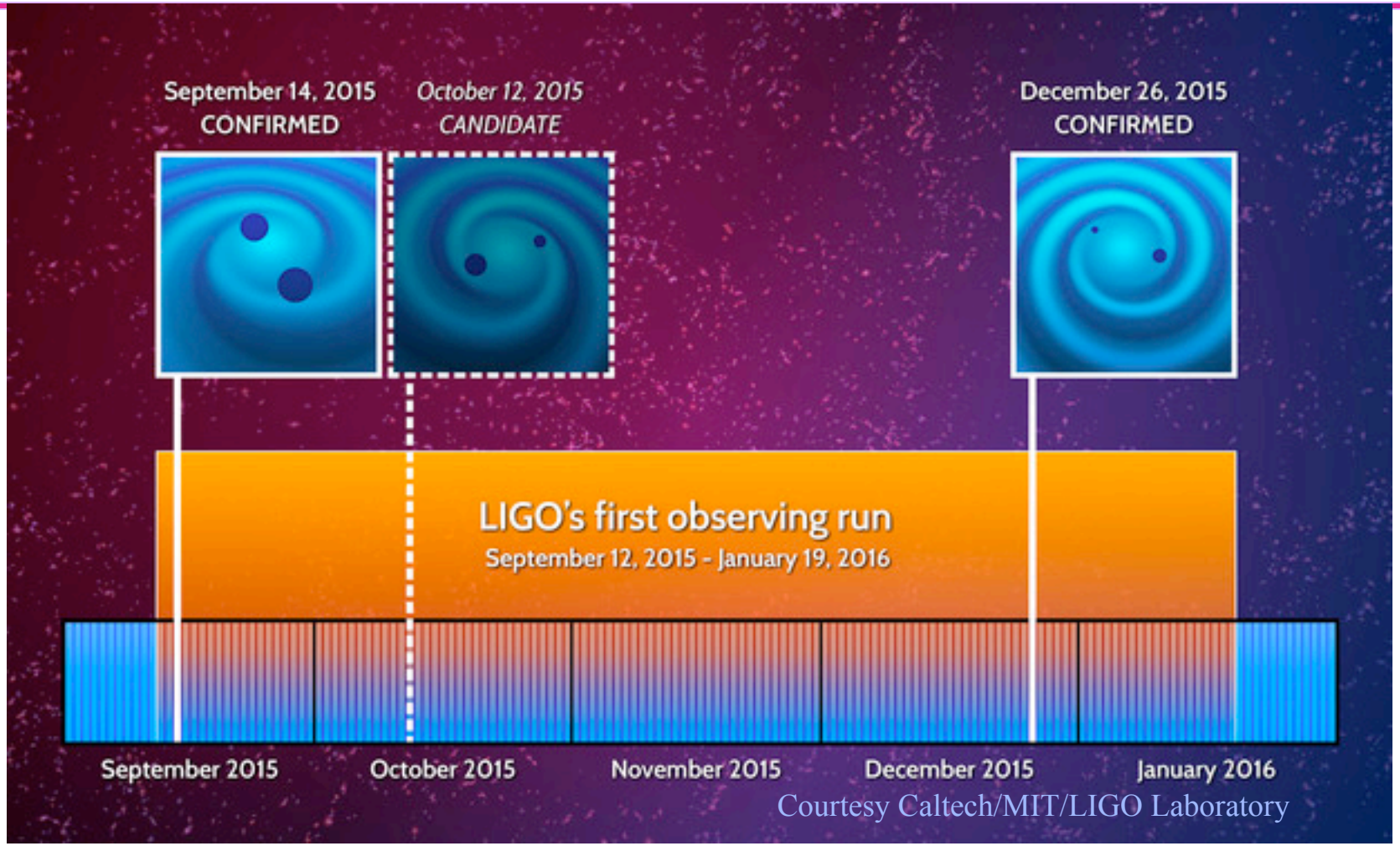


Light you see from M31 tonight has been traveling from M31 since Astralopithecus and Homo Habilis roamed the Earth.

M31 is our closest large galaxy. In the volume that we can see systems like GW150914, there are more than 5 million galaxies.

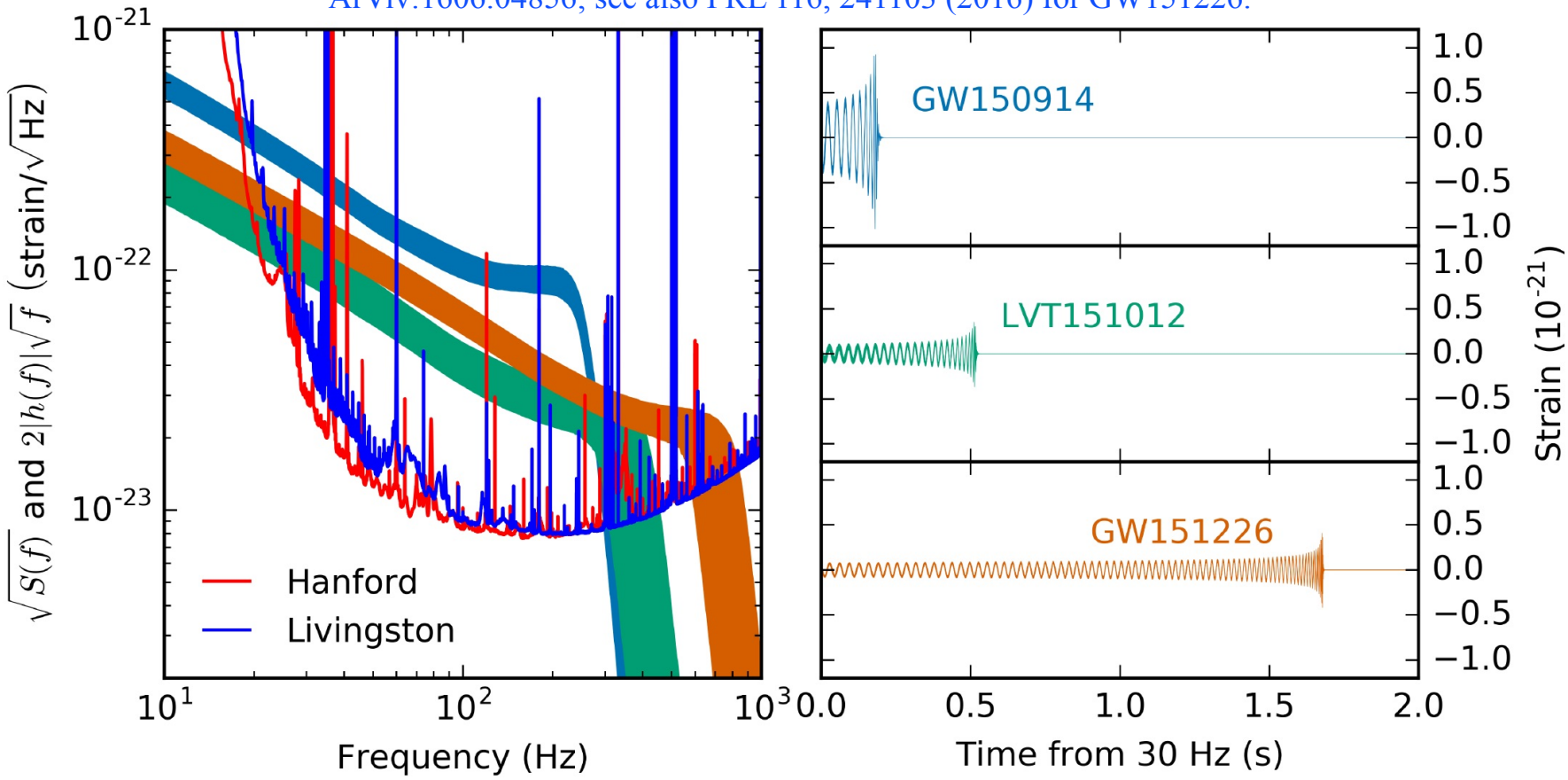
- This first gravitational wave discovery was named GW150914:
  - » Event type = gravitational wave
  - » Detection year = 2015
  - » Detection month = 09 = September
  - » Detection day = 14
- This was the most energetic event ever detected by humans, converting a mass equivalent to a million Earths into gravitational-wave energy.
- For a few tenths of a second the power in this gravitational wave was 50 times greater than the total power output of all the stars in the universe.
- But there were more discoveries to come…

Discovery Timeline – Advanced LIGO's 1st Observations

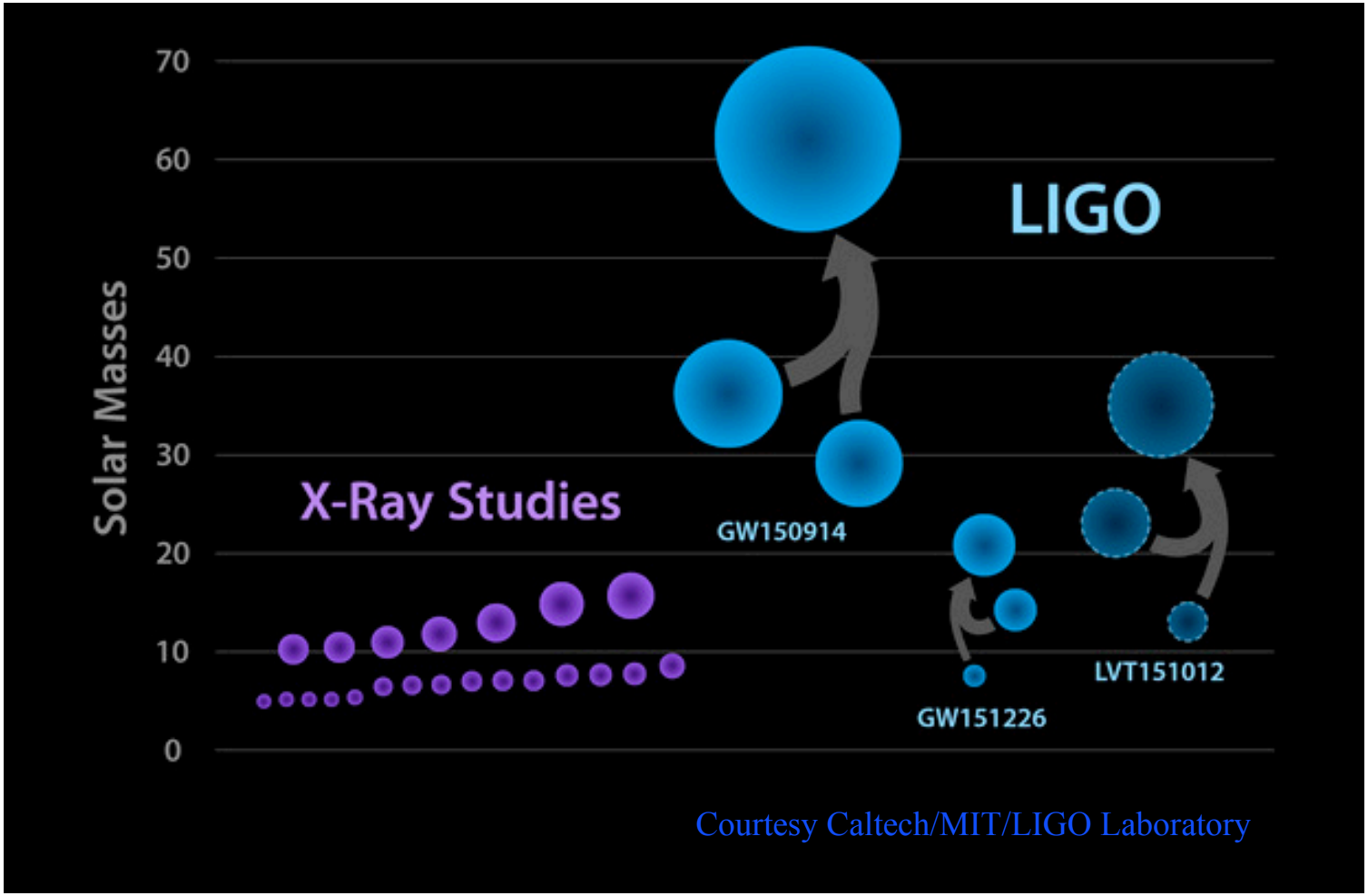


Advanced LIGO's First Observations

ArViv:1606.04856; see also PRL 116, 241103 (2016) for GW151226.



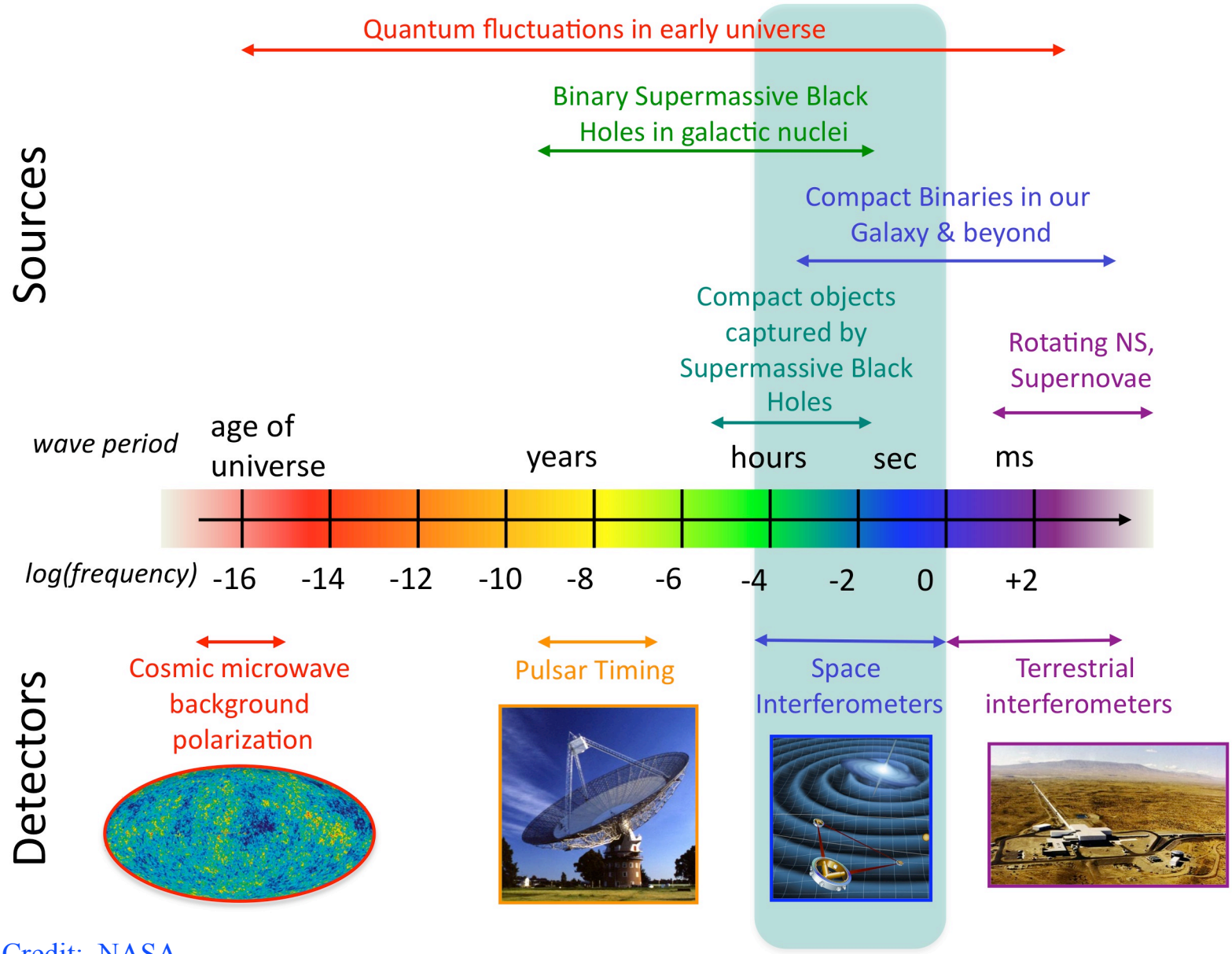
Known Stellar-Mass Black Holes – June 2016



What will be the legacy of LIGO discoveries?

- Attempts in the 19th century to explain why the sky is blue, sunsets red and clouds white led to the 20th century economy:
  - » Atomic and nuclear physics and modern materials
  - » Modern chemical and pharmaceutical industries
  - » Modern electronics and computer industries
  - » Unraveling the structure of DNA and other bio-molecules, leading to modern biochemistry and gene therapy
  - » Development of almost all medical diagnostic machines
  - » Also a new phrase, “Blue-sky research”
- LIGO discoveries likely will revolutionize our understanding of space, time, matter and energy, as well as redefine what people can imagine and build

The Gravitational Wave Spectrum



Credit: NASA

Summary

- The 1st observing run of LIGO's 2nd-generation detectors have initiated Gravitational-Wave Astronomy.
- We have seen the annihilations and the births of black holes for the first time.
- General Relativity provides a powerful framework from Earth-bound physics to mergers of stellar mass black holes at velocities near the speed of light.
- Black Hole Binaries exist and merge hourly somewhere in the universe
- An emerging international network of detectors soon will provide more accurate positions of sources to enable EM follow-ups of GW events.
- It is possible to develop more powerful generations of detectors and there is much physics still to be harvested from their observations.