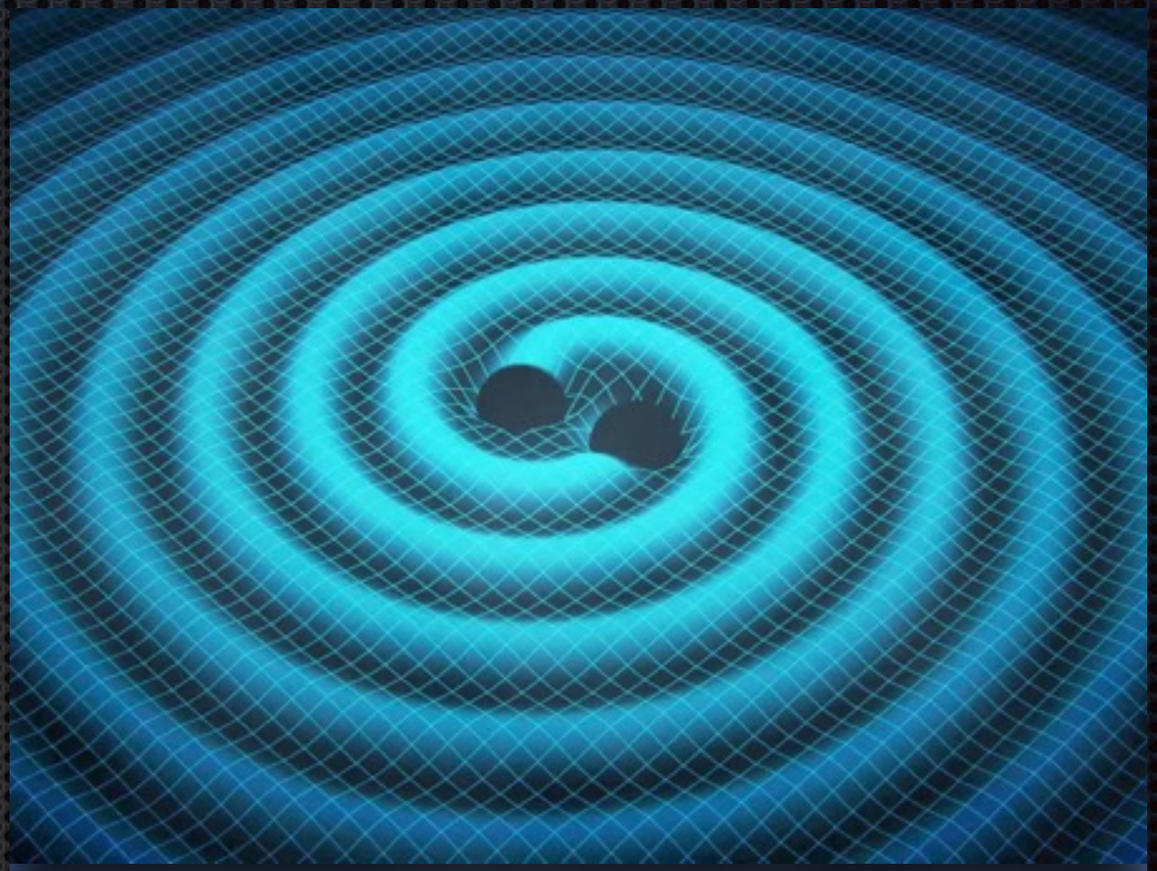
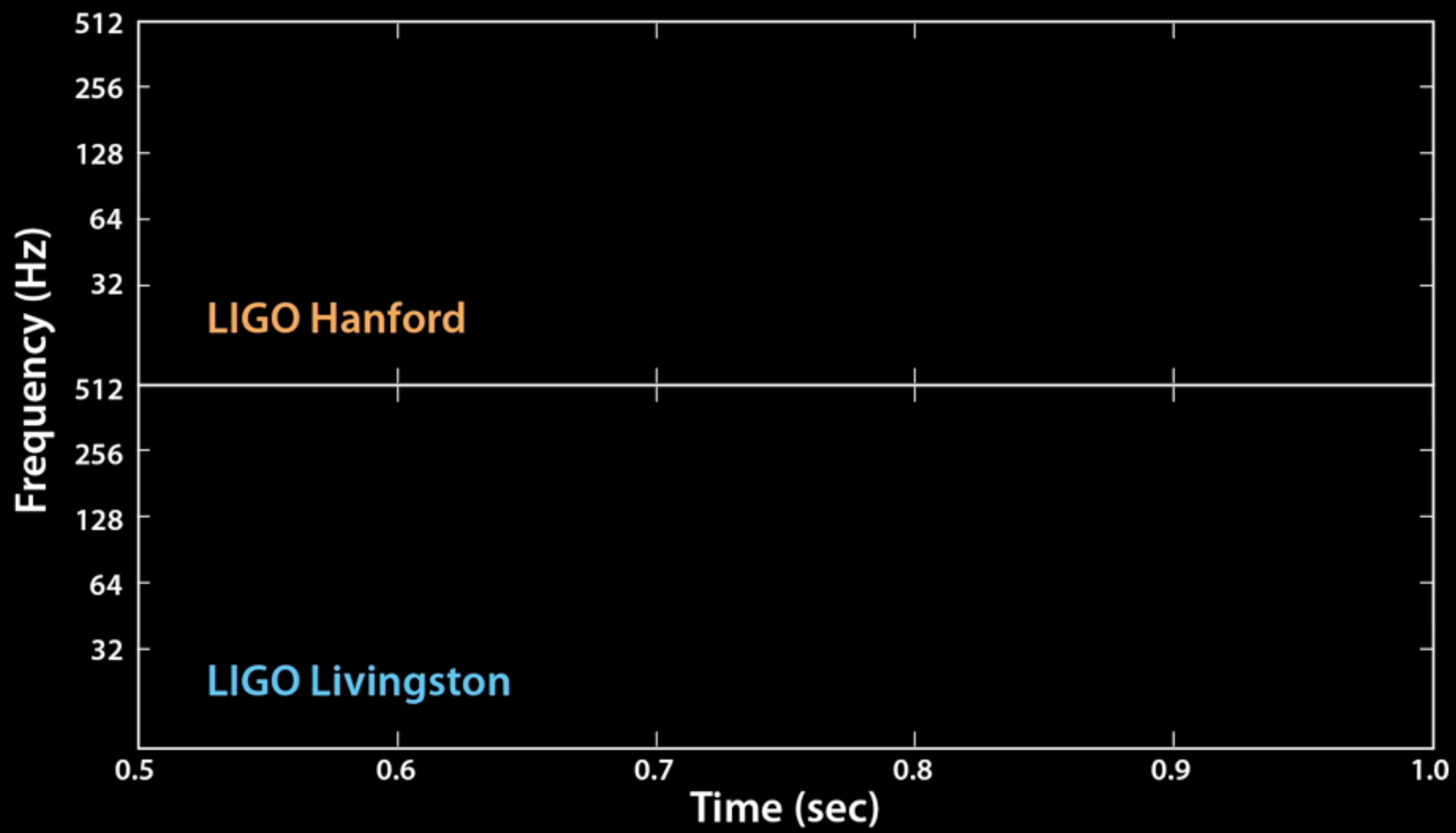
Gravitational Waves



Daniel Holz
University of Chicago

On September 14, 2015 we heard the sound of two black holes colliding

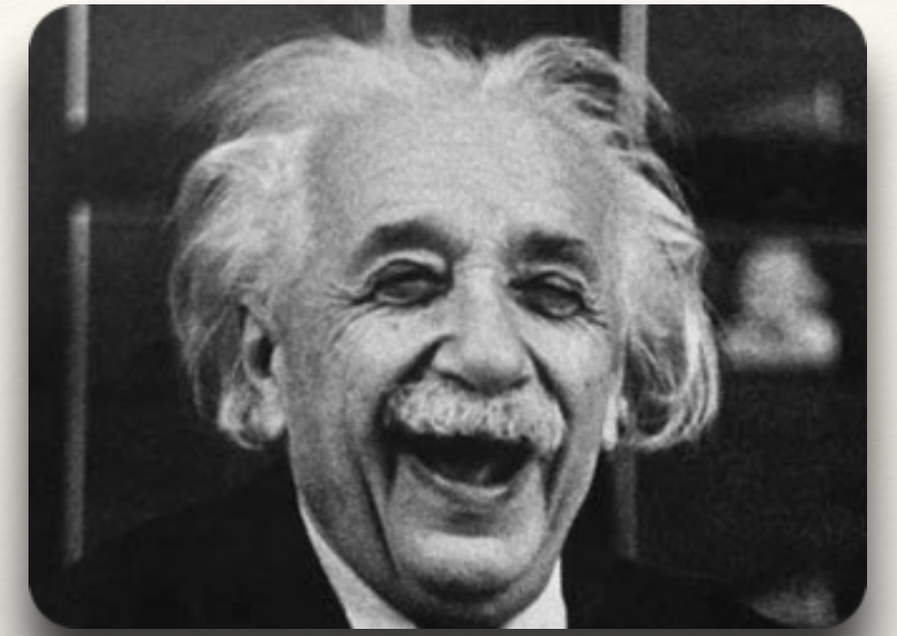


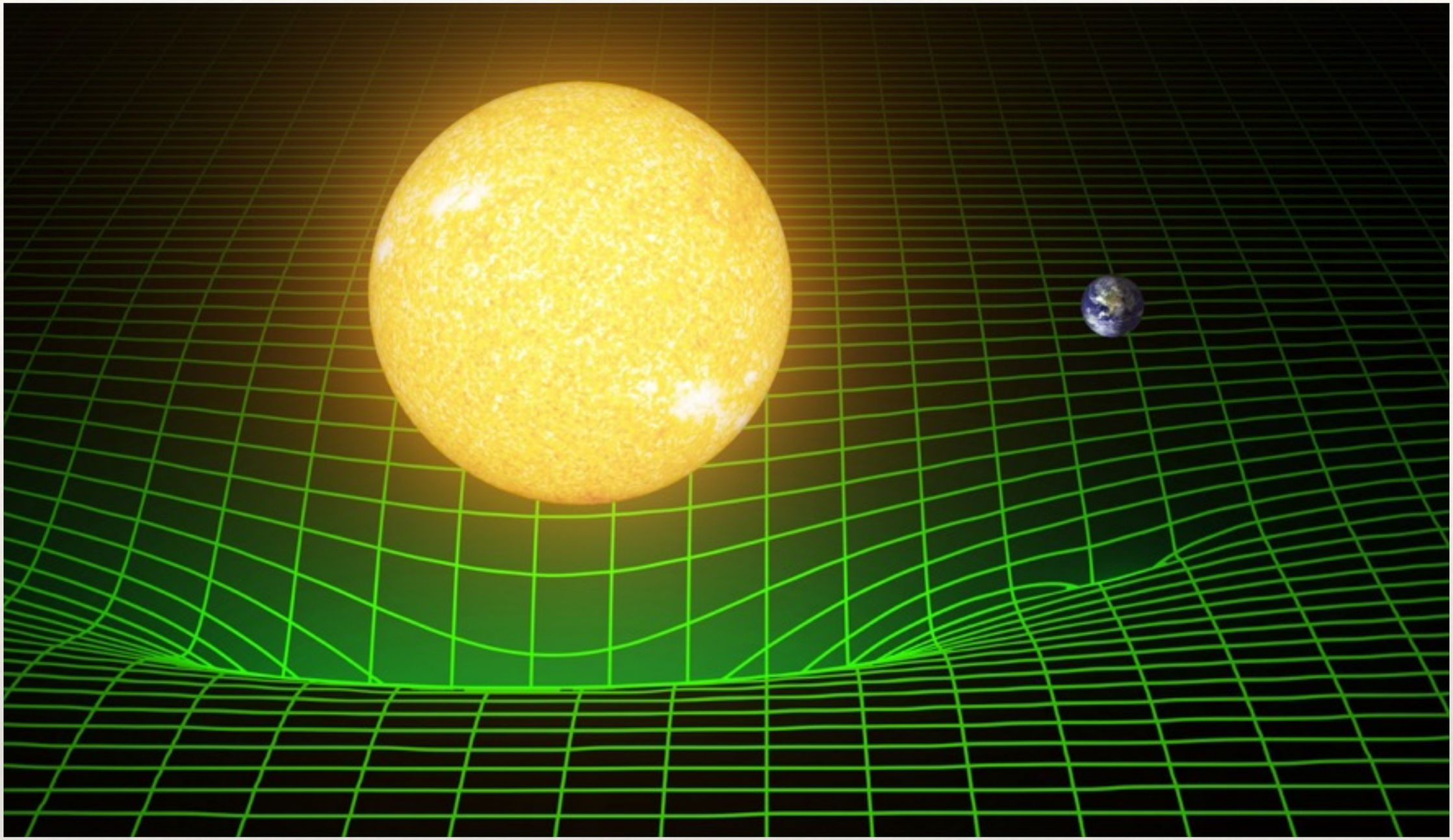
Why was this important?

- Einstein was right
- Black holes exist
- A whole new way to “listen” to the Universe!

1915: General Relativity

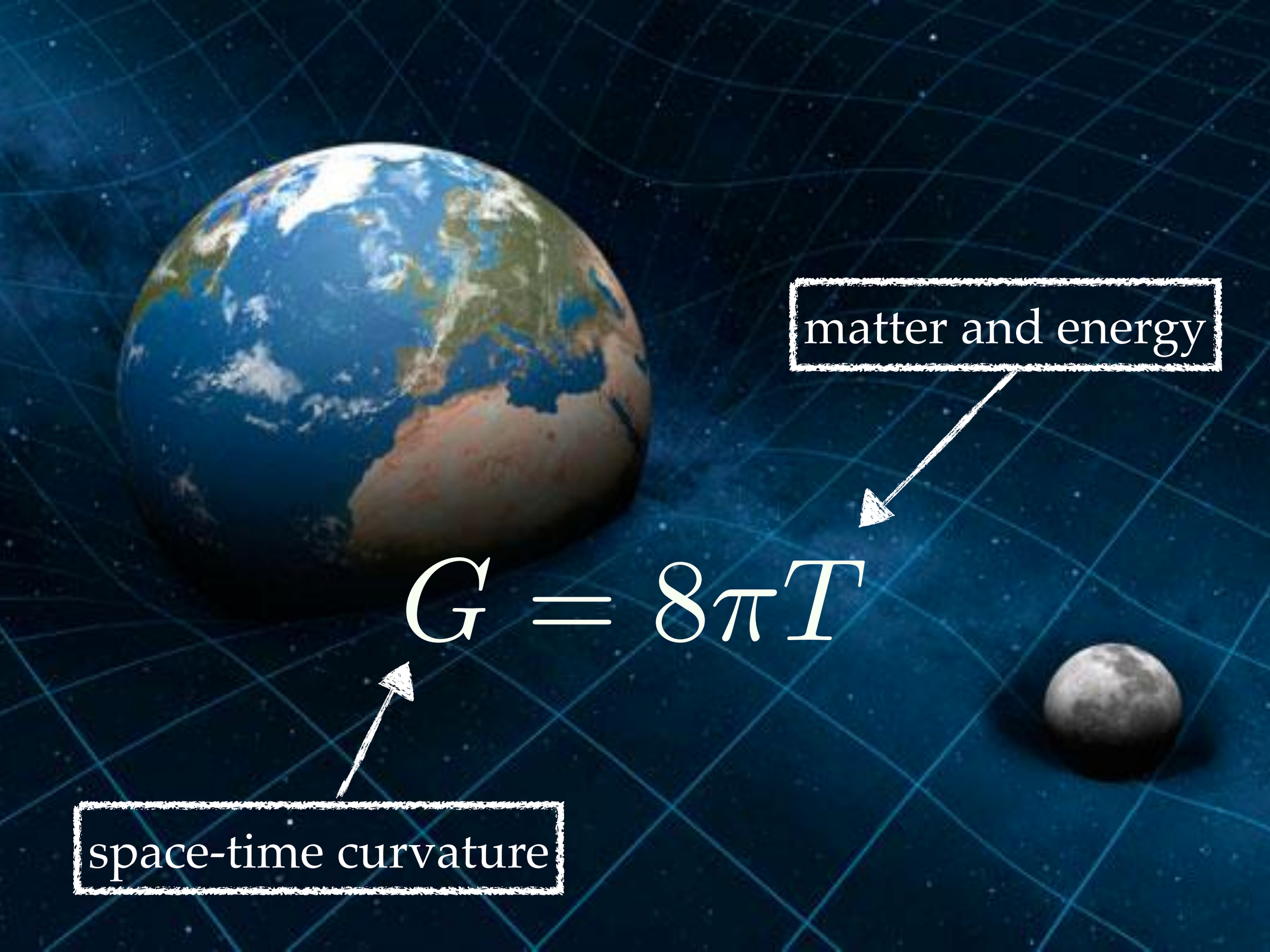
- Space and time are inextricably linked: **spacetime**
- Spacetime can become infinitely warped: **black holes**
- Spacetime can wiggle: **gravitational waves**



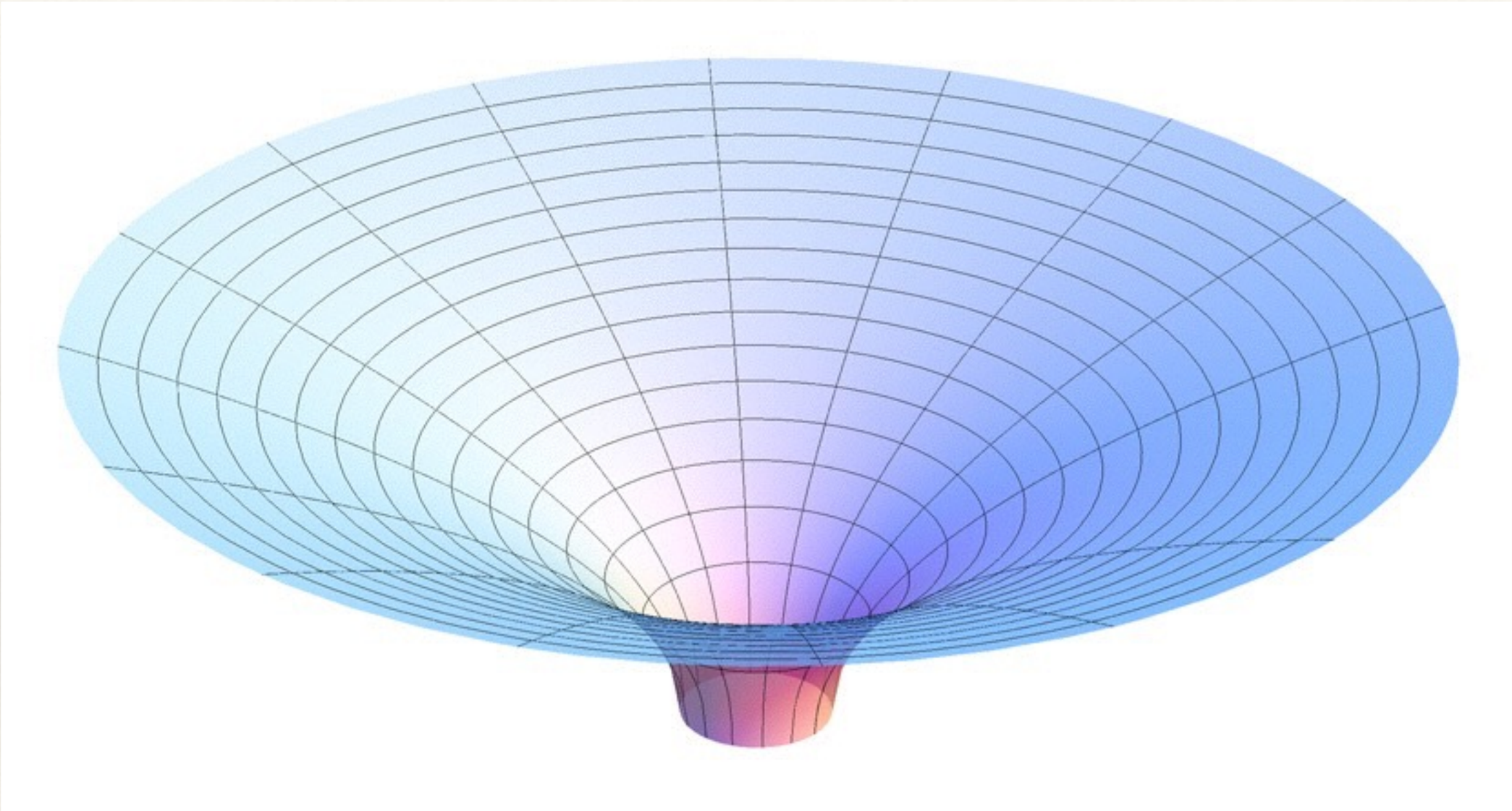


Spacetime tells matter how to move
Matter tells spacetime how to curve

–John Archibald Wheeler


matter and energy
$G = 8\pi T$
space-time curvature

Black Holes

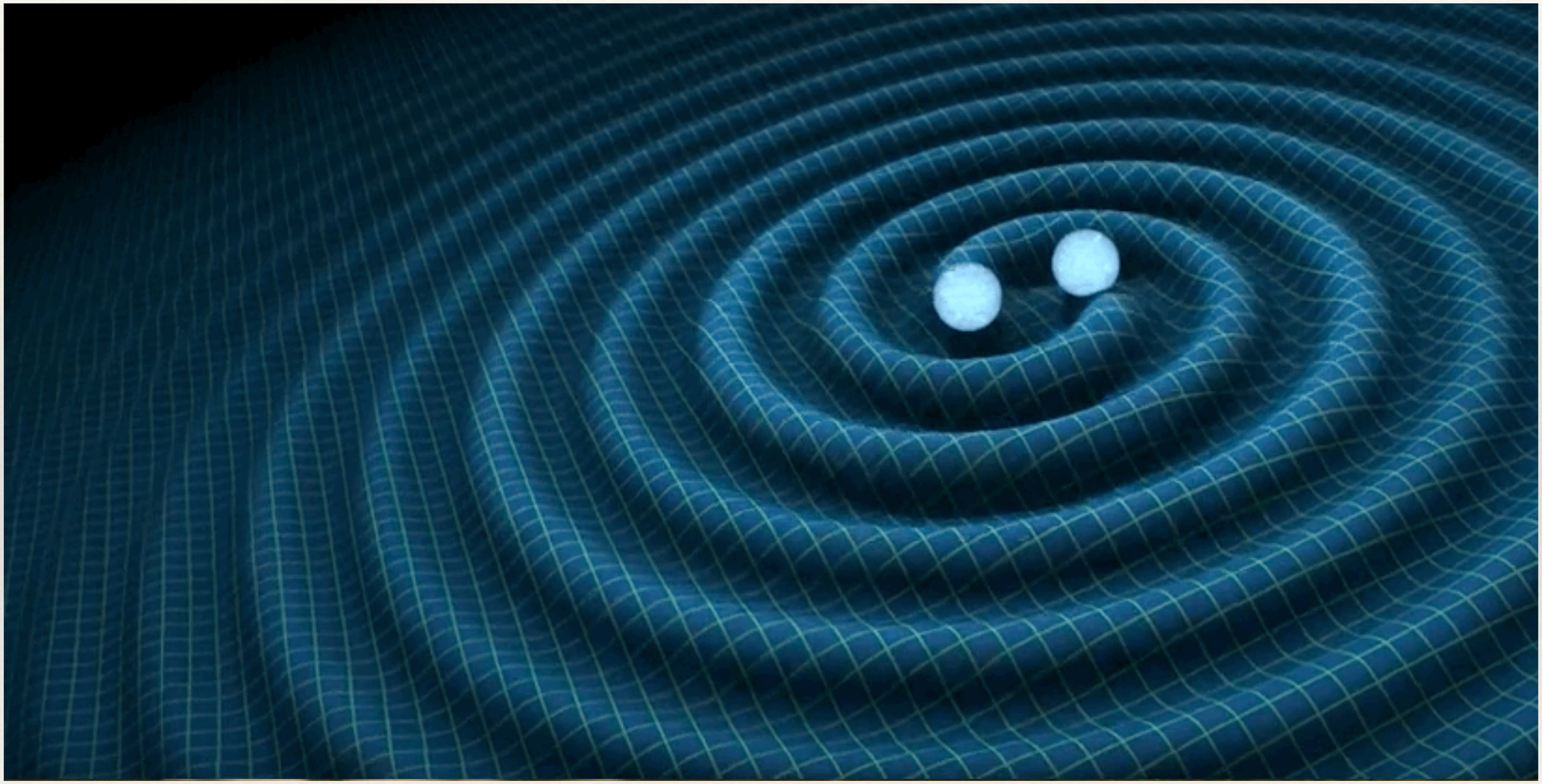


Not even light can escape

Gravitational waves

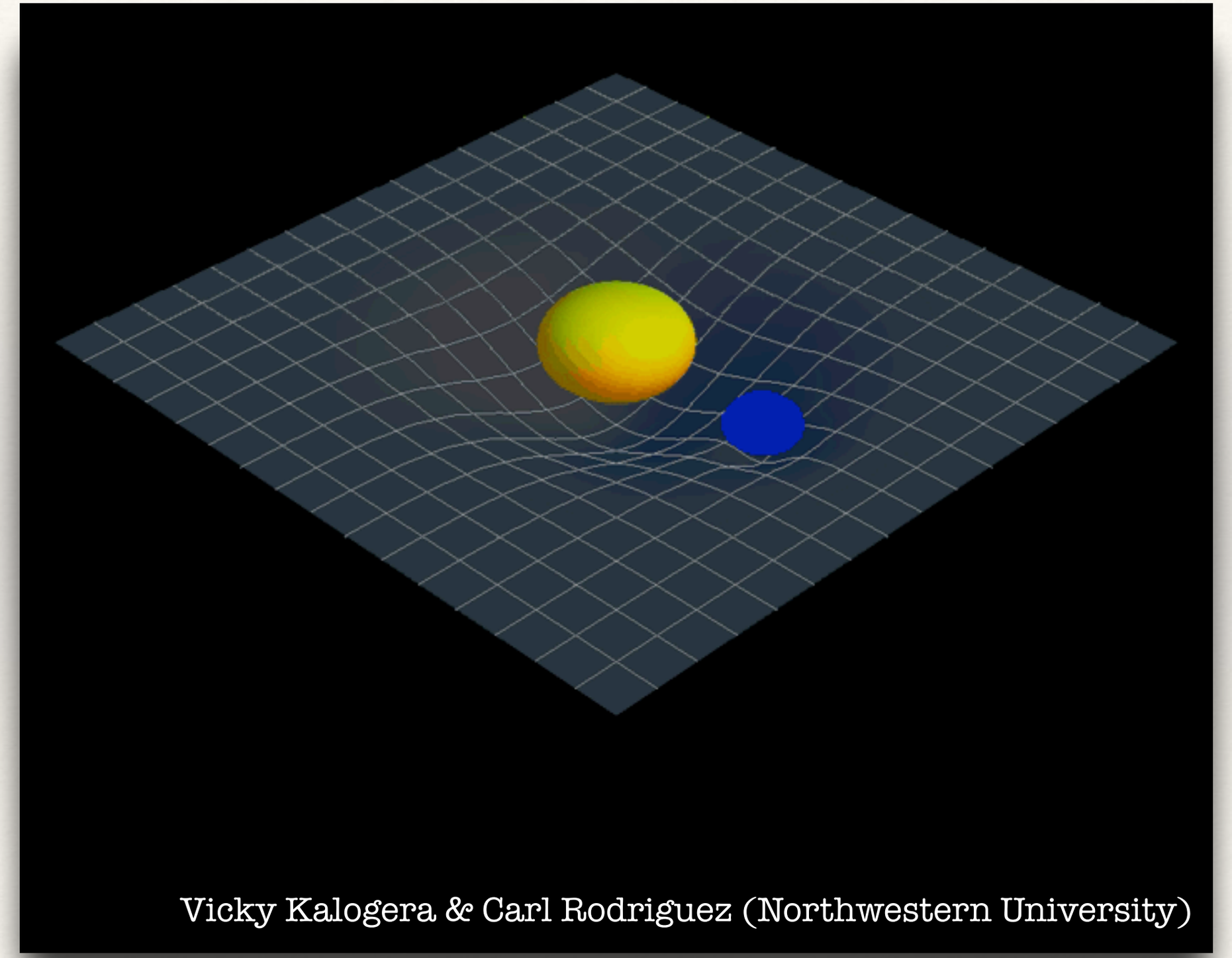
Ripples in the fabric of spacetime

Gravitational waves

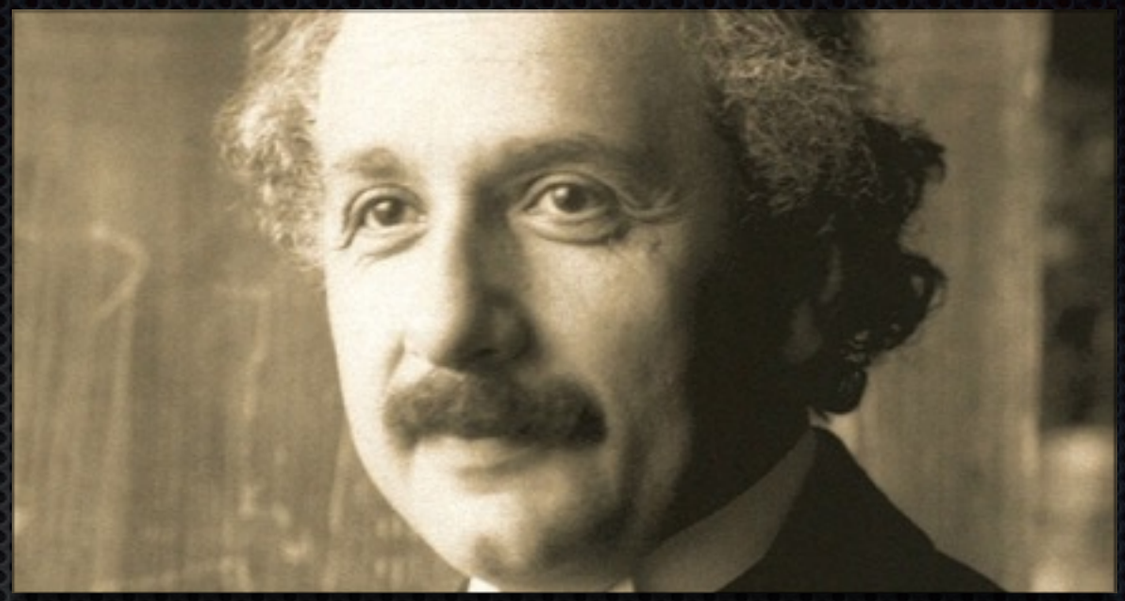


Ripples in the fabric of spacetime

Gravitational waves



Gravitational waves
Sordid history
Theory



- 1916: Einstein predicts gravitational waves
- 1922: Eddington: “Gravitational waves travel at the speed of thought”
- 1936: Einstein writes a paper showing that gravitational waves don’t exist
- 1950–1960: Theoretical arguments about existence of gravitational waves
- 1960s: Consensus that gravitational waves do in fact exist

Gravitational waves
Sordid history
Experiment

- 1916: Einstein predicts gravitational waves
- 1960: Joe Weber starts building detectors
- 1969: Joe Weber announces first detection of gravitational waves (“Evidence for discovery of gravitational radiation”)
- 1970–: Weber’s waves are never reproduced
- 1974–1979: Hulse-Taylor binary pulsar
- 1993: Nobel prize to Hulse and Taylor
- 1992–today: LIGO
- September 14, 2015

What are gravitational waves?

Heuristic argument

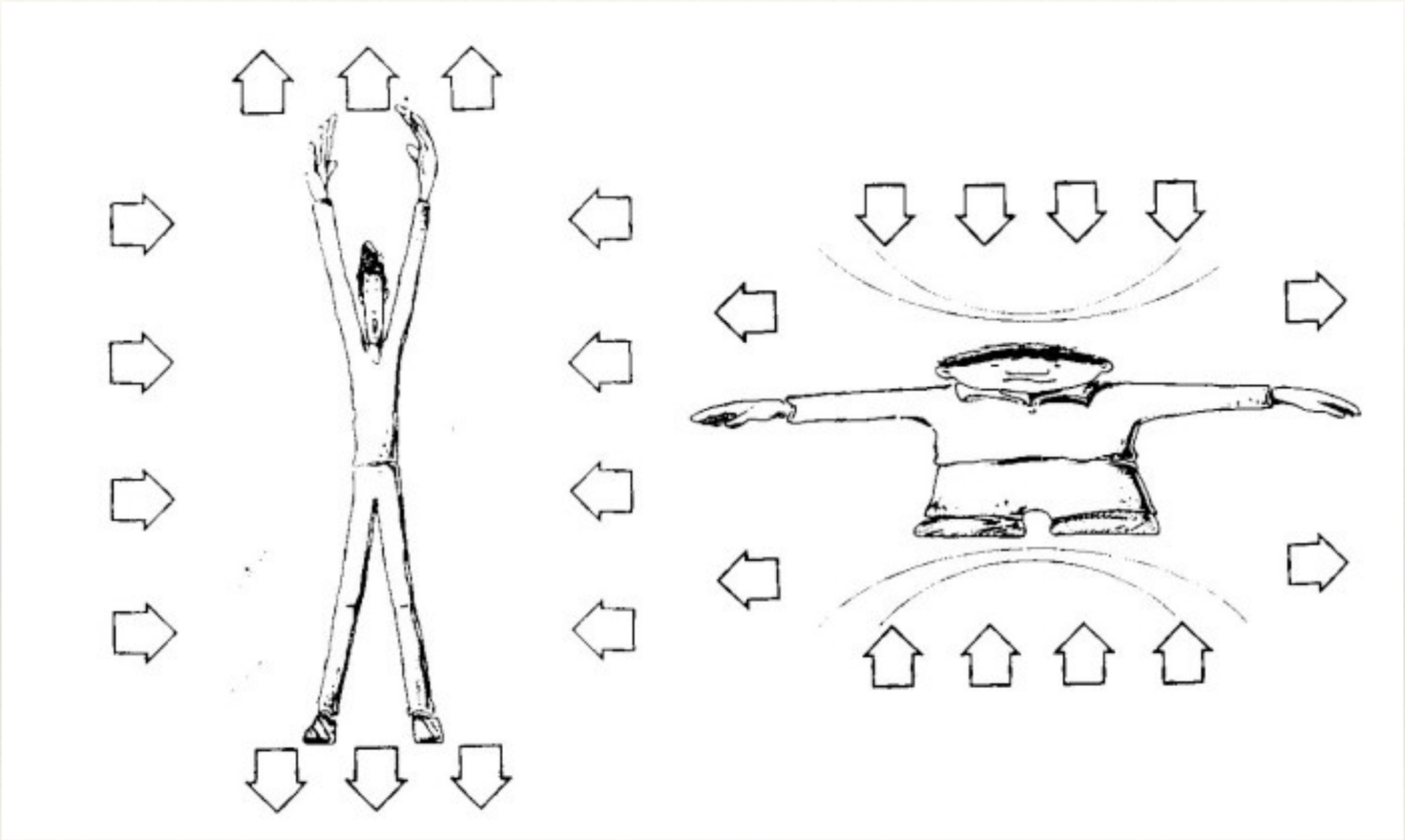
- Nothing travels faster than the speed of light. Not even information
- If a massive object moves, how do we find out?
  - Something must travel from the object to us, to let us know
  - These are gravitational wave

What are gravitational waves?

Heuristic argument

- Gravitational waves are the way the Universe keeps track of where everything is

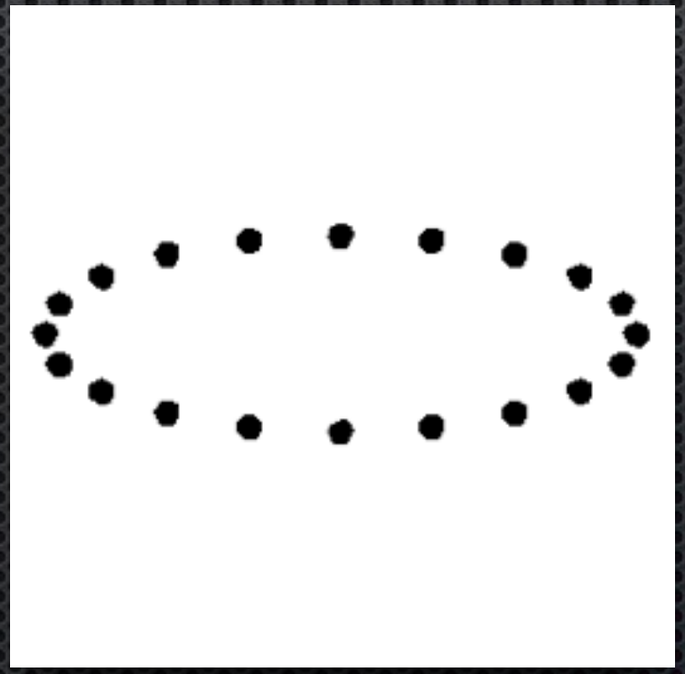
What do gravitational waves do?



The effect of gravitational waves on matter is to stretch & squeeze it … but the effect is **really tiny**

What do gravitational waves do?

- Consider a ring of marbles floating in empty space, and a gravitational wave goes by:



- Distances between the masses oscillate as gravitational wave passes

Listening to the Universe

GWs are like sound, not light:

- detectors are omnidirectio
- detectors don't image
- GWs from bulk, no e, processes
- phase coheren
- weak
- difficult ter/absorb
- freque s of stellar mass events occur in human auditory band

Analogy! caveat emptor

Where do gravitational waves come from?

- Essentially everything generates gravitational waves
- Essentially all sources of gravitational waves are staggeringly weak
- To produce strong detectable GWs need large masses (e.g., the mass of the Sun) accelerating very fast (e.g., to near the speed of light in a short time)

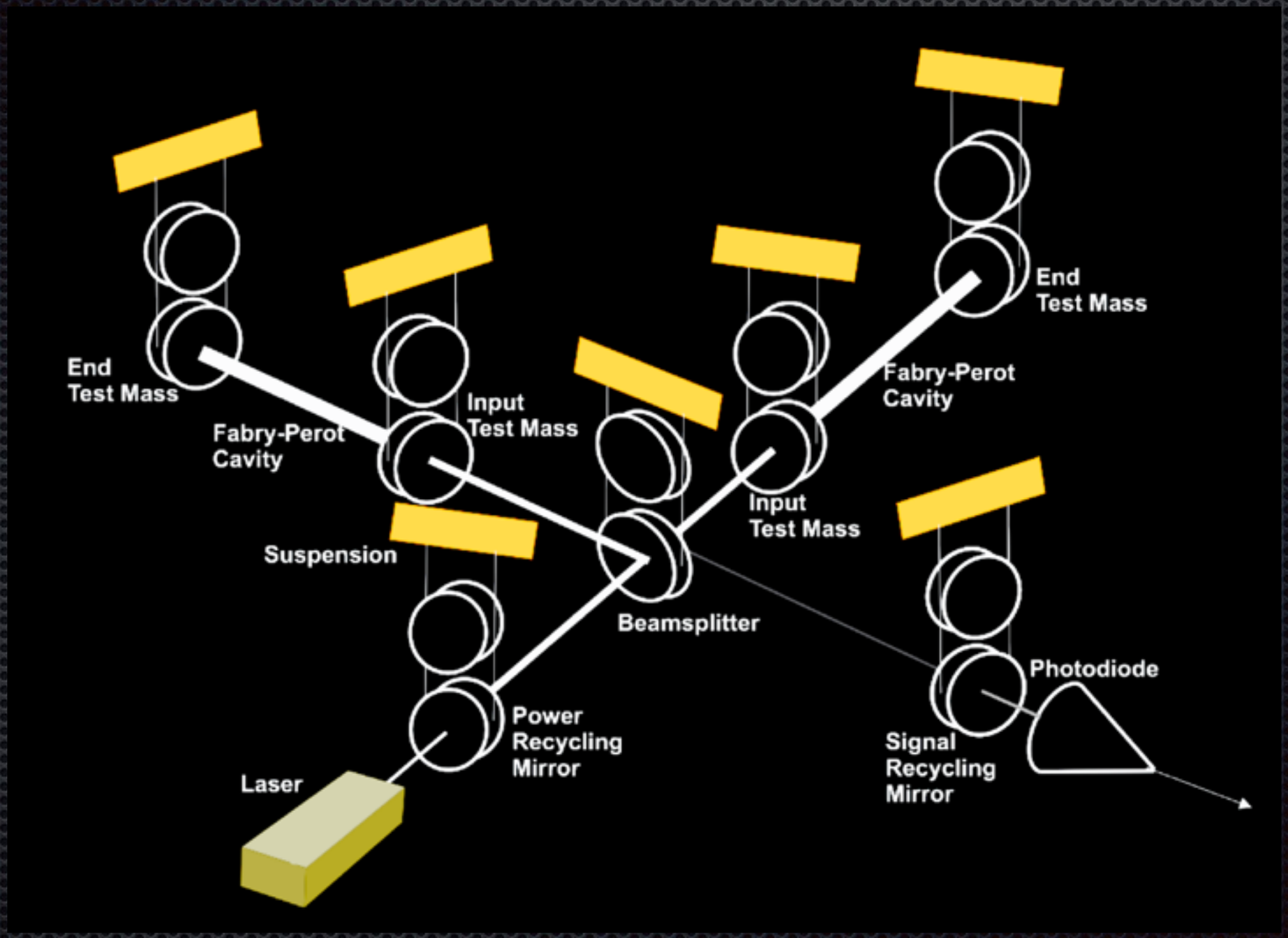
Strong sources of gravitational waves

- Two black holes (or neutron stars) crash into each other
- A star falls into a big black hole
- A supernova explodes (asymmetrically)
- Big bang/inflation (maybe)

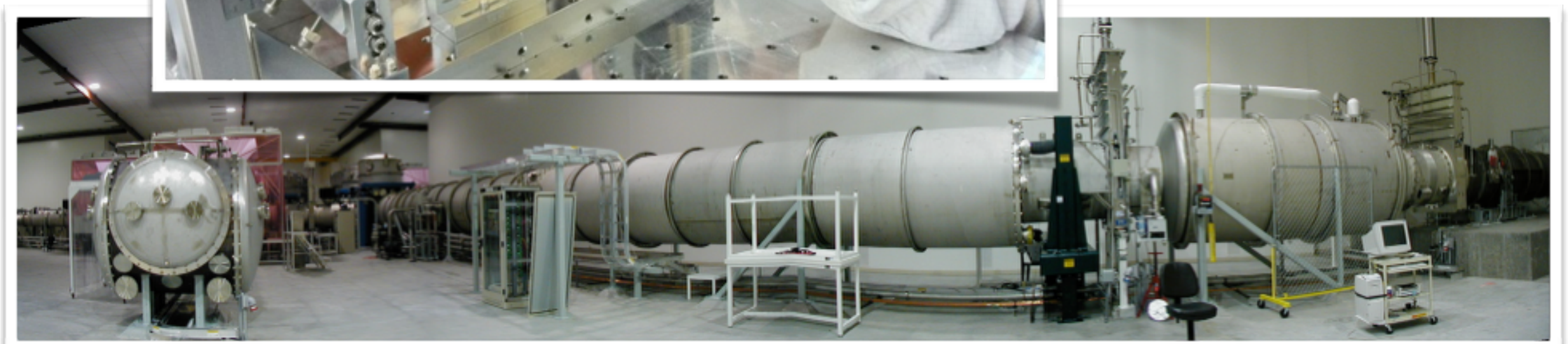
How do we detect these waves?

- Laser Interferometer Gravitational wave Observatory (LIGO)
- Two fancy Michelson interferometers
- It is the most sensitive machine ever built

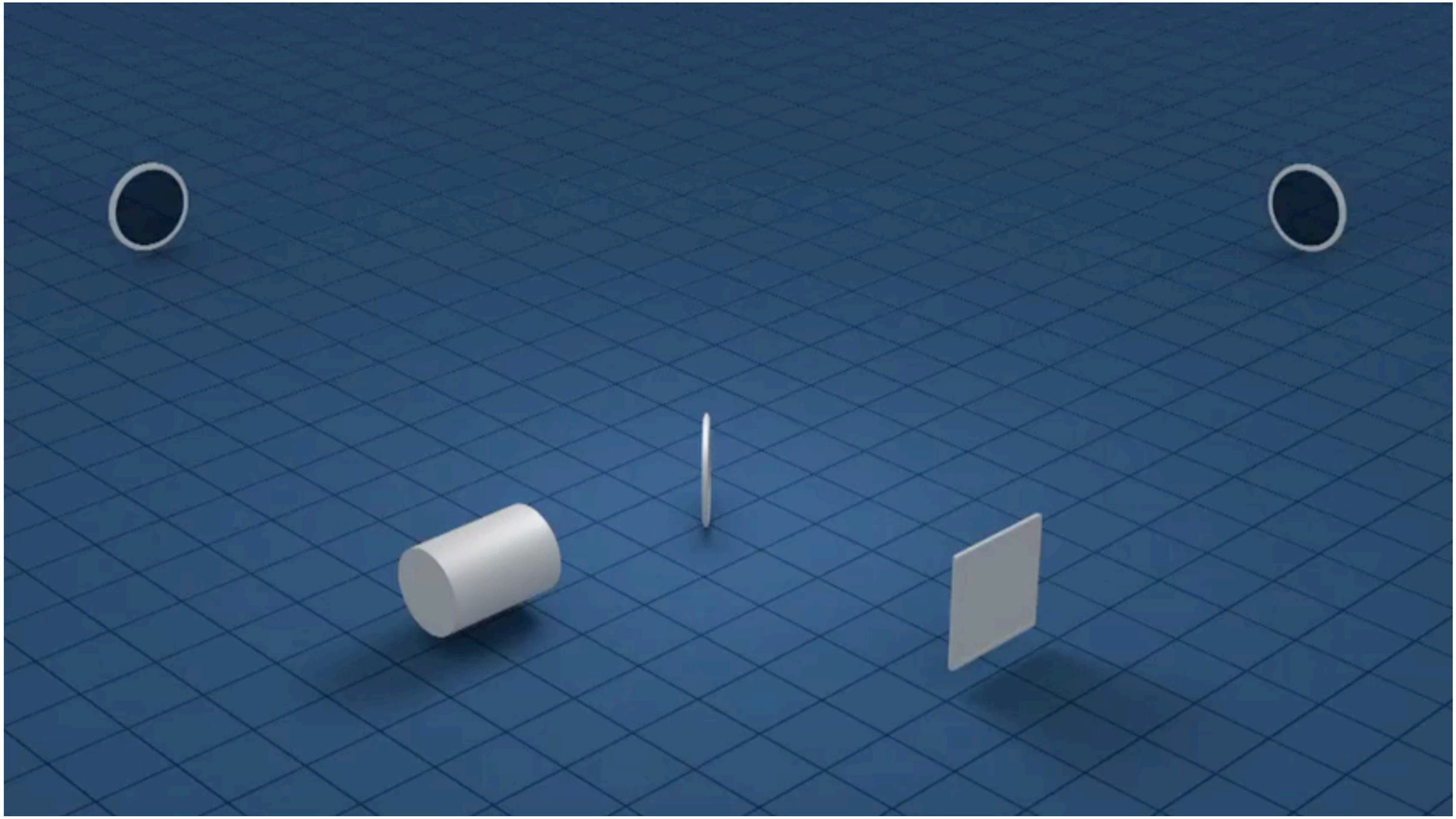
LIGO is awesome



What is inside LIGO? Nothing! (mostly)



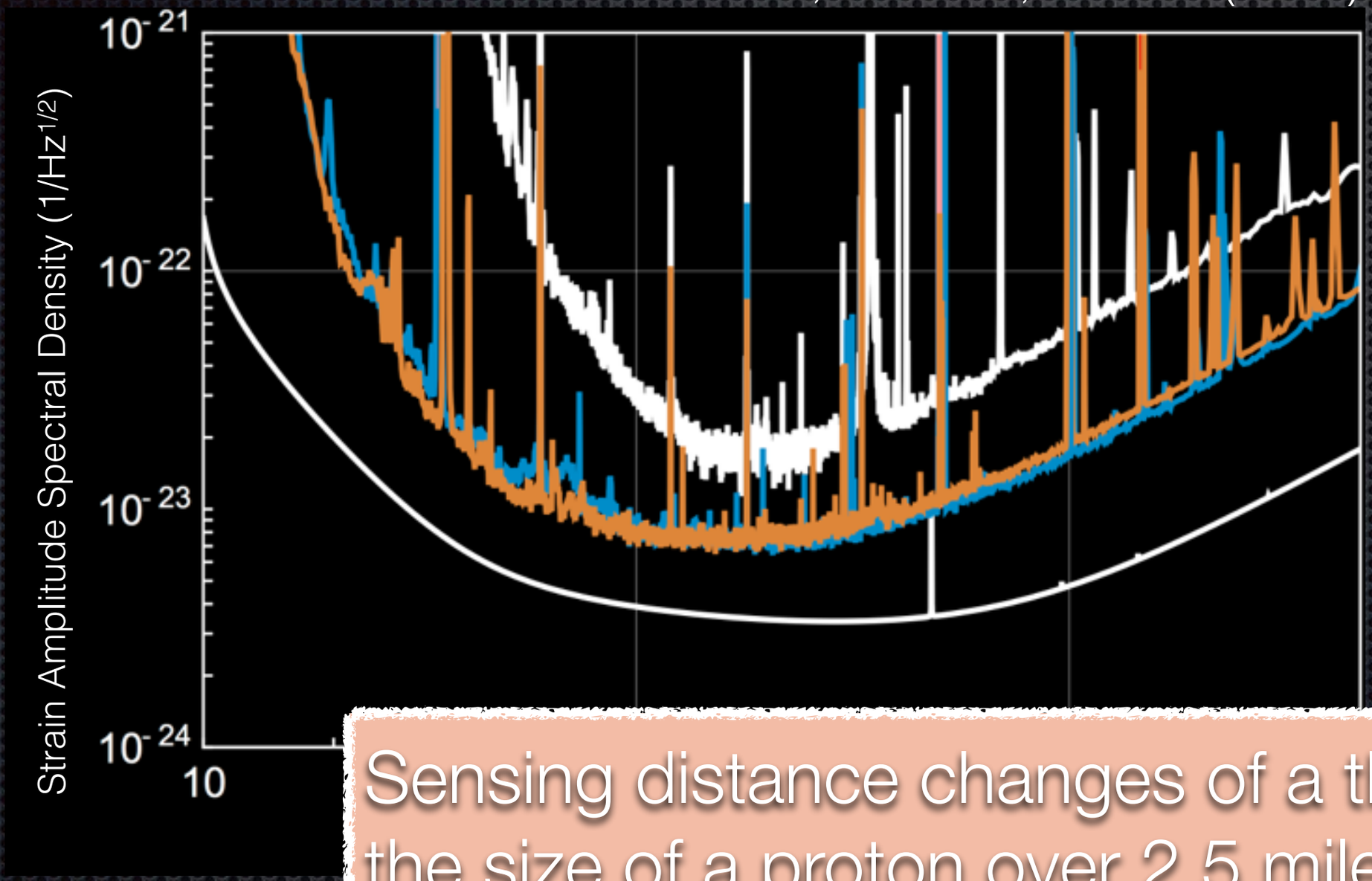
How does LIGO work?



LIGO is the most precise measuring tool ever made

LIGO should blow your mind!

Abbott+, PRL **116**, 131103 (2016)



Initial LIGO
Hanford
Livingston
aLIGO
Design

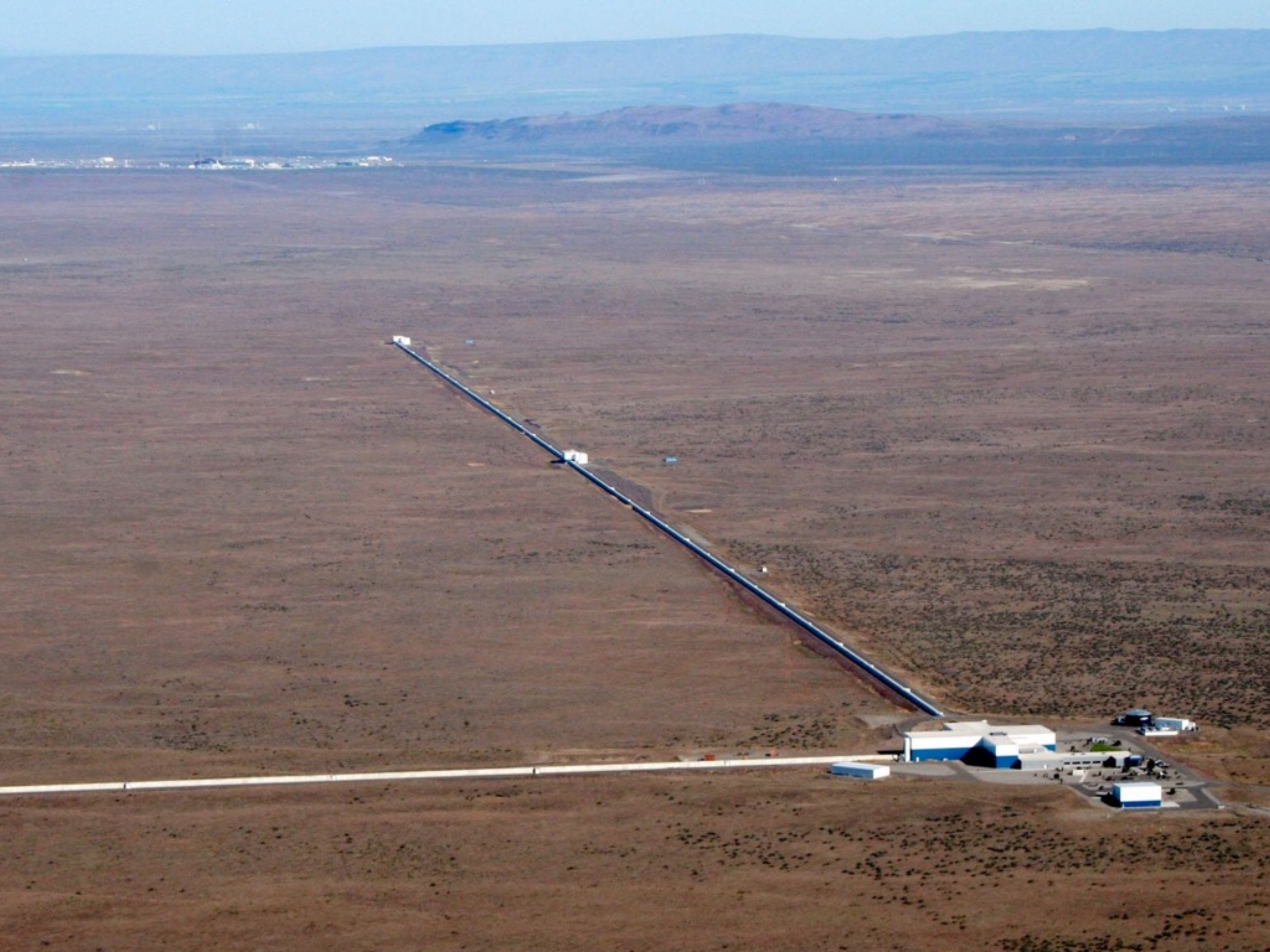
Sensing distance changes of a thousandth the size of a proton over 2.5 miles

Why did this take 100 years?

- Gravi hey pass by
- A "lou hange the distar tar (4.3 light hair!

Earth

Alpha Centauri



LIGO Scientific Collaboration

- Over 1,000 scientists from 83 institutions in 15 countries
- Many types of scientists involved: theorists, experimenters, data analysts, engineers, astrophysicists…

LIGO Scientific Collaboration

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
Whitman College
American University
University of the West of Scotland
UWS
Texas Tech University
Tsinghua University
R·I·T
Leland Stanford Junior University
Max Planck Institute for Gravitational Physics
Albert Einstein Institute
University of Strathclyde
Michigan
Massachusetts Institute of Technology
Scientia Vincere Tenebras
Universitas Bruxellensis
NASA
Goddard Space Flight Center
ICTP SAIFR
PAH
CITA | ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique
Università degli Studi del Sannio
The University of Western Australia
University of Cambridge
Montana State University
The University of Chicago
Southern University and Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
The University of Mississippi
The University of Adelaide Australia
University of Minnesota
University of Birmingham
The University of Melbourne
Universitas Scientiarum Szegediensis Szegedi Tudományegyetem
UIB Universitat de les Illes Balears
University of Washington
GEO 600
UTRGV
Tsing Hua University
Sigill. Coll. Carleton Northfield, Minn. A.D. 1866
University of Wisconsin UWMilwaukee
Universität Hamburg
Syracuse University Suos Cultores Scientia Coronat Founded AD 1870
Cardiff University
Prifysgol Caerdydd
Northwestern
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
Penn State
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

Funded by the National Science Foundation

September 14, 2015

[calibration] Very interesting event on ER8 ligo x

Marco Drago <marco.drago@aei.mpg.de> 9/14/15

to burst, cbc, LIGO, Calibration, dac, burst, detchar, losc-devel, lsc-all

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

It is not flag as an hardware injection, as we understand after some first investigation. Someone can confirm that is not an hardware injection?

Eric Chassande-Mottin <ecm@apc.univ-paris7.fr> 9/14/15

to burst, cbc

Hi Marco,

very interesting indeed! Looks like a high-mass inspiral?
I don't see any CBC event in the neighbors section of the GraceDB entry.
Does that mean that GST LAL nor MBTA saw the event?

Andrew P Lundgren <aplundgr@syr.edu> 9/14/15

to burst, calibration, cbc, LIGO, dac, burst, detchar

Hi all,

The Omega scans have finished and I do not see any DQ issues at the time of the trigger. The data looks quite clean at both detectors, except that H1 is slowly and steadily losing inspiral range.

Klimenko, Sergey <klimenko@phys.ufl.edu> 9/14/15

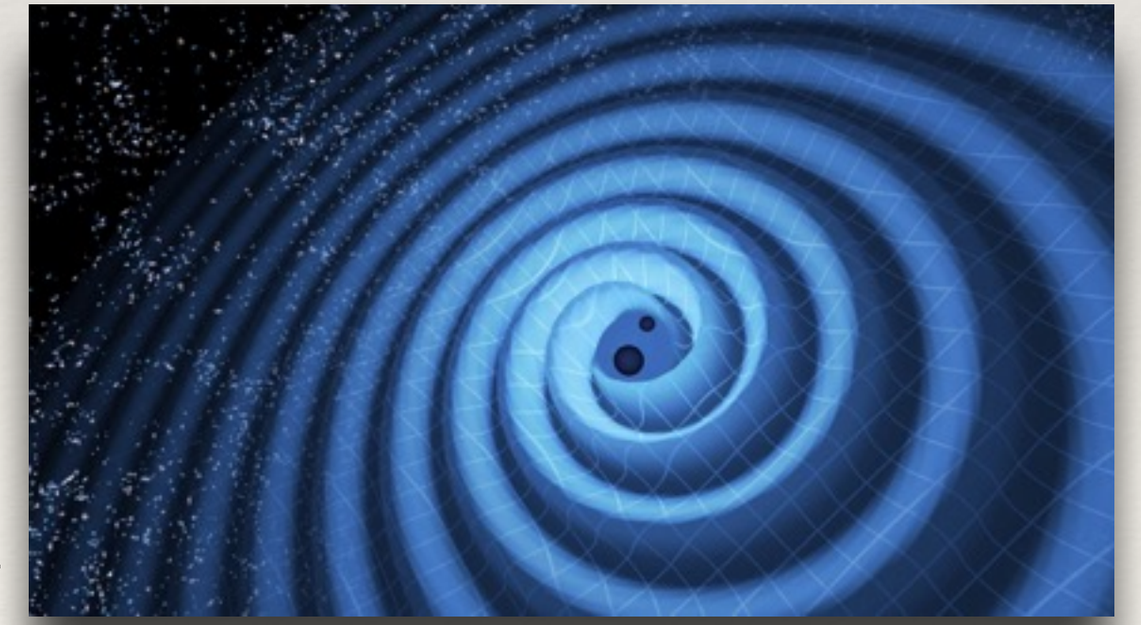
to David, Gabriela, Dave, Stan, burst, calibration, cbc, dac, detchar

This is clean and very significant inspiral with Mchirp = 27 +- 2 Mo.
The polarization is close to circular.
The cWB ER8 offline analysis accumulated ~236 years of background
so far, this event FAR << 1.e-10 Hz. If this is not injection,
I guess, we need to do the detection checklist...
Sergey

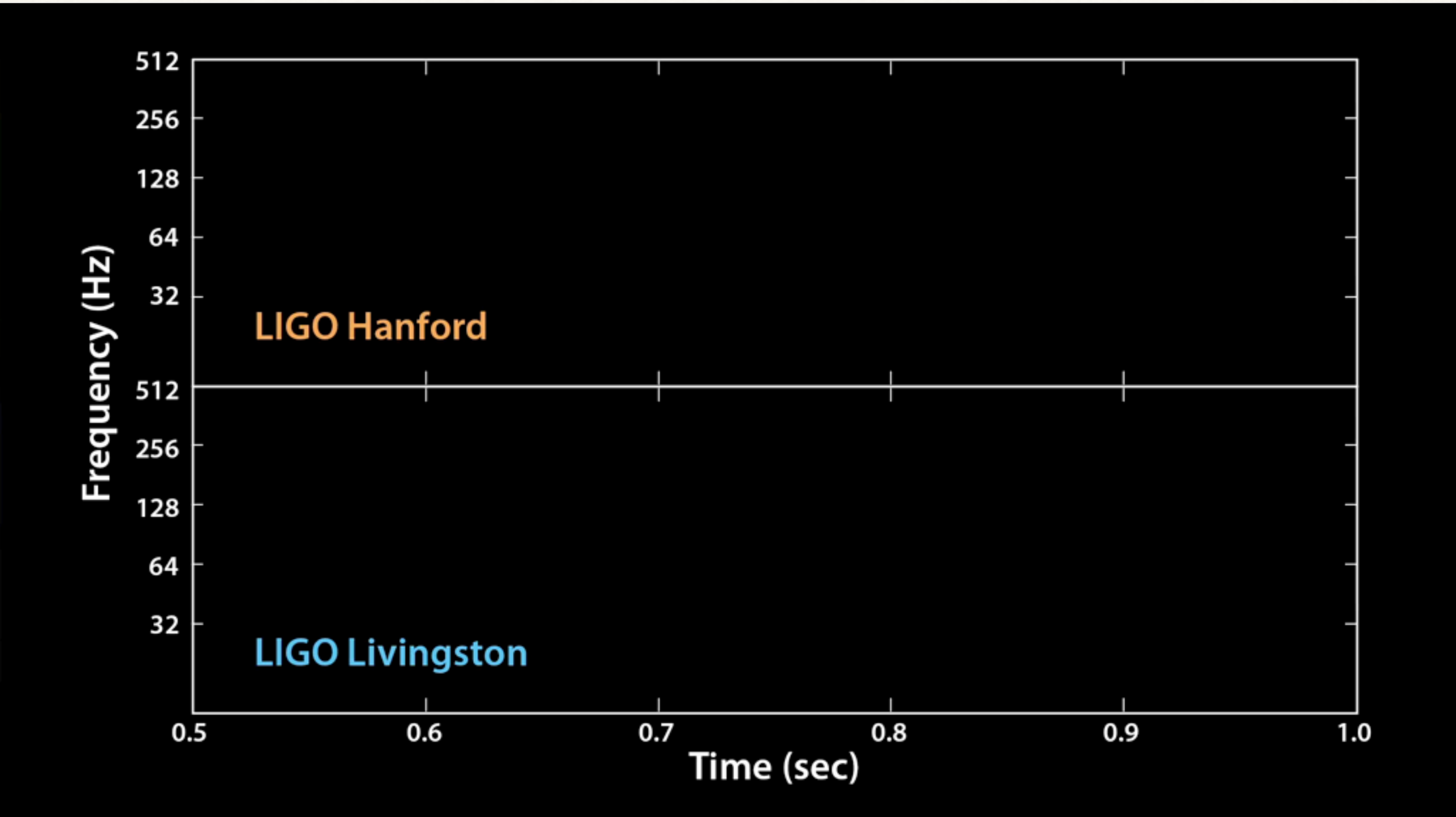
- All within 2.5 hours of the event!

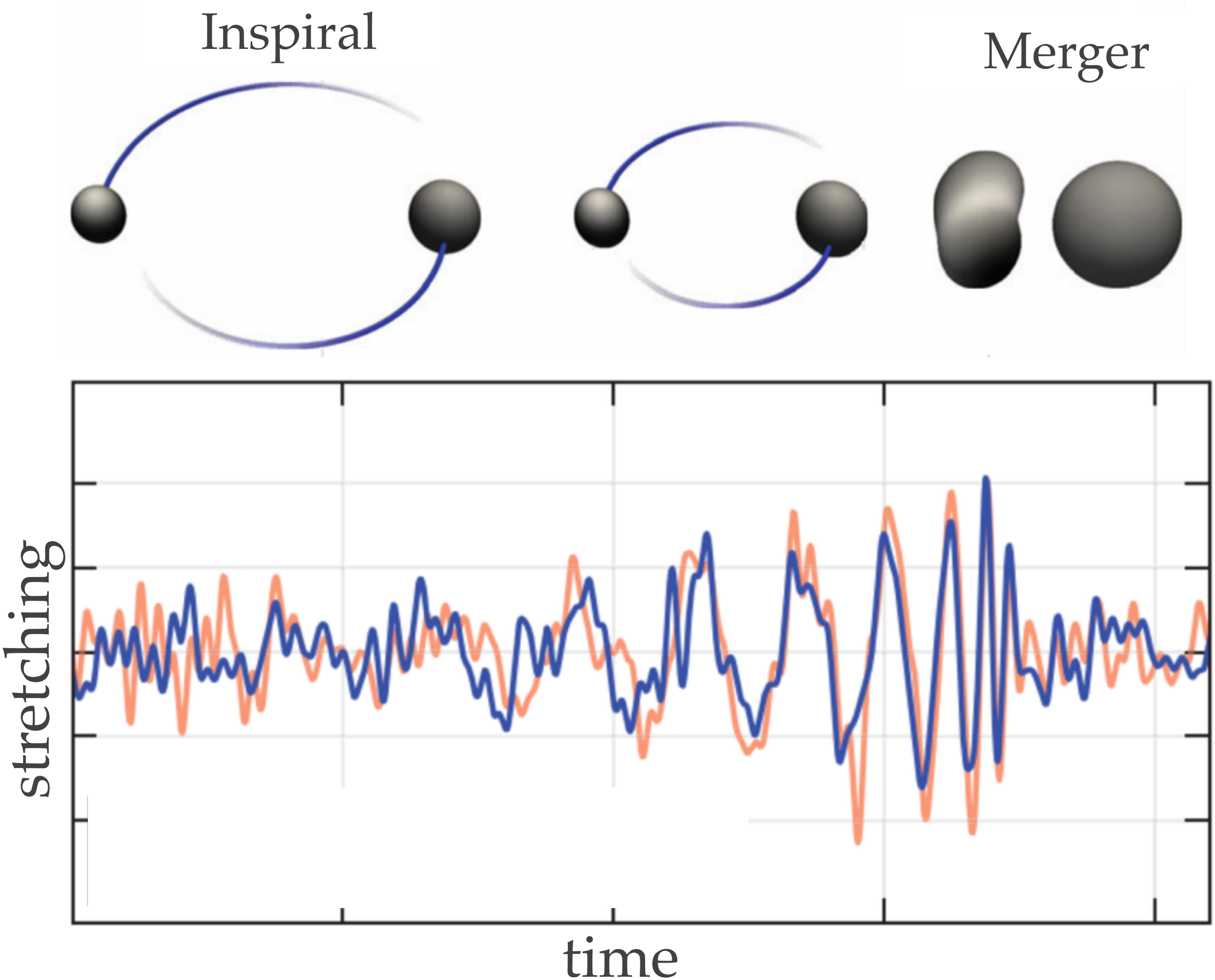
What did we detect?

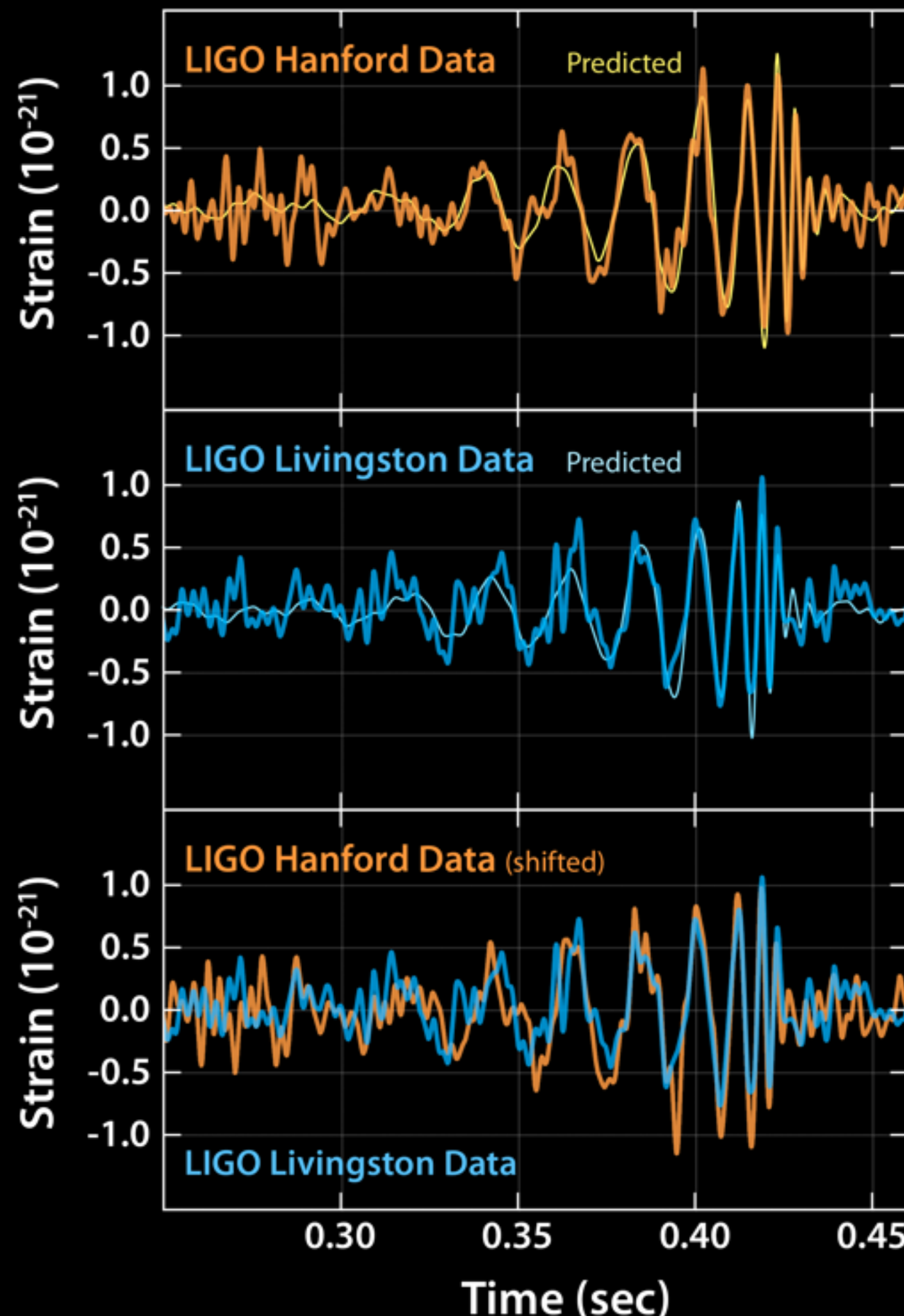
- Two black holes crashing into each other at over half the speed of light
- Each black hole was 30 times more massive than the Sun
- These black holes were 1 billion trillion miles away
- For a fraction of a second this event emitted more energy than all the stars in the Universe **combined**



The sound of 2 black holes colliding

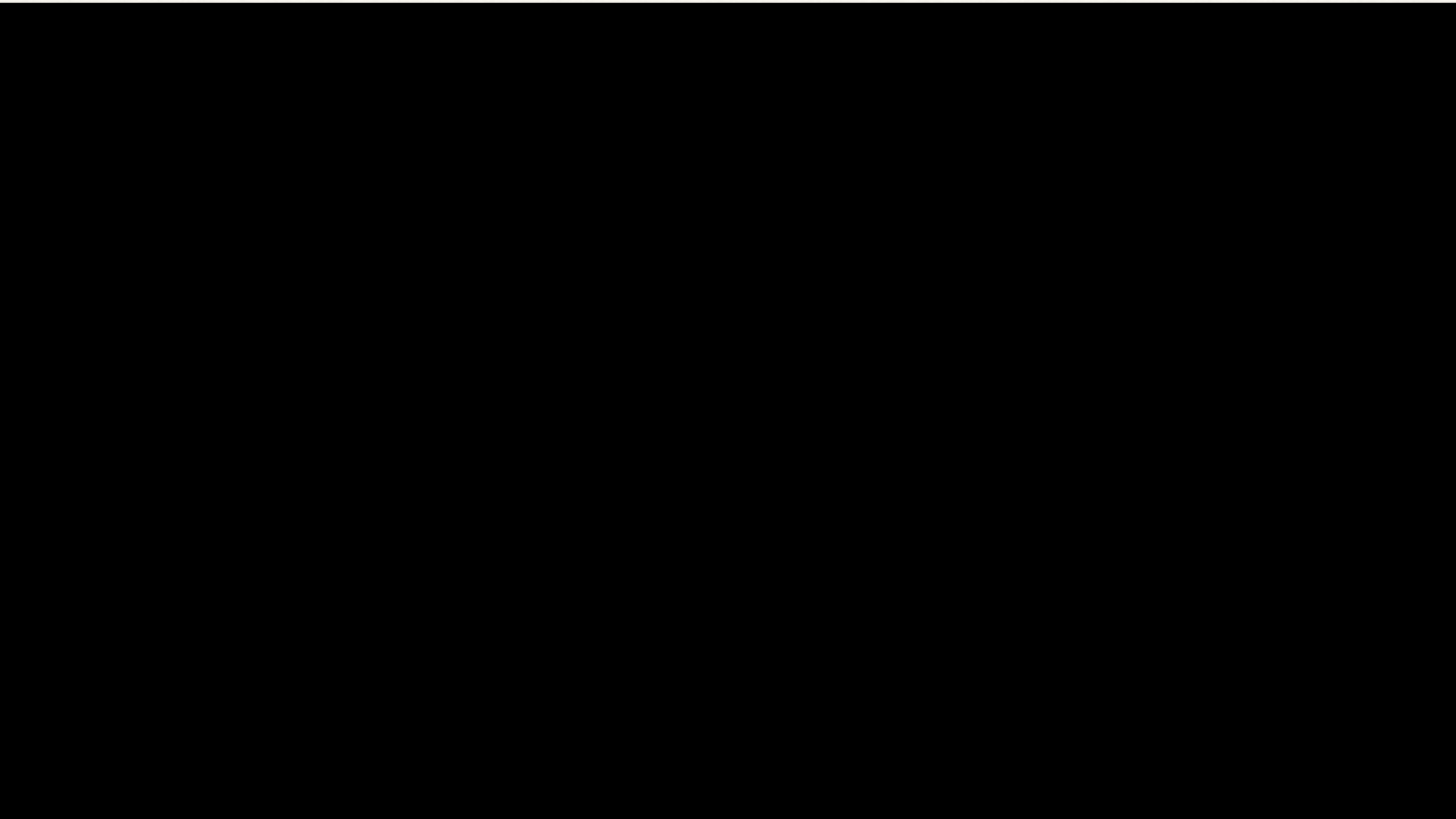



Inspiral
Merger
stretching
time

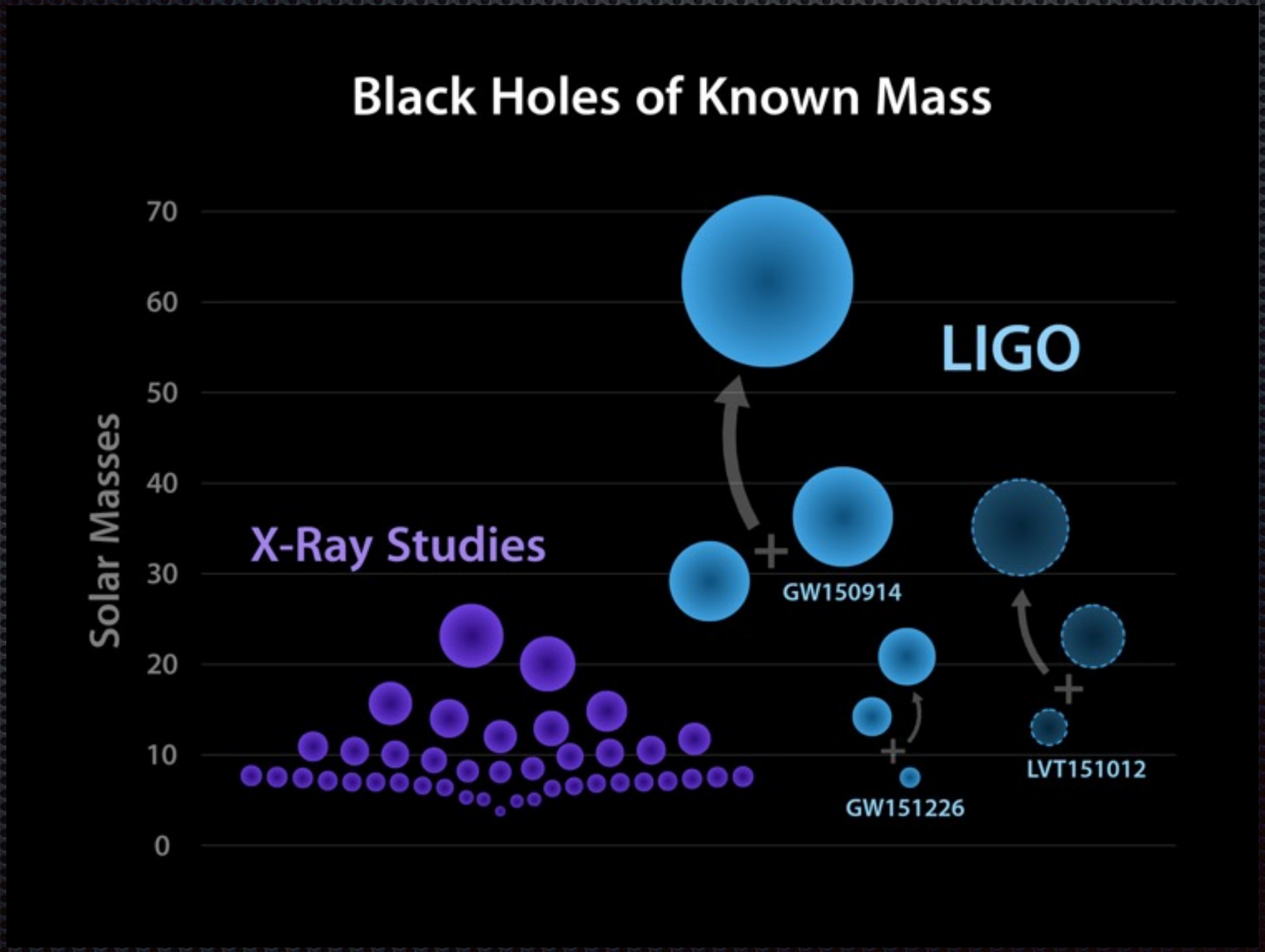

LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

December 26, 2015

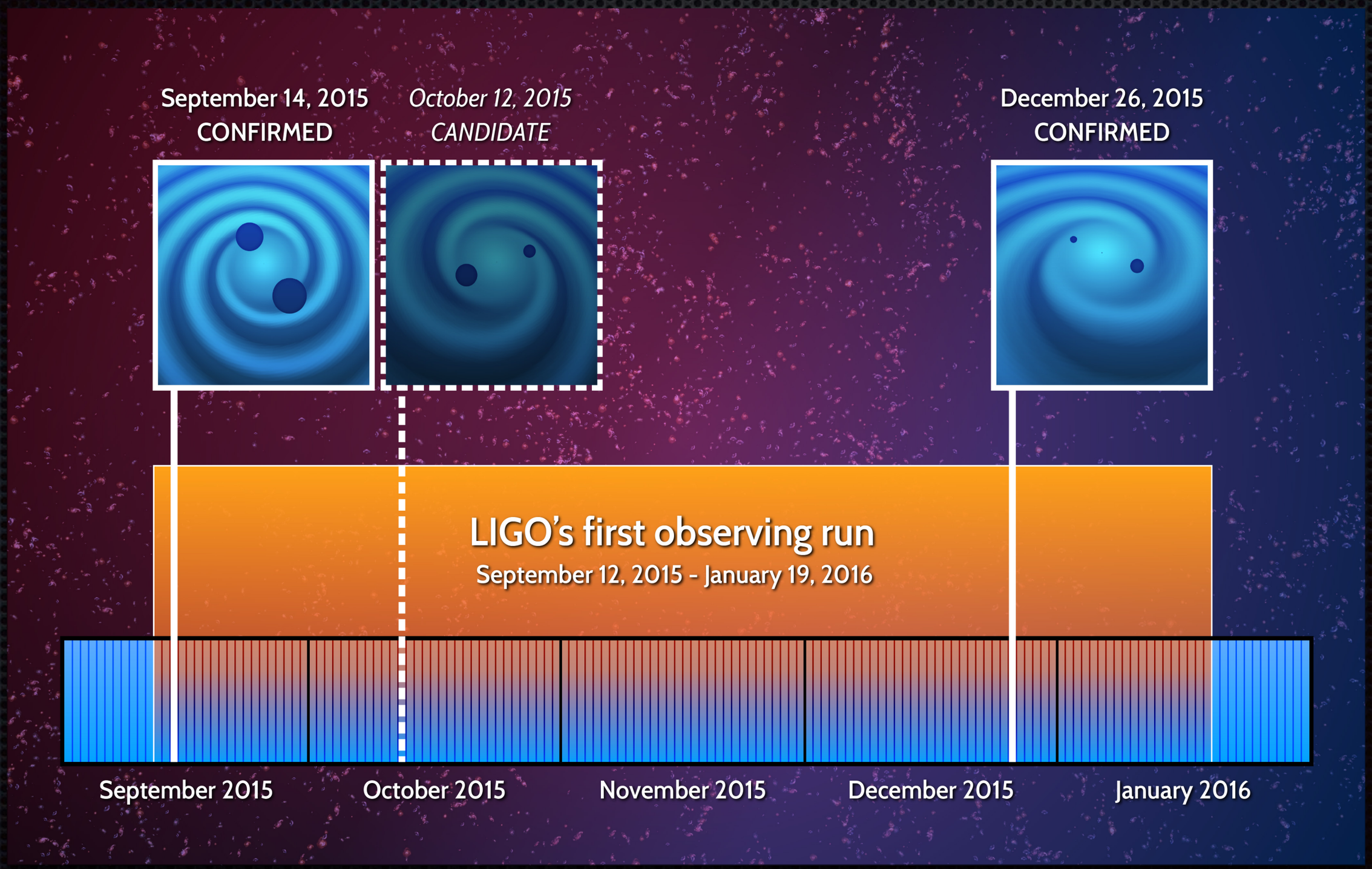
Another sound of 2 black holes colliding



The masses of all known stellar black holes

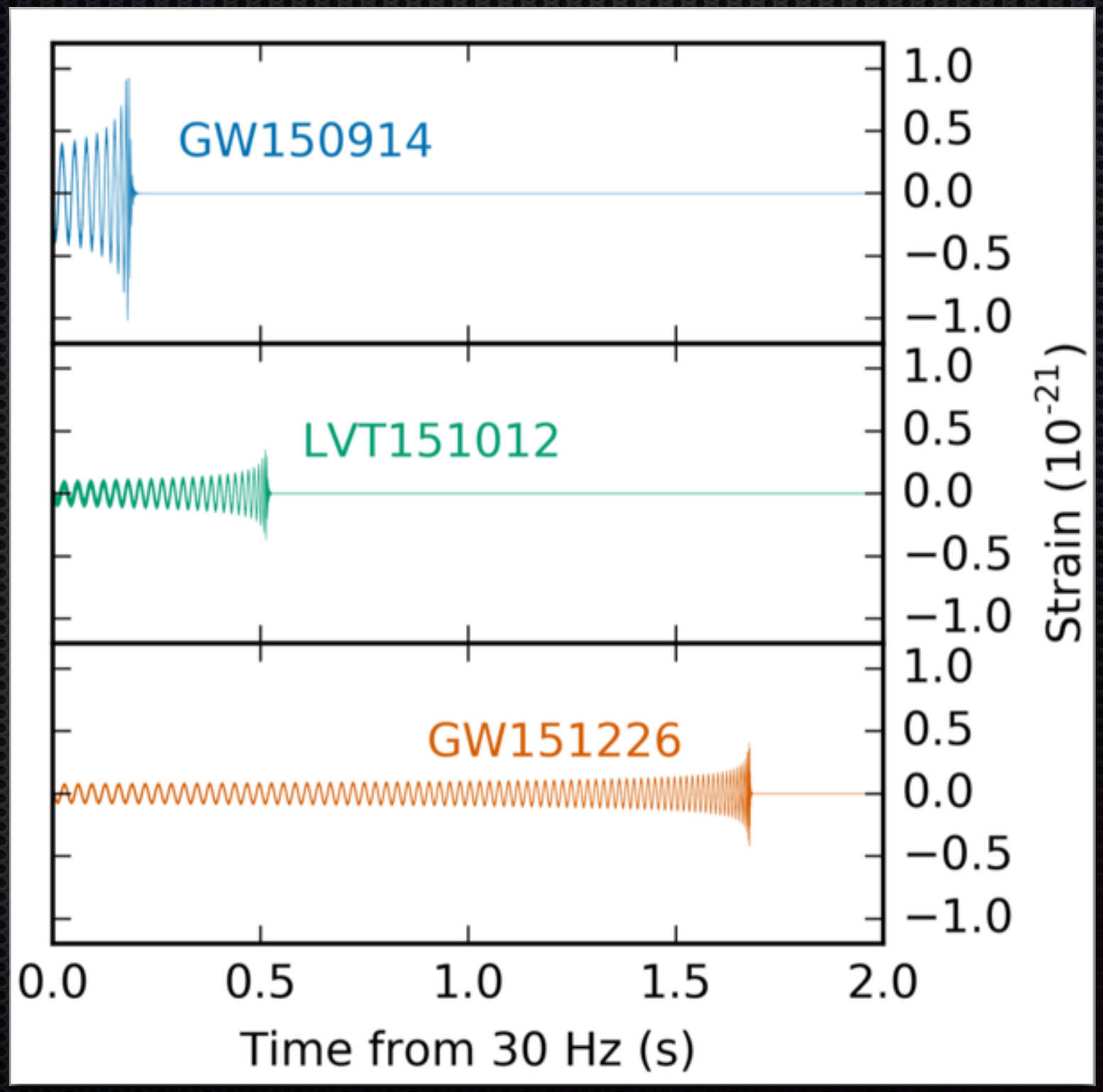


2.9 Sources

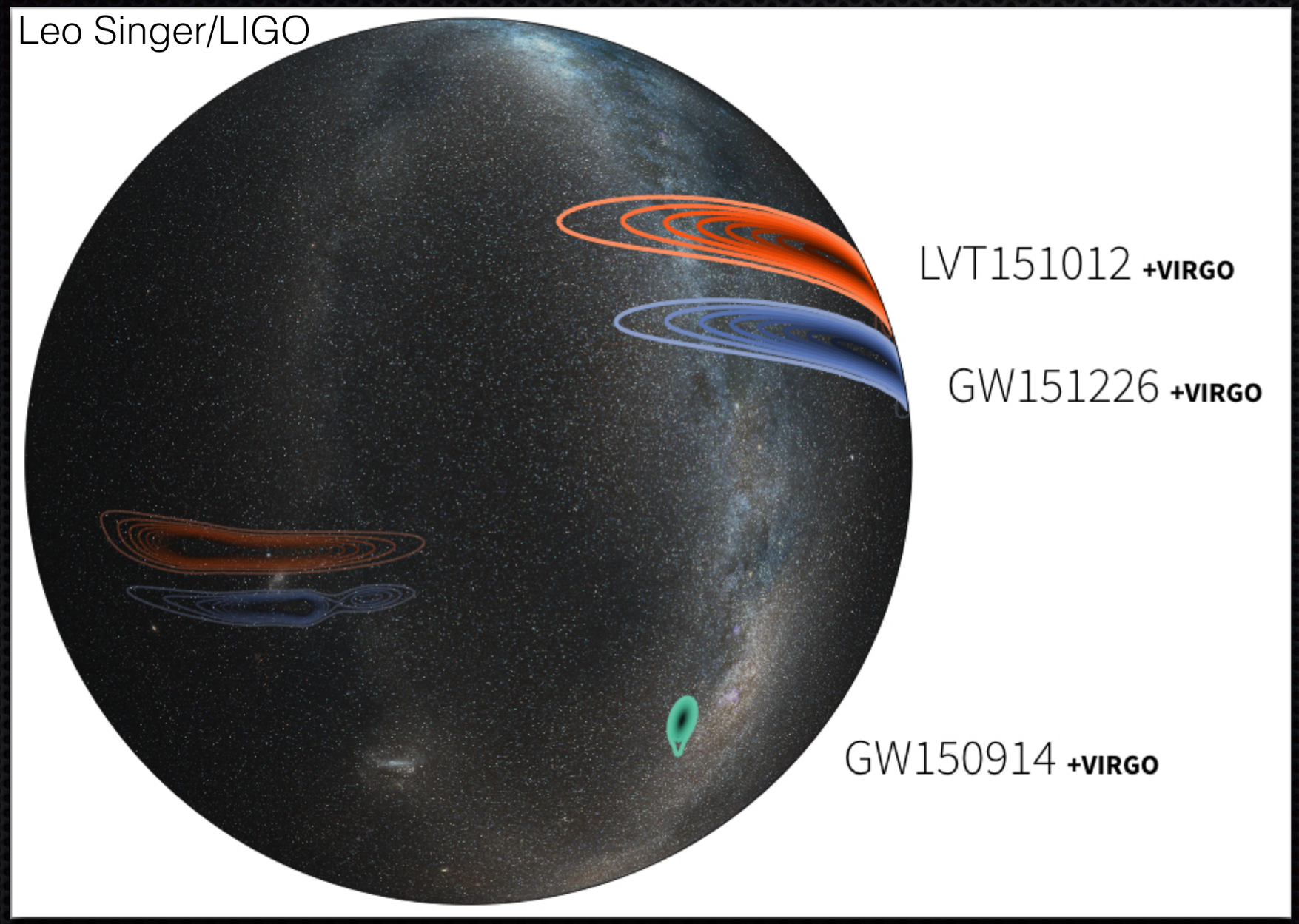

September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

Waveforms

Abbott+, arXiv:1606.04856

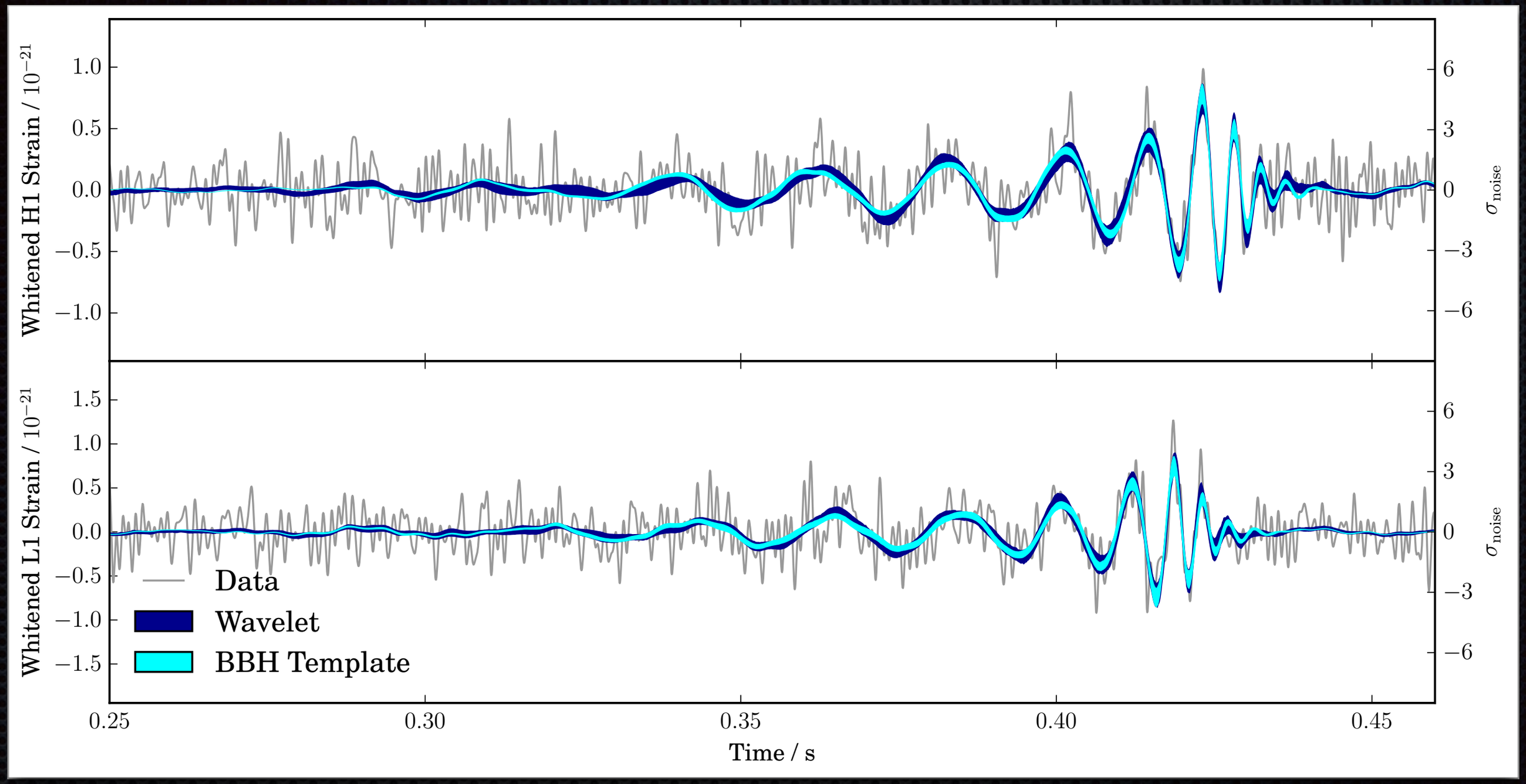


Where on they on the sky?



- Virgo (or another detector) would dramatically improve localization

Are they really black holes?

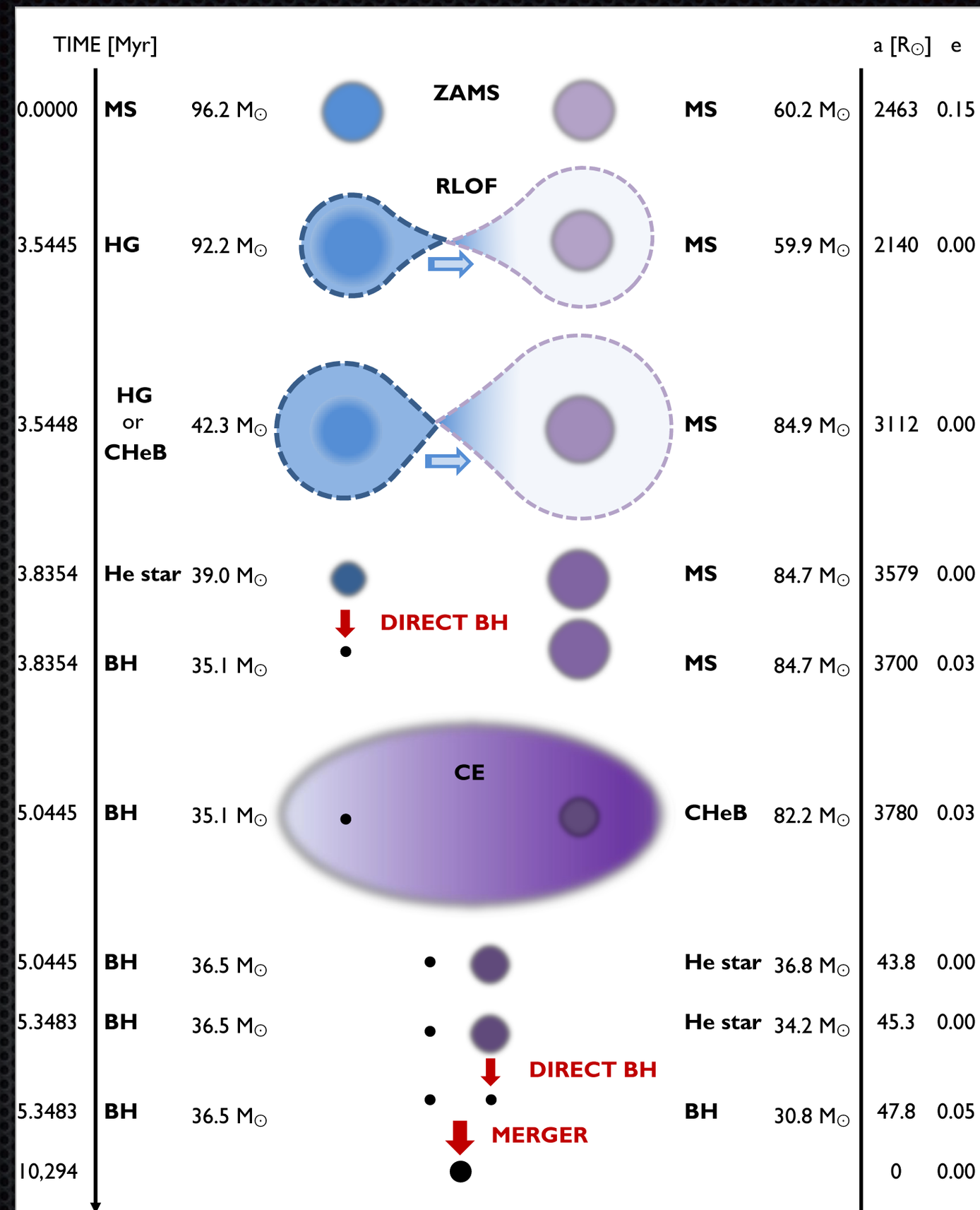


Abbott+, *PRL* **116**, 241102 (2016)

- Whitened data
- Wavelet is unmodeled sine-Gaussian (no general relativity)
- BBH template is general relativity
- Agreement between Wavelet and GR!

How did the Universe make these black holes?

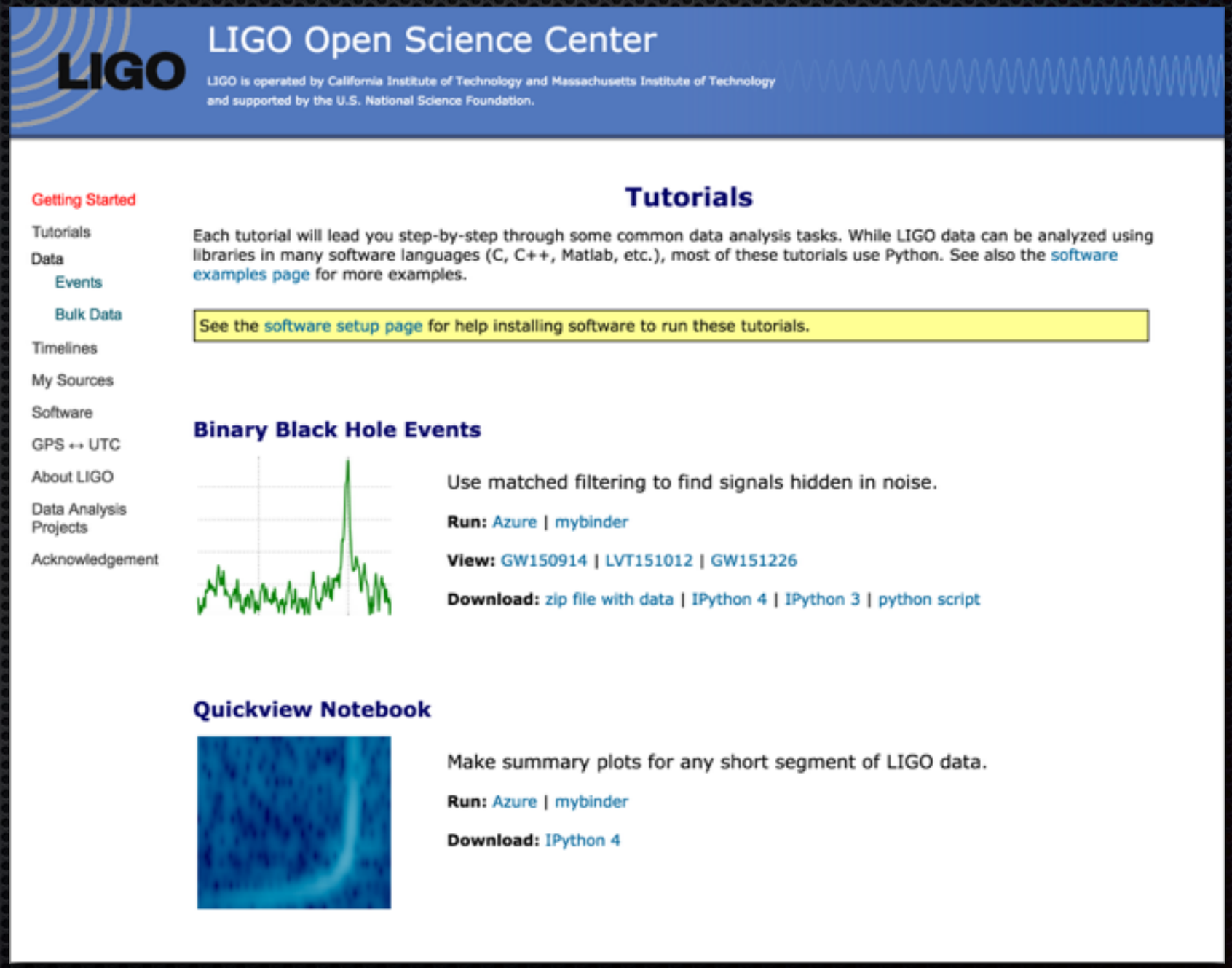
- Example of a binary similar to GW150914, from birth, through evolution, to merger
- Lots of complicated astrophysics!



Belczynski, Holz, Bulik, & O'Shaughnessy, *Nature* **534**, 7608 (2016)

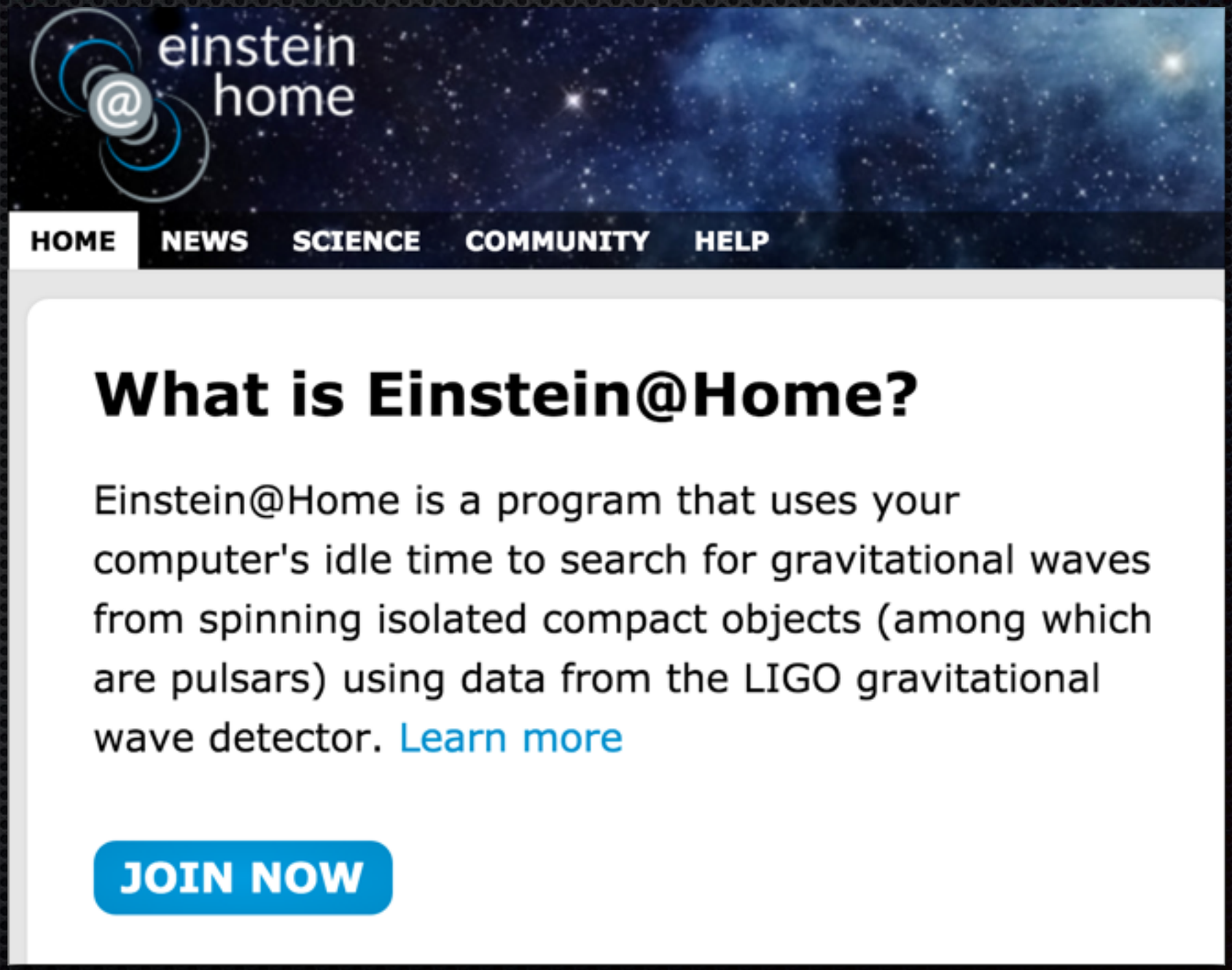
You can analyze LIGO data!

- LIGO Open Science Center: losc.ligo.org
- All analysis code is public
- IPython notebooks



You can contribute to LIGO analysis!

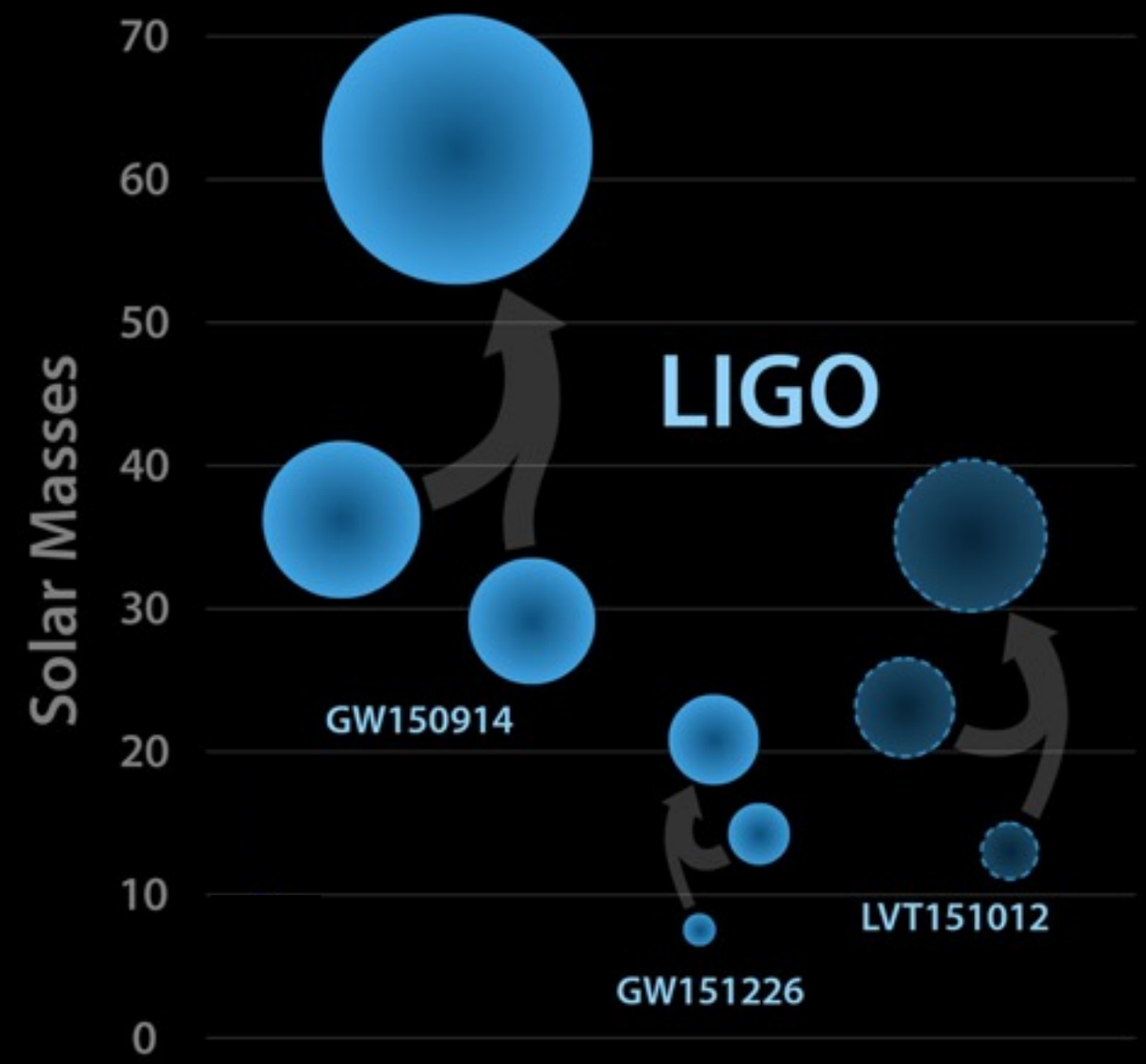
- Einstein@Home
- Help us search for spinning neutron stars!



You can contribute to LIGO analysis!

- Zooniverse: GravitySpy
- Look for interesting sources in LIGO data

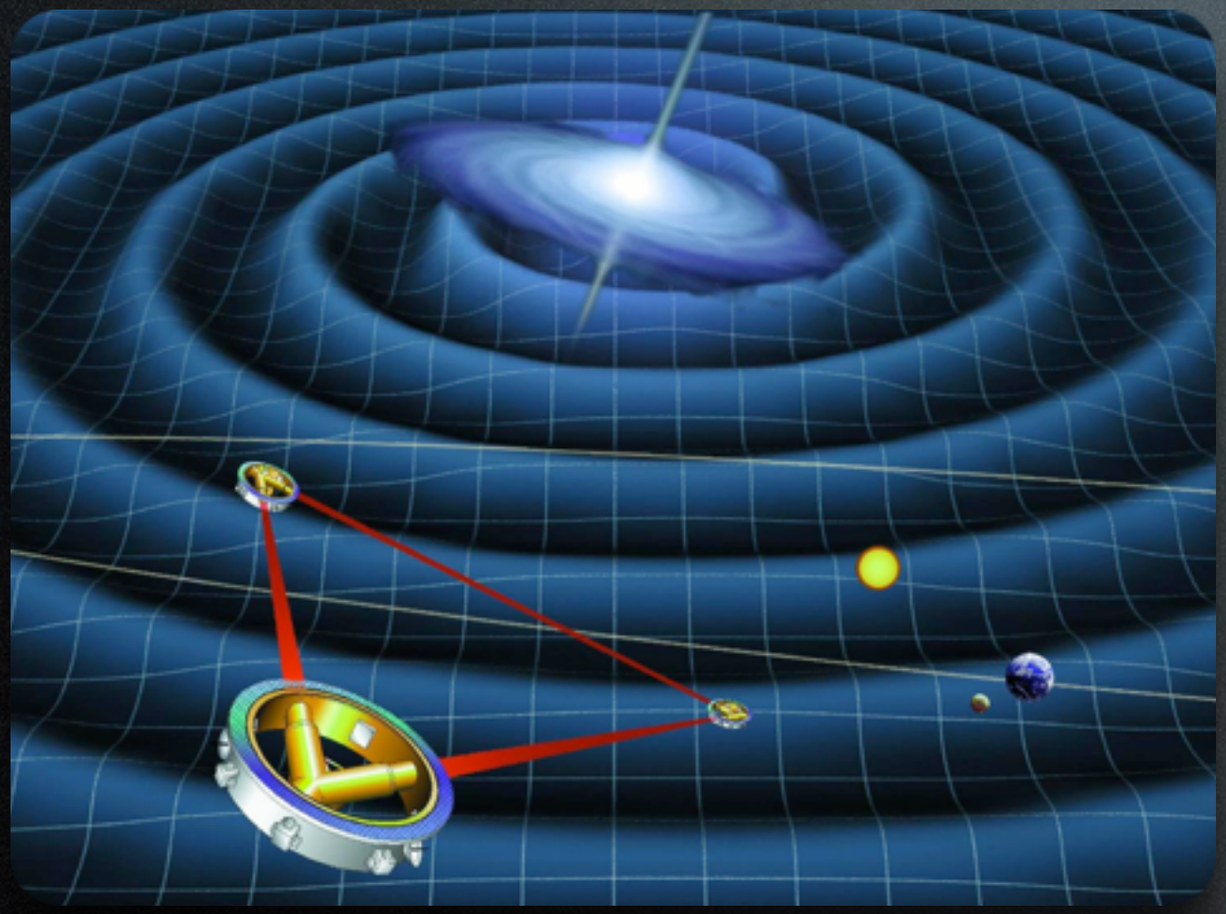
What happens next?



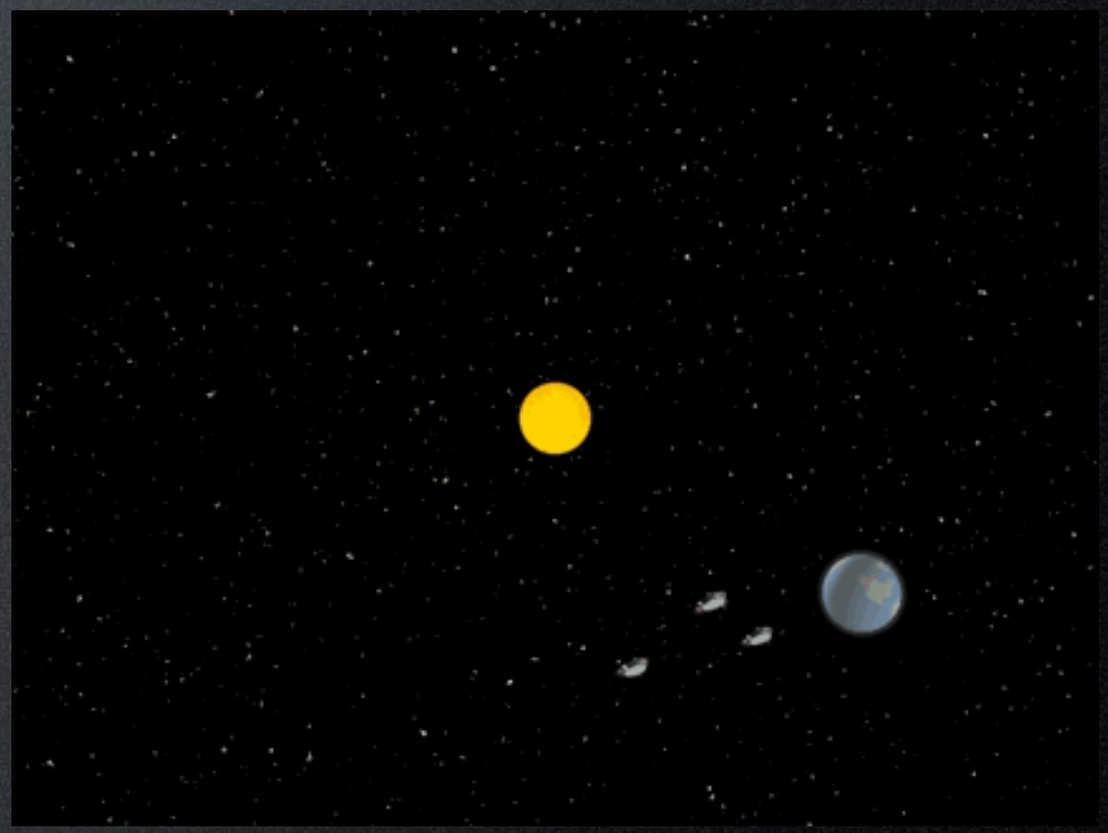
LIGO turns back on next month!

Worldwide GW network

Detecting gravitational waves in space!



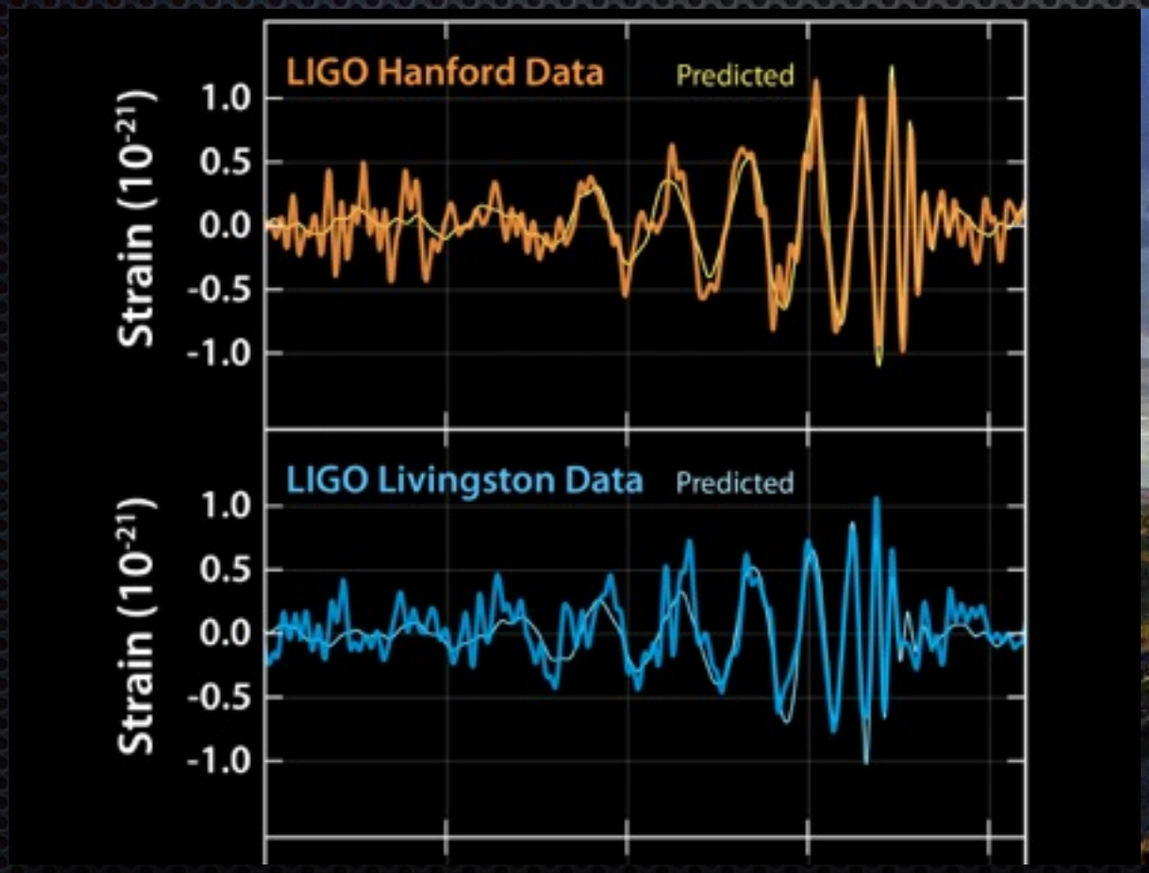
Laser Interferometer Space Antenna (LISA)



Detects supermassive black hole mergers anywhere in the Universe

We have a new way to
listen to the Universe

We hear the echoes from black holes crashing into each other billions of lightyears away



What will the Universe tell us next?!