Hearing the Universe: Gravitational-Waves from Black Holes and Neutron Stars

Maya Fishbach
Ask-a-Scientist, Fermilab
November 3, 2019

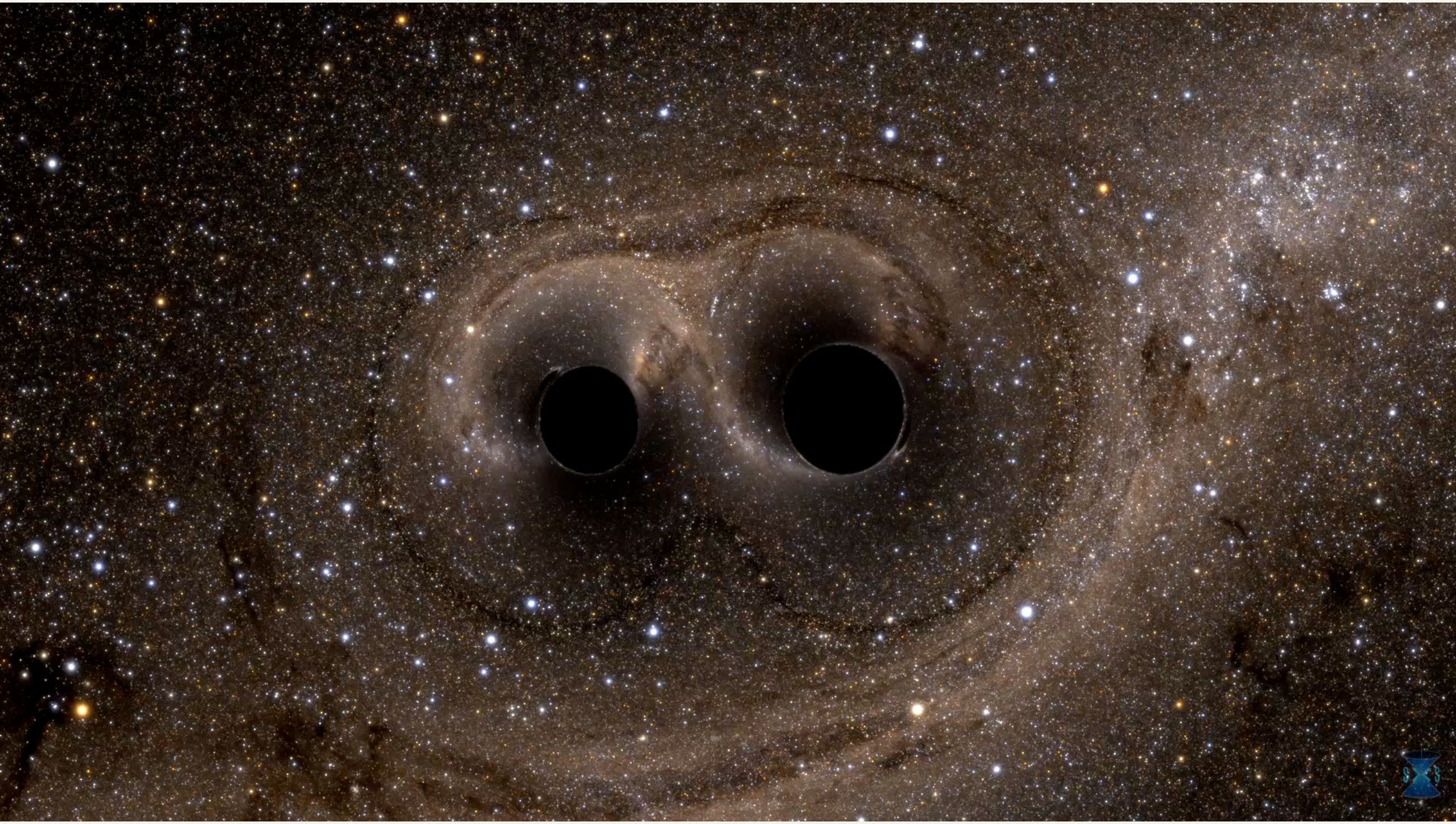
THE UNIVERSITY OF CHICAGO

Today's talk will cover:

- What are **gravitational waves**?
- What are **black holes** and **neutron stars**?
- How can we observe them with gravitational waves?

The First Direct Detection

- On September 14, 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) detects gravitational waves.
- These gravitational waves originate from the collision of two **black holes** 1 billion light years away.
- A new field of astrophysics is born.



Two black holes crashing into each other at over half the speed of light

They were each 30 times the mass of our sun.

They merged about 1 billion light years away.

This event emitted more energy than the entire rest of the Universe **combined** (for a fraction of a second).

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 28. **Tonight,** a flurry or heavier squall late, low 15. **Tomorrow,** windy, frigid, high 21. Weather map, Page A19.

VOL. CLXV . . . No. 57,140 + © 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016 $2.50

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by bashing his past criticism of President Obama — a remark that Mr. Sanders called a "low blow."

With tensions between the two Democrats becoming increasingly obvious, the debate was full of new lines of attack from Mrs. Clinton, who faces pressure to puncture Mr. Sanders's growing popularity before the next nominating contests in Nevada and South Carolina.

She is wagering that even voters excited by Mr. Sanders's inspiring message will reconsider

CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

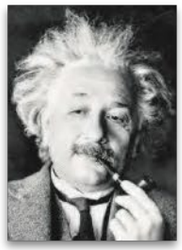
A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most foreboding (and unwelcome) part of his theory.



More generally, it means that a century of innovation, testing, questioning and plain hard work after Einstein imagined it on pa-

Long in Clinton's Corner, Blacks Notice Sanders

Courted Hard in South Carolina, Loyalists Listen Closely

By RICHARD FAUSSET

ORANGEBURG, S.C. — When Helen Duley was asked whom she would vote for in the South Carolina primary, she answered as if the very question were absurd.

"What I'm seeing is a bunch of confusion, hearsay and foolish-

eran: Hillary Clinton."

But that was late January. In-

candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an undecided voter and planned to do some homework on Mr. Sanders.

Mrs. Clinton has long looked forward to the Feb. 27 Democratic contest in South Carolina, the first state where blacks will

Last Occupier In Rural Oregon Is Coaxed Out

This article is by ***Dave Seminara, Richard Pérez-Peña*** *and* ***Kirk Johnson.***

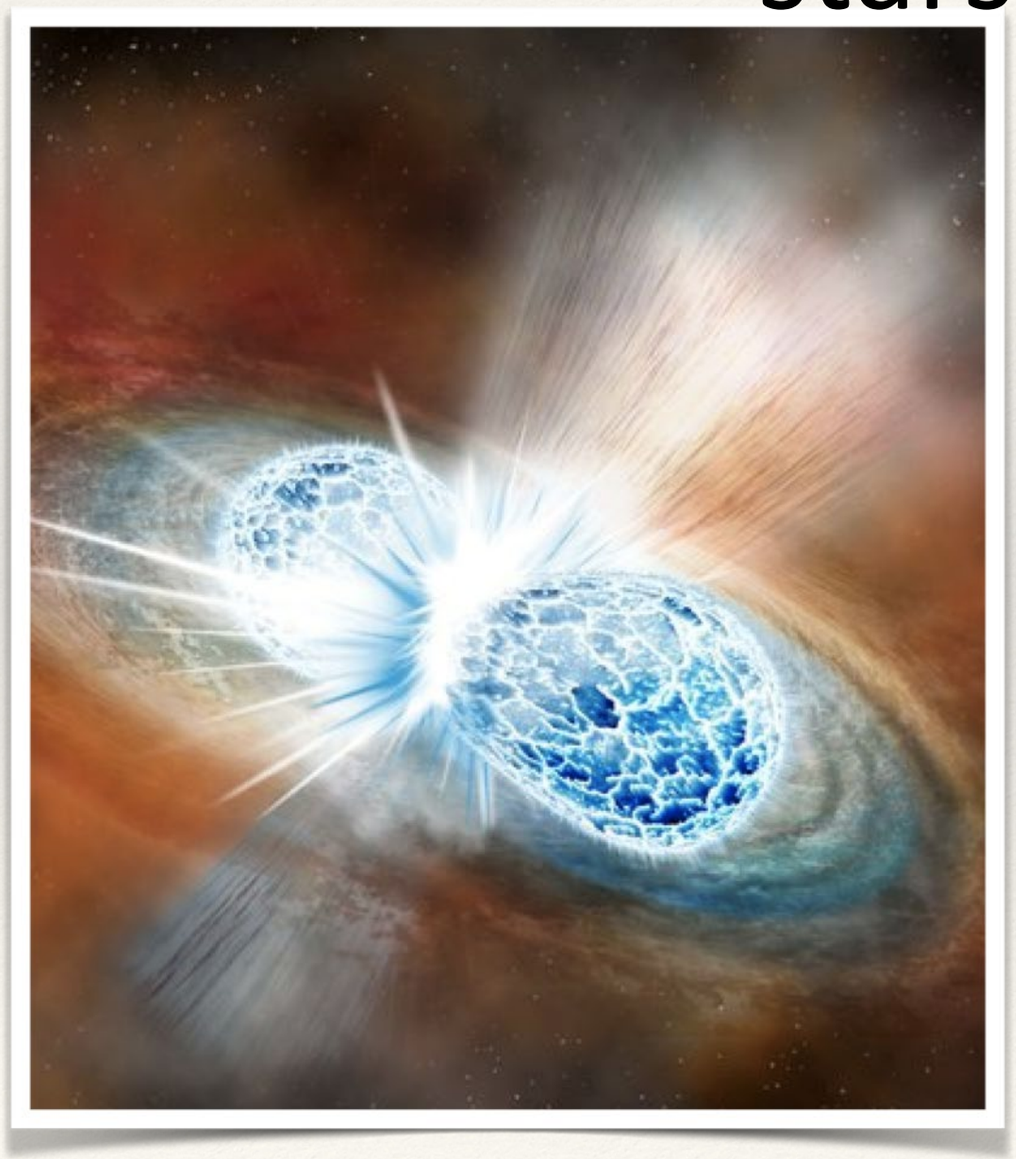
PRINCETON, Ore. — They im-

What is all the excitement about?

- Einstein was right! Gravitational waves exist.
- **Black holes** merge!
- A new way to observe the universe!

Fast forward 2 years…

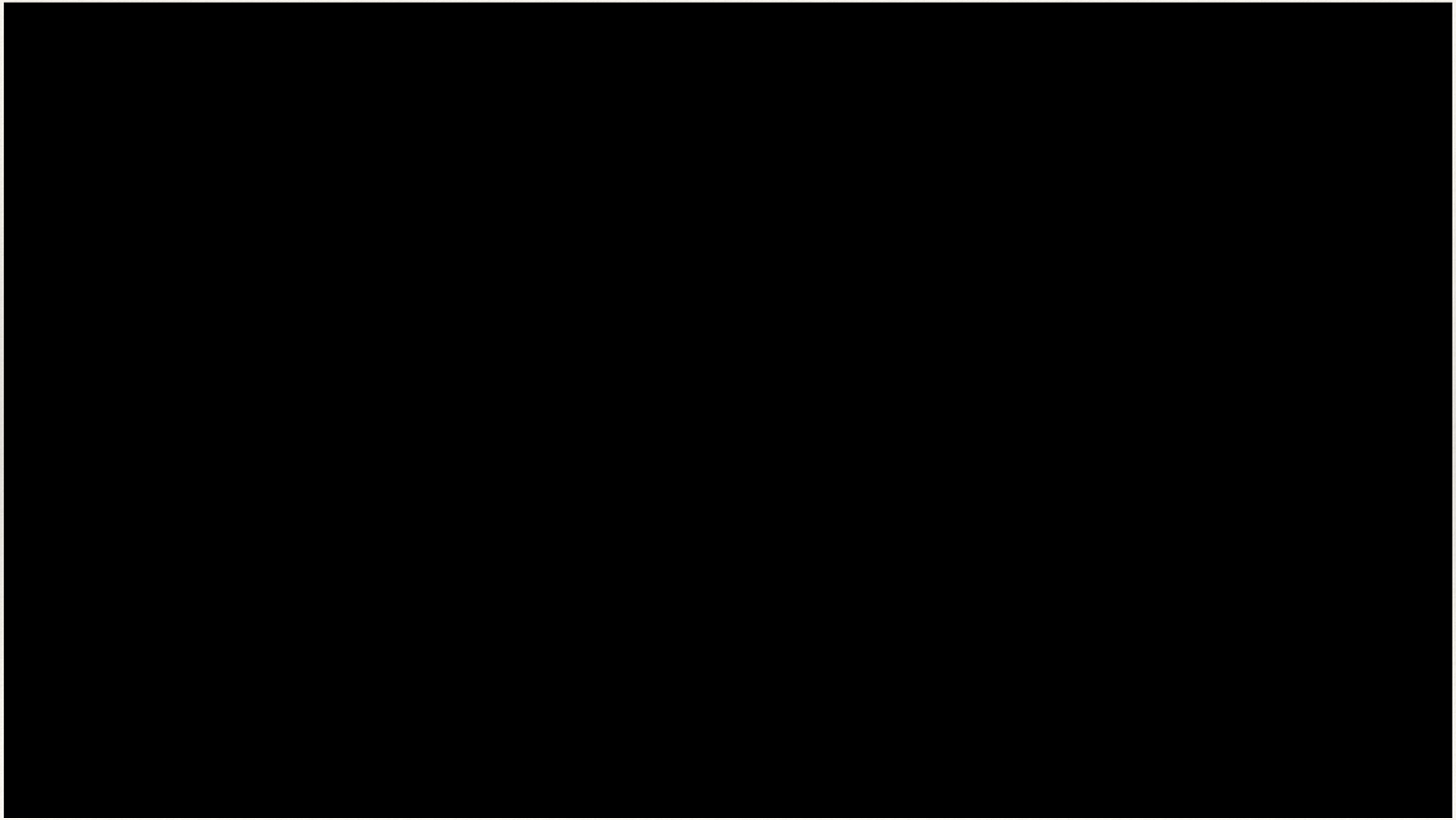
We detected merging neutron stars



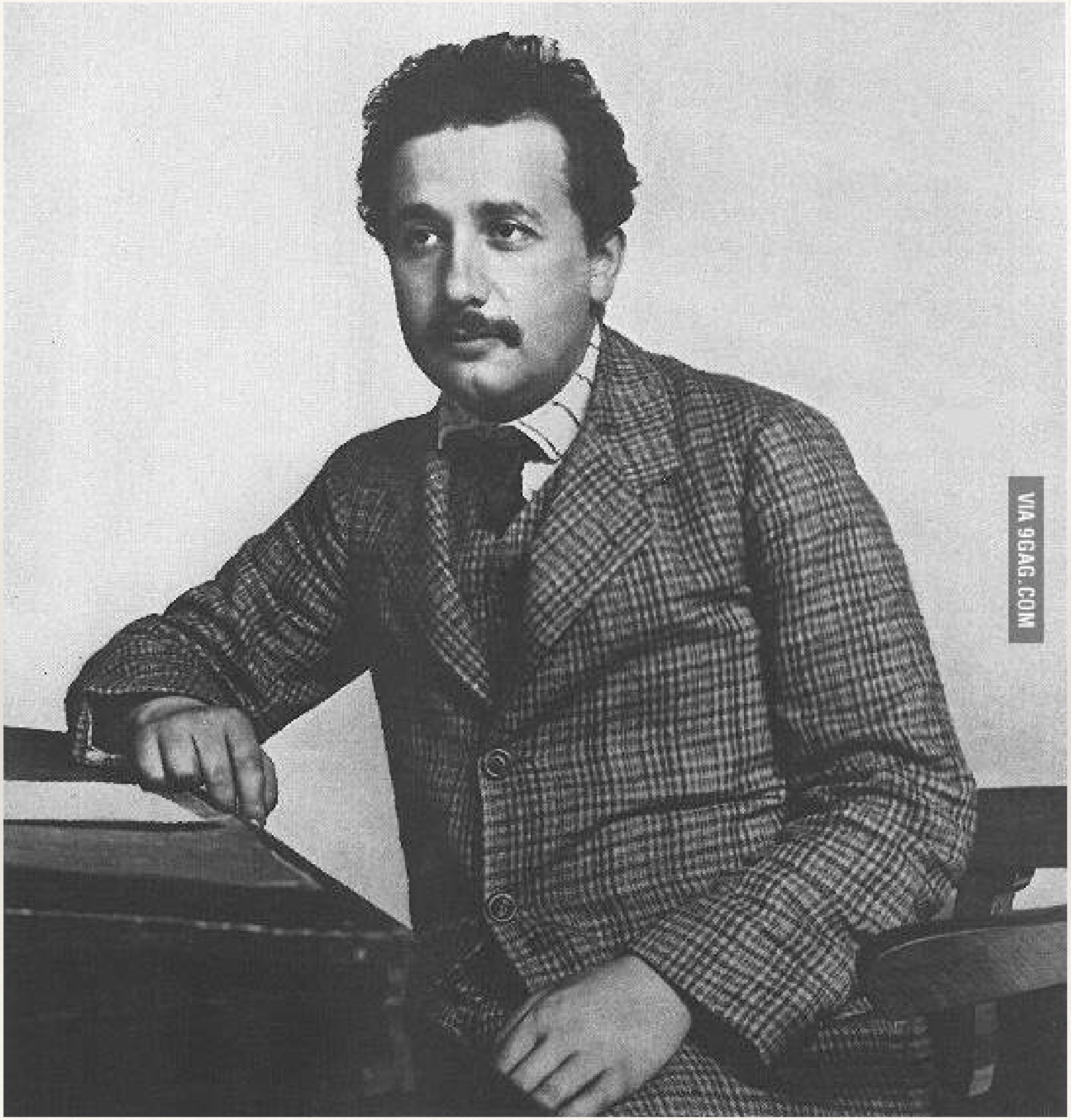
Cosmic fireworks!

August 17, 2017:

First Detection of a Neutron Star Merger

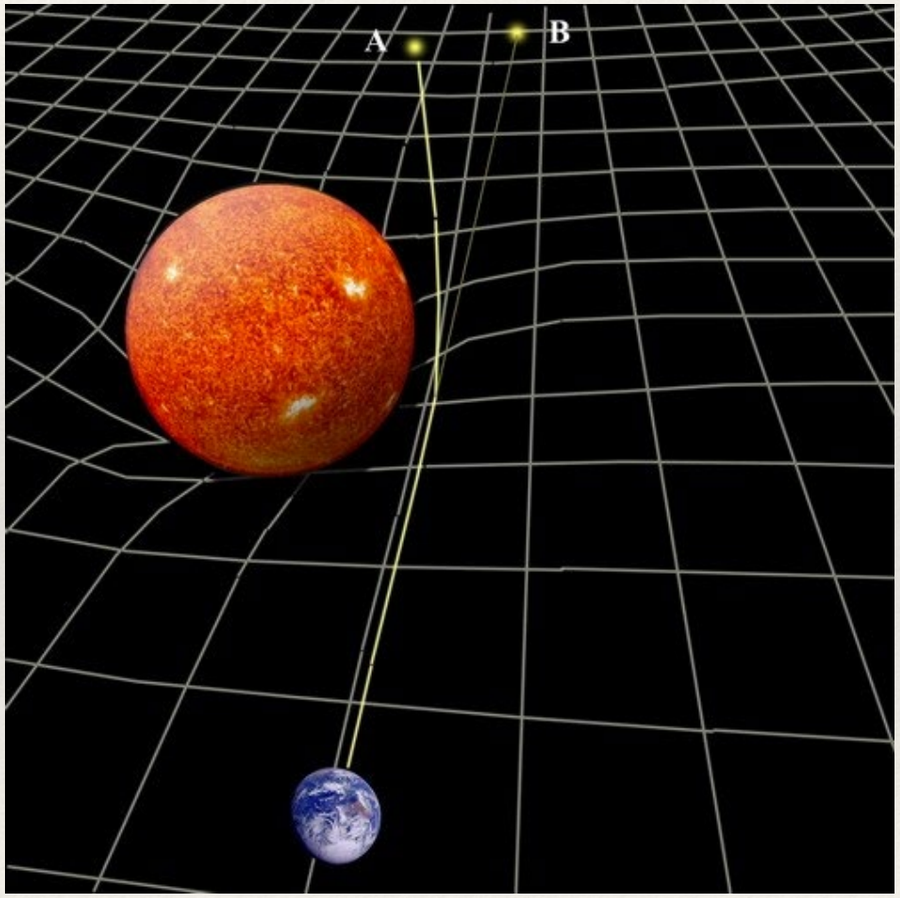


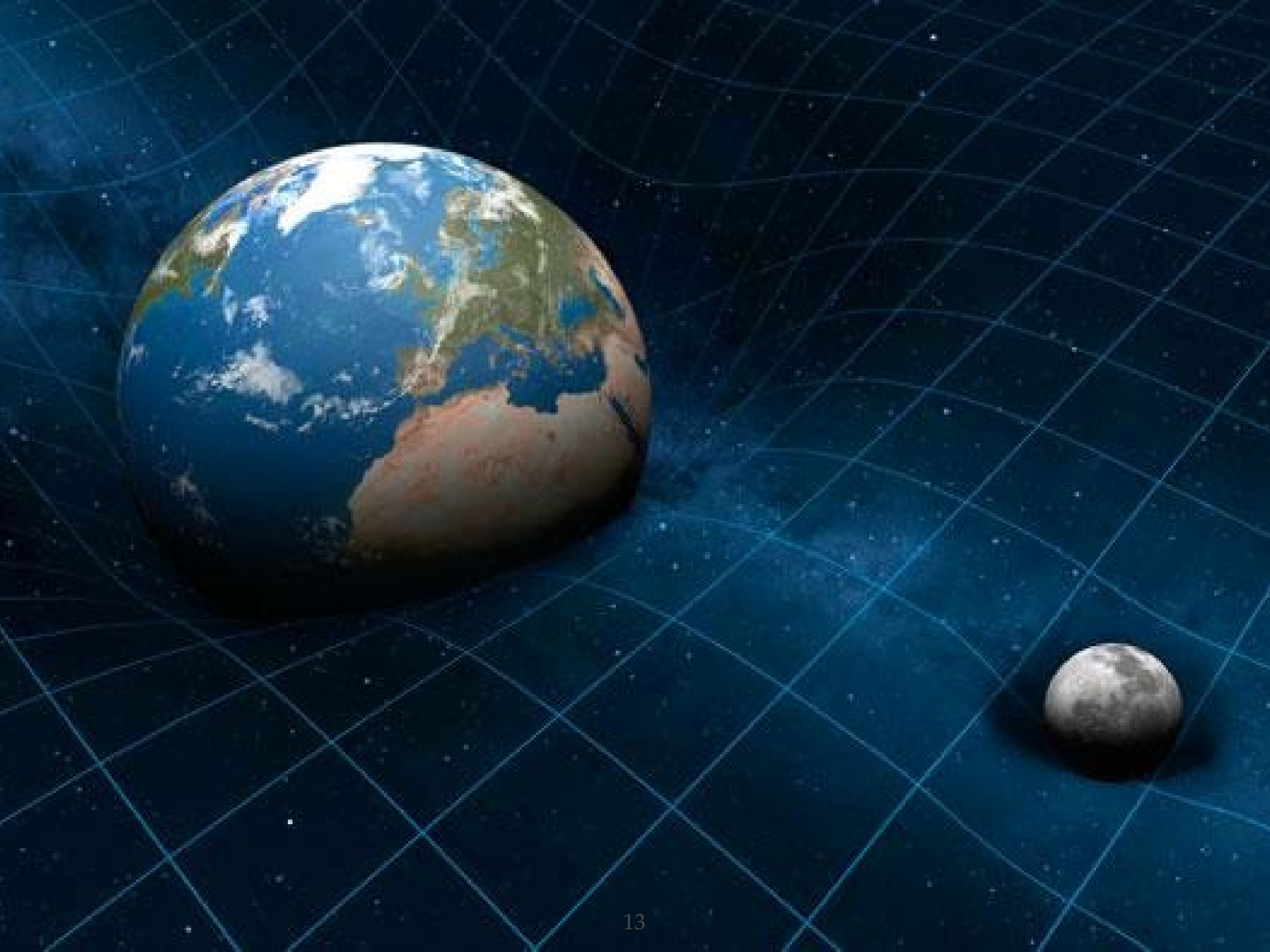
So what are **gravitational waves?**


VIA 9GAG.COM

Einstein's Gravity (1915)

- Space and time are inextricably linked — "spacetime"
- Massive bodies curve spacetime
- Curved spacetime causes objects to move and "feel gravity"
- Gravity is the bending of spacetime!





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

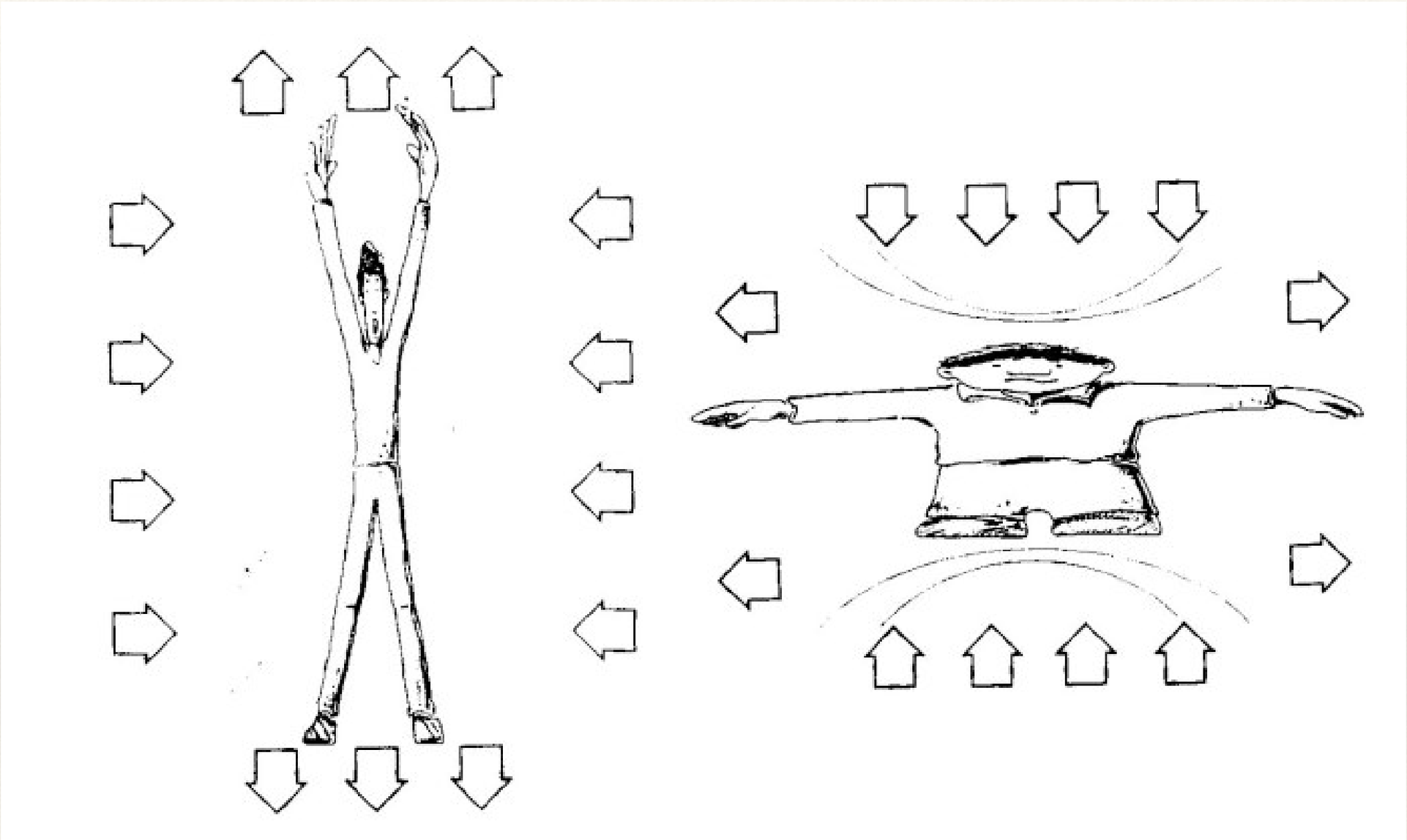
–John Archibald Wheeler

Extremely massive objects moving at extreme speeds cause ripples in spacetime.

These ripples are gravitational waves.

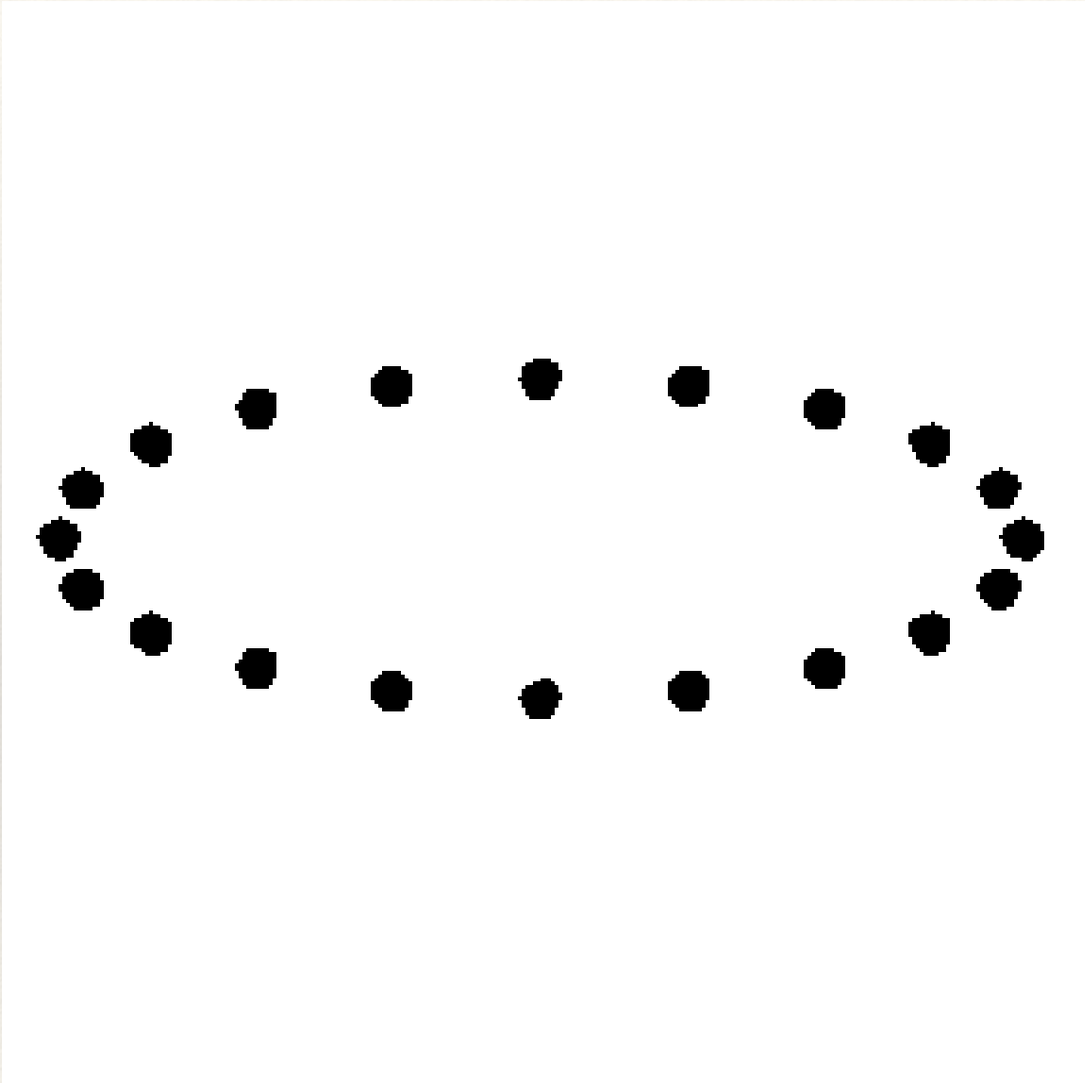
Scale of Effect Vastly Exaggerated

What do Gravitational Waves do?



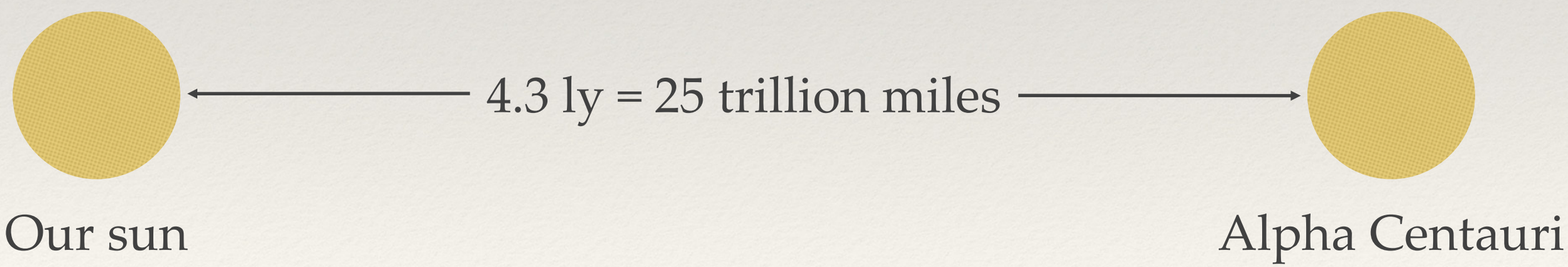
The effect of gravitational waves on matter is to stretch & squeeze it … but the effect is really small.

Visualizing Gravitational Waves



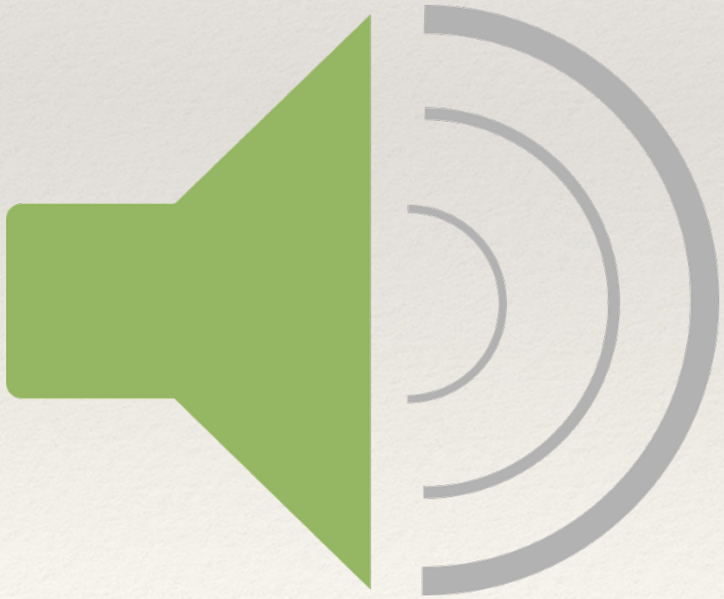
Gravitational Waves Are “Weak”

- A “loud” gravitational wave only changes the distance between our sun and the next closest star (4.3 lightyears away) by the width of a human hair!



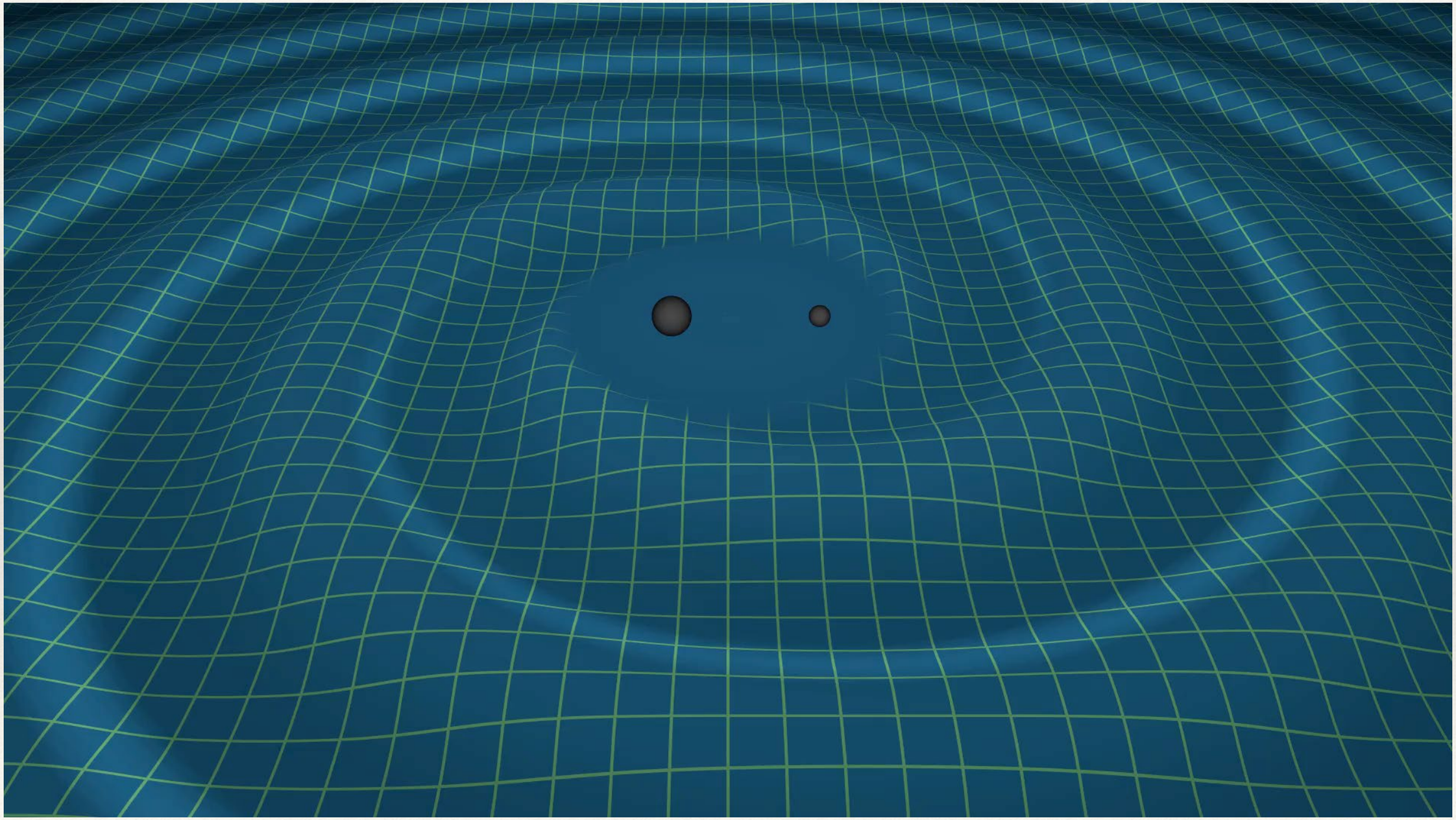
Detection Prerequisites

A “loud” source of gravitational waves



REALLY precise detector

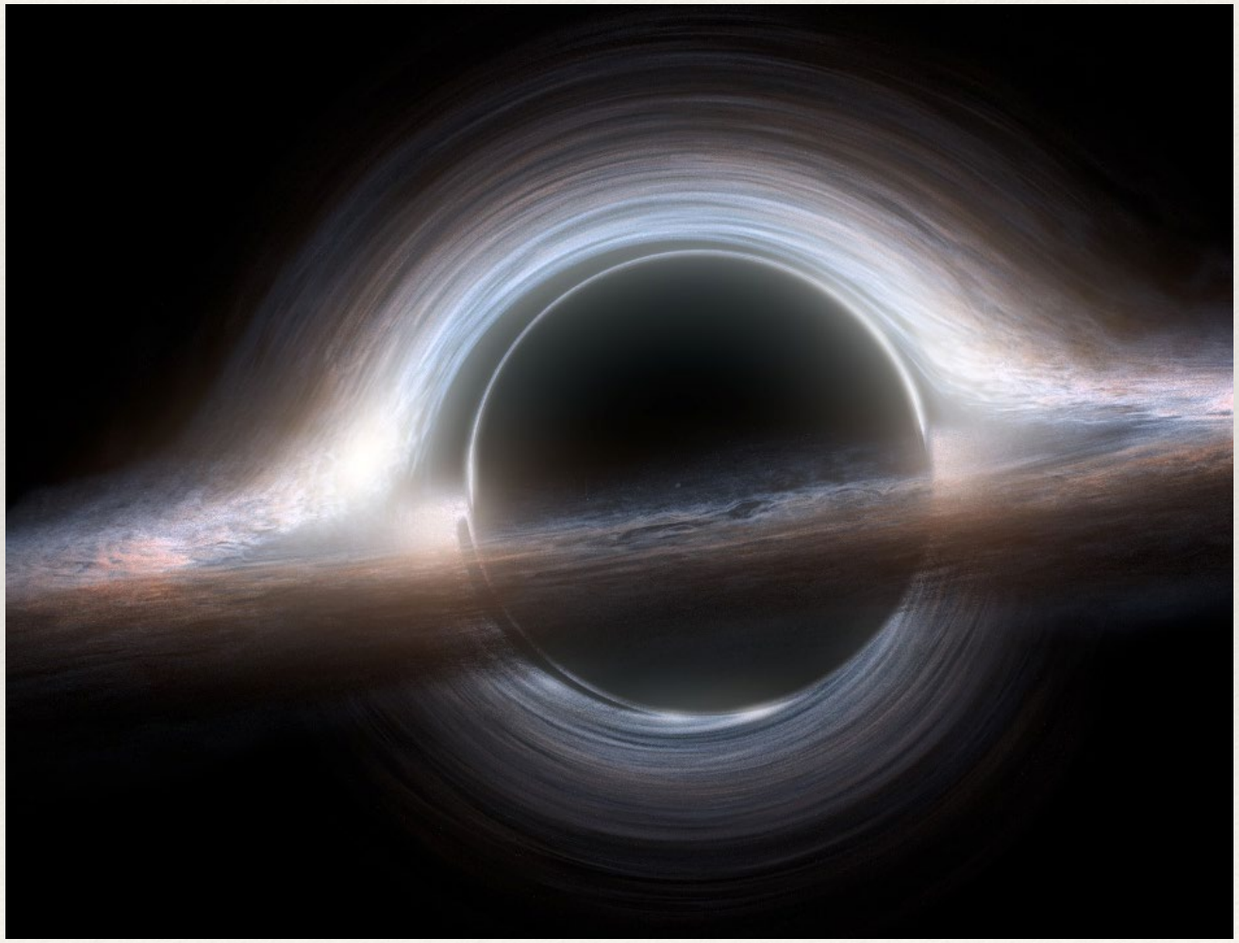
Merging black holes and neutron stars produce loud gravitational waves!



What are Black Holes?

Spacetime can infinitely warp!

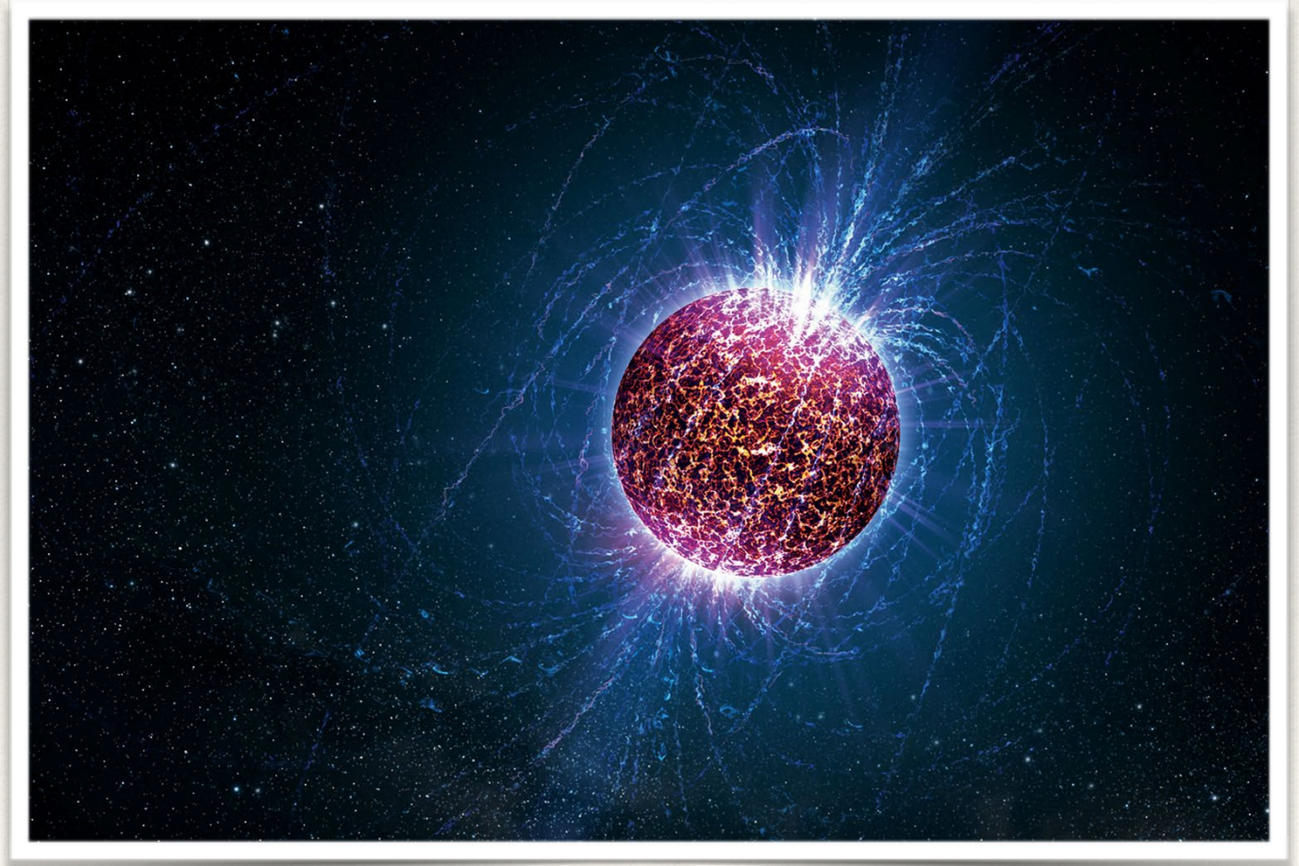
- Black hole: a region of spacetime from which nothing can escape.
- "Densest" objects in the universe
- Completely dark



What are Neutron Stars?

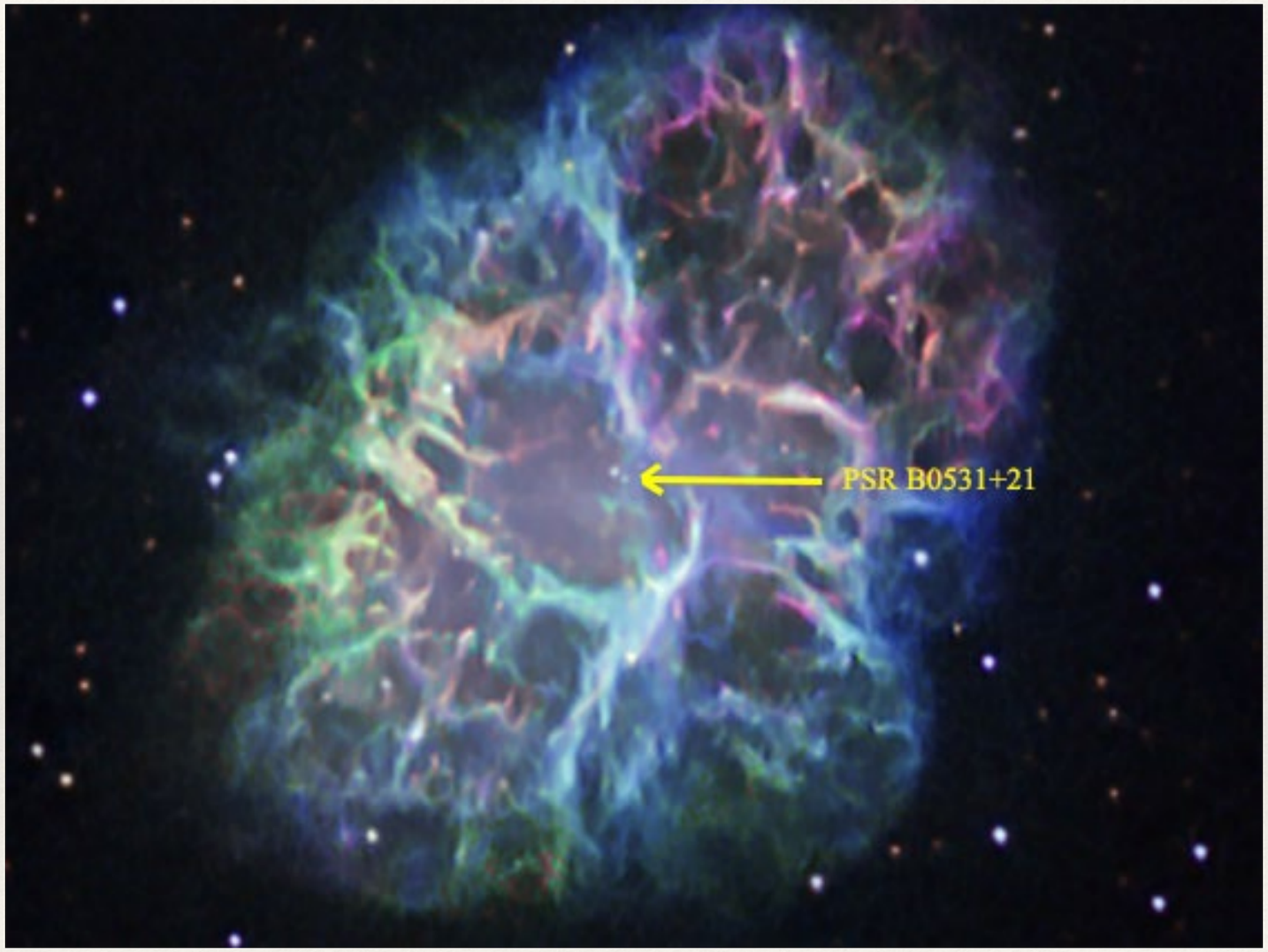
Made entirely of neutrons!

- Less dense than black holes
- But still denser than anything we can imagine…
- **Not dark!!!**



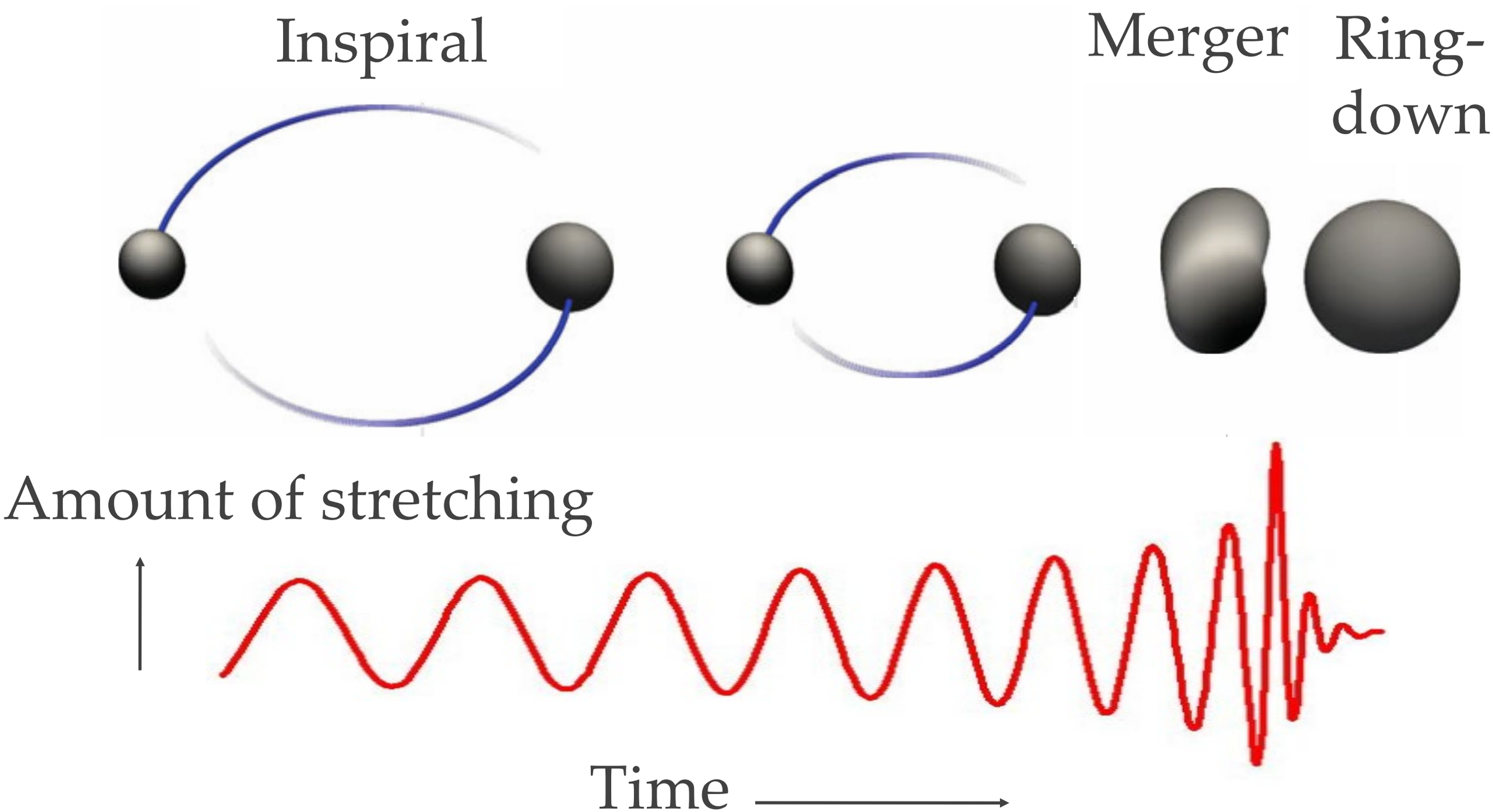
How are black holes and neutron stars made?

- A massive star runs out of fuel
- Explodes as a supernova
- Leaves behind neutron star or black hole

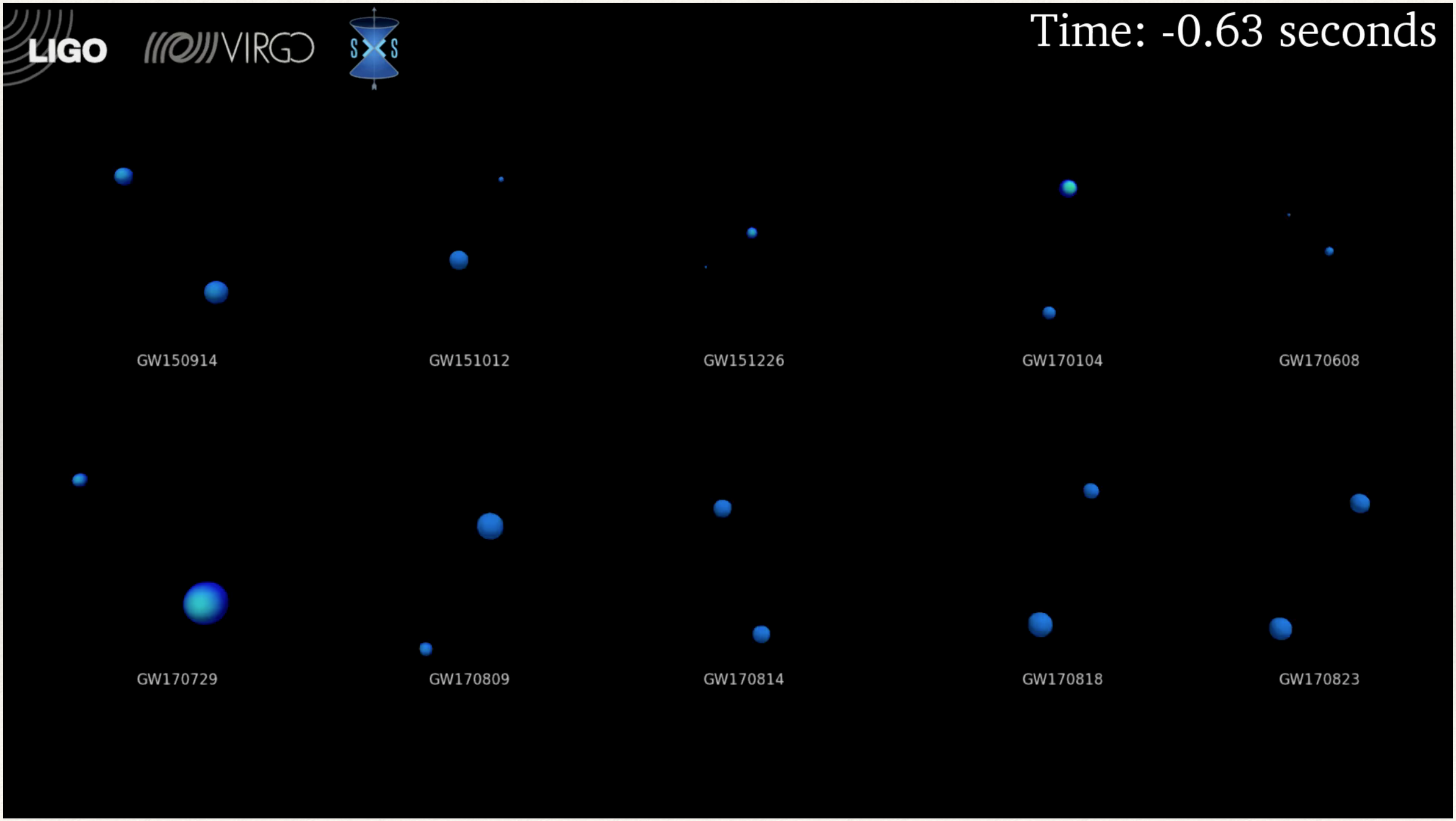


To detect gravitational waves, we have to measure the stretching of space

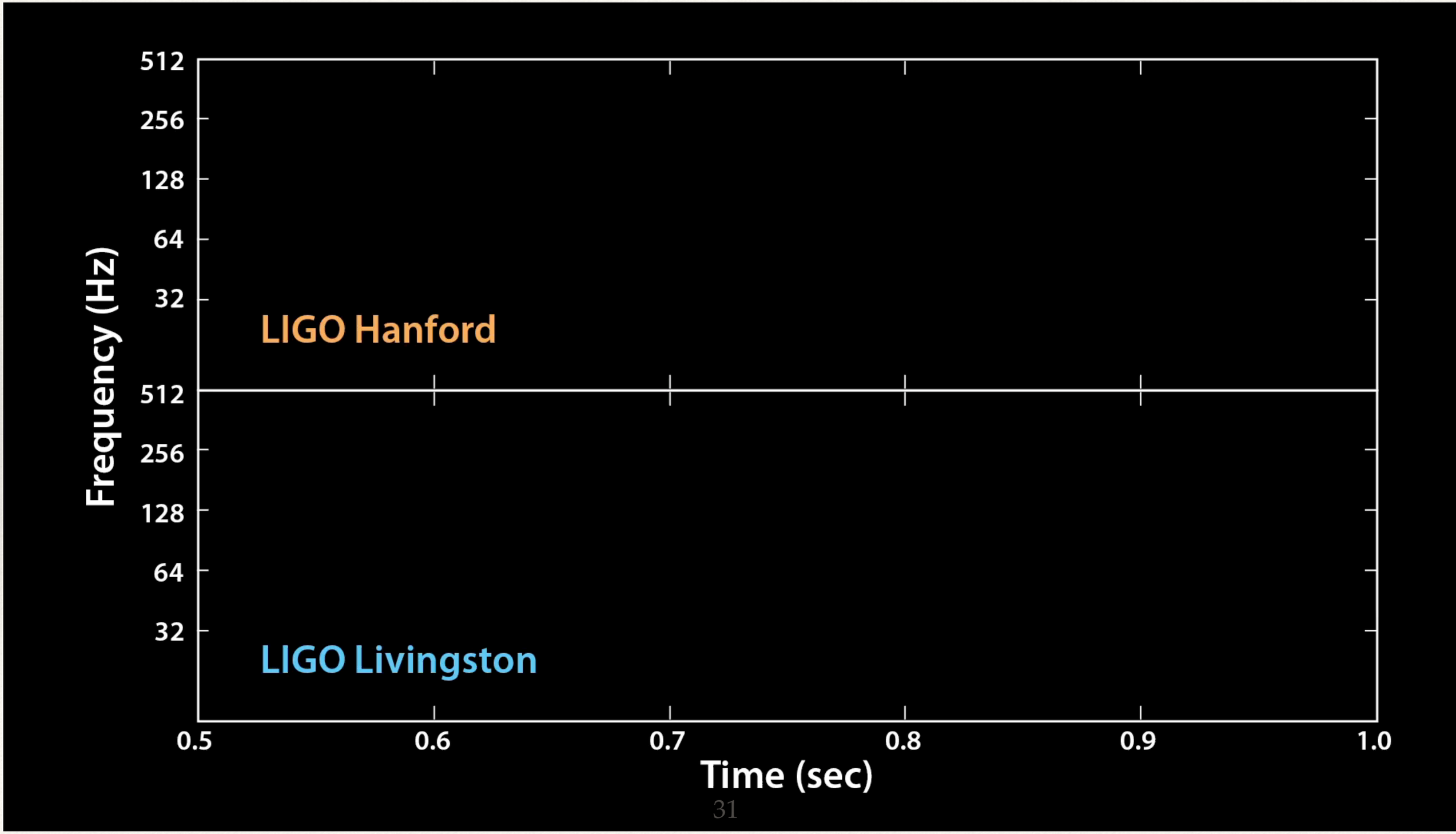
Gravitational Wave Signal



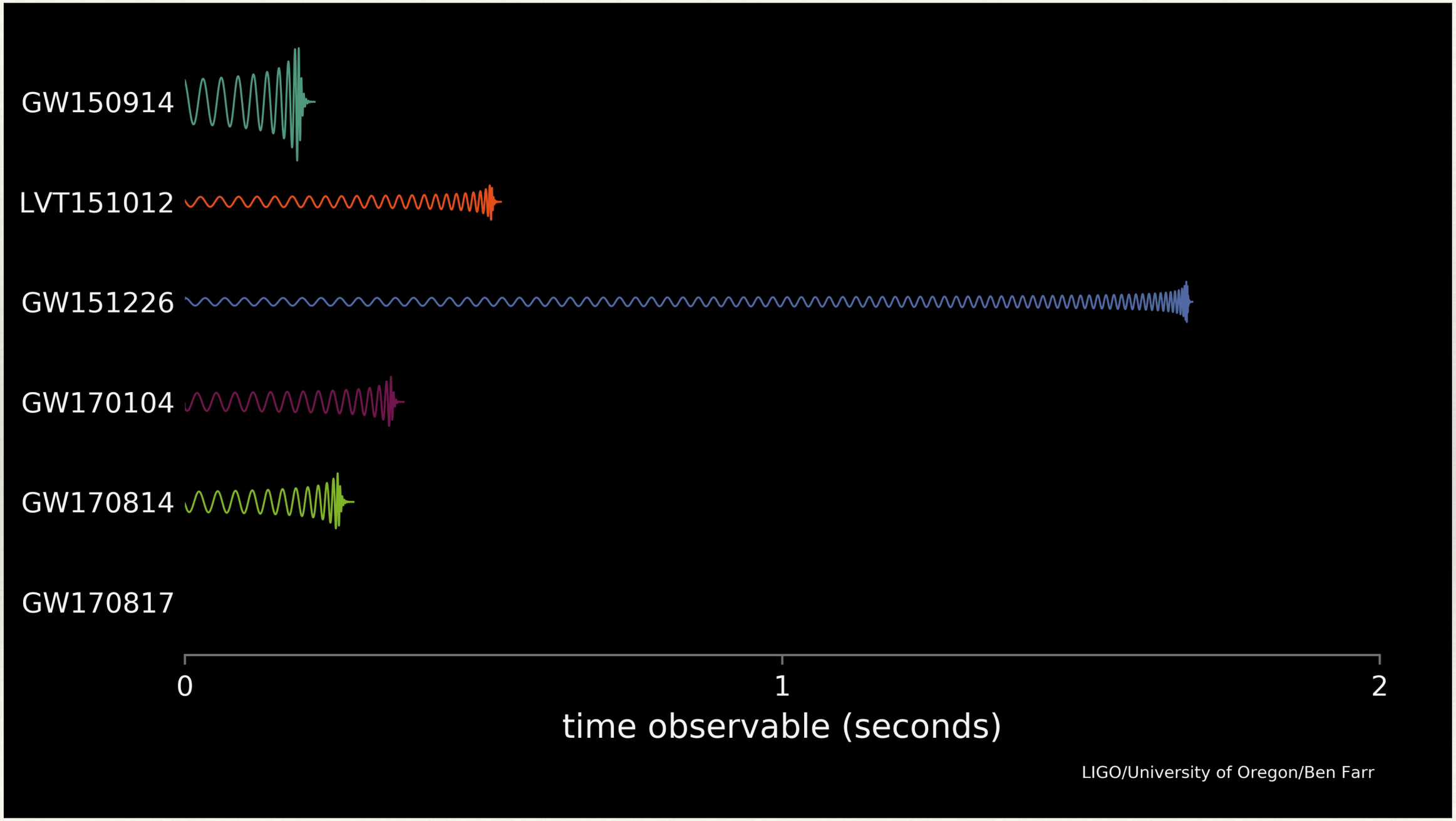
Gravitational Waves Detected So Far

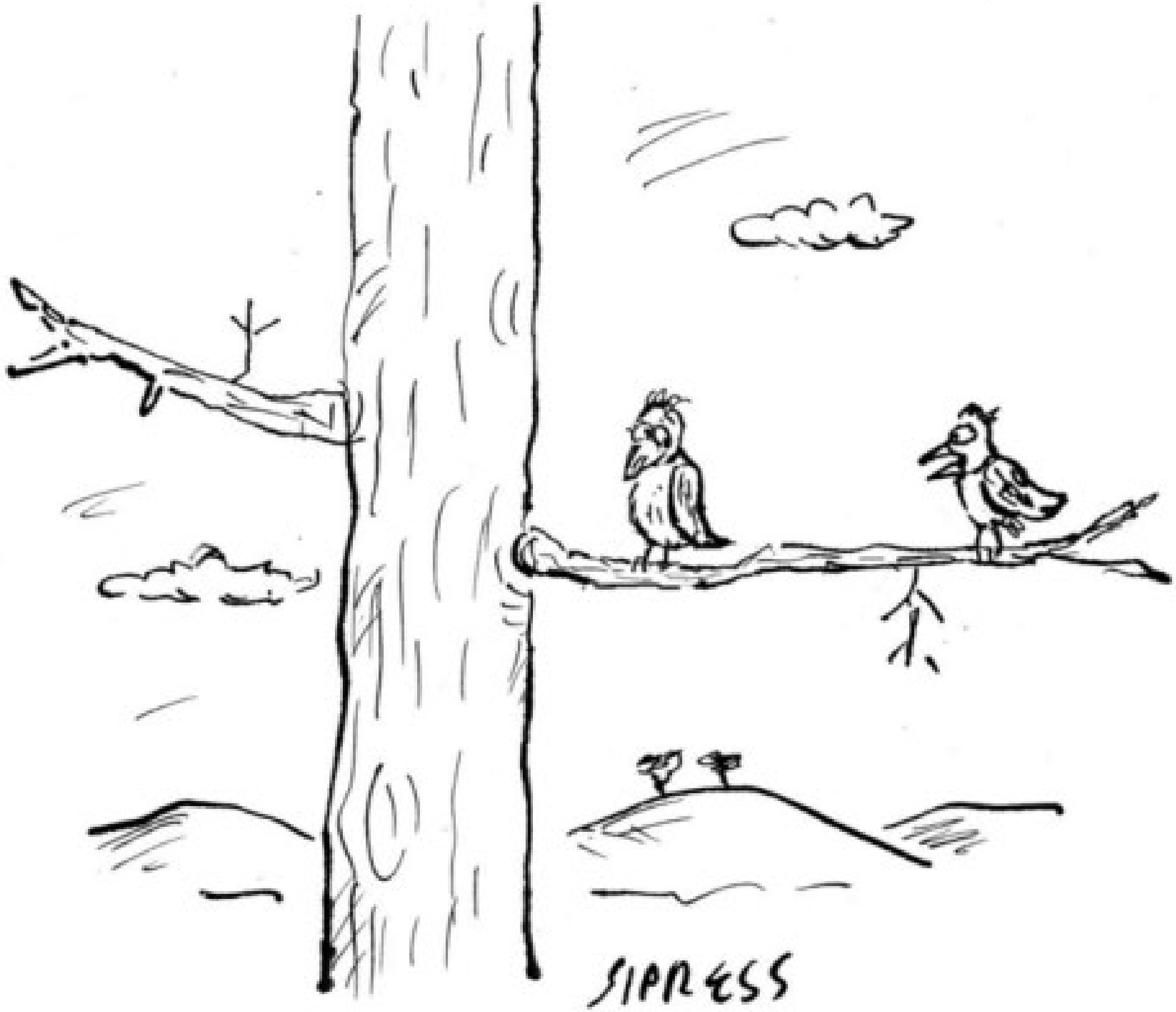


The "chirp" of 2 black holes colliding



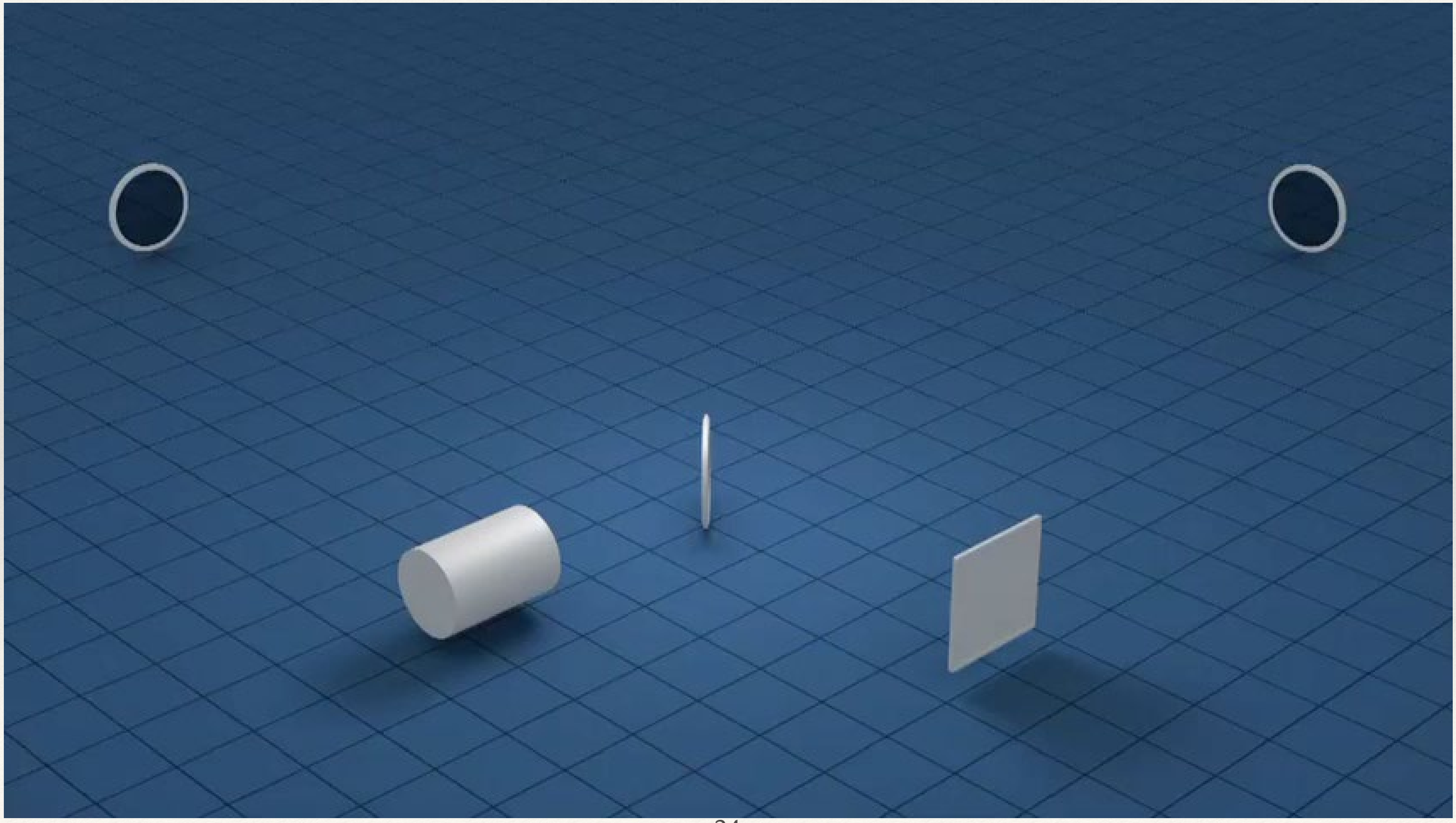
Neutron star chirp is much longer!





"Was that you I heard just now, or was it two black holes colliding?"

How are Gravitational Waves Detected?



Inception of LIGO

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

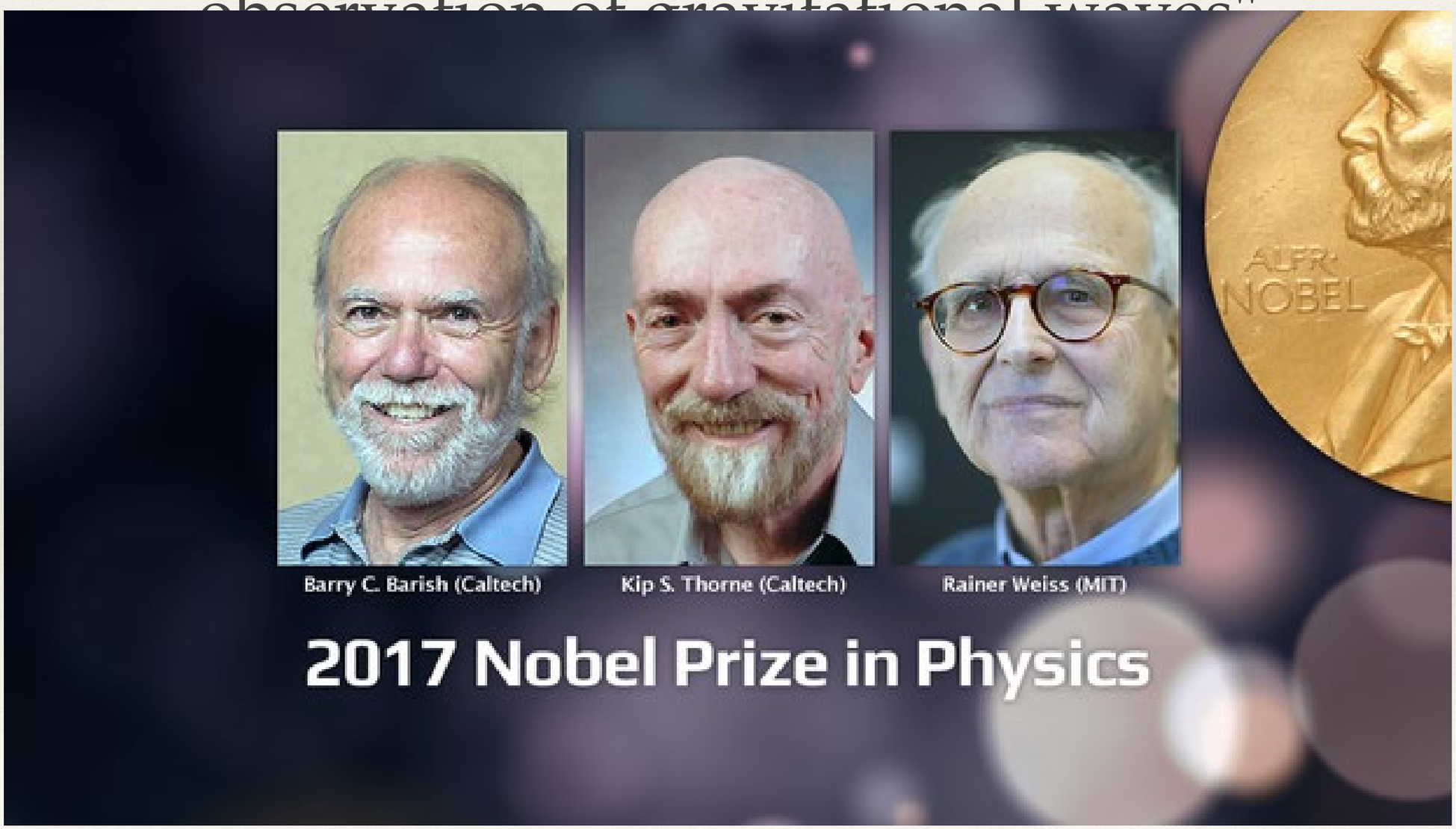
Kip S. Thorne
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

The Nobel Prize in Physics 2017

"for decisive contributions to the LIGO detector and the observation of gravitational waves"



LIGO Scientific Collaboration

- Over 1000 scientists from 83 institutions in 15 countries
- Many types of scientists involved: theorists, experimentalists, data analysts, engineers, astrophysicists…

August 12, 2019

Humans of LIGO

MAYA FISHBACH

—

"My family is my biggest support network -- I'm really lucky that I get to live at home during my PhD! I love to take my 7-year-old brother Tommy to the Adler planetarium and talk to him about space. He thinks that black holes are really cool, and whenever I feel stressed about research, I like to remind myself of this perspective by looking at one of his gravitational-wave inspired drawings that I keep at my desk. I also get a lot of support from my sister, who, like me, is a graduate student at the University of Chicago (studying medicine). My sister and I recently adopted a pet hamster; playing with her is also a great way to relieve stress!"

Maya Fishbach is a PhD student at The University of Chicago. Maya uses data analysis techniques and gravitational-wave detections to study the "demographics" of black hole binaries we observe in LIGO and to constrain the expansion rate of the universe. During the day she plays with her dog Dobby, at night she holds her hamster Mitski, and at all times she bakes pretzels. You can follow Maya on Twitter at @mayaKfish and on Instagram at @mayafishie.

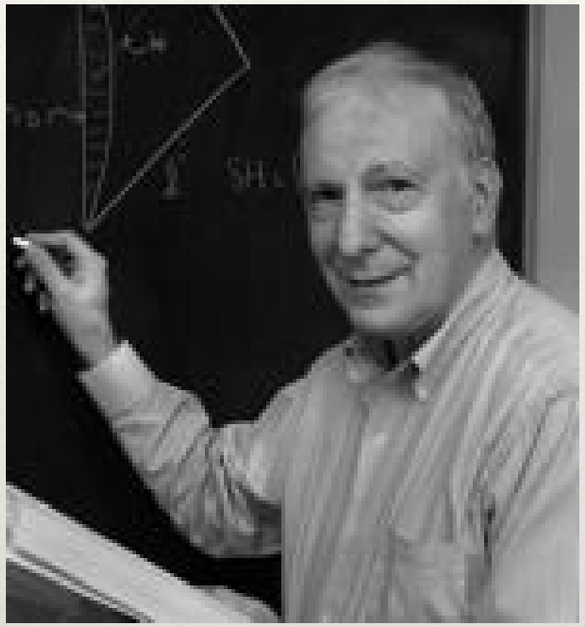
LIGO Scientific Collaboration

LIGO

LSC

Caltech
American University
Andrews University
Washington State University
California State University Fullerton
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
Leland Stanford Junior University 1891
The University Of Sheffield.
University of Maryland 1856
indigo
PennState
Montclair State University
Texas Tech University
清華大學 Tsinghua University
Max Planck Institute for Gravitational Physics Albert Einstein Institute
International Institute of Physics
Cal State LA
Bellevue College
Universitat de les Illes Balears
University of Cambridge
Université de Montréal
Monash University
Polytechnique Montréal
The University of Adelaide Australia
University of Southampton
NCSA
University of Wisconsin UWMilwaukee
University of the West of Scotland UWS
University of Glasgow
Bothell
Michigan
Trinity University
Australian National University
OzGrav
Cornell University Founded A.D. 1865
Syracuse University Suos Cultores Scientia Coronat Founded AD 1870
The University of Western Australia
R·I·T
Columbia University in the City of New York
Lomonosov Moscow State University
Sonoma State University
Cardiff University Prifysgol Caerdydd
The University of Chicago
Whitman College
Montana State University
University of Washington
University of Minnesota
Sigill. Coll. Carleton Northfield, Minn. A.D. 1866
NASA
Charles Sturt University
Marshall Space Flight Center
LSU Louisiana State University
INPE
University of Birmingham
King's College London
Università degli Studi del Sannio
University of Zurich
UTRGV
University of Strathclyde
東京大学 The University of Tokyo
Georgia Institute of Technology
Korean Gravitational Wave Group
ACIGA
The University of Melbourne
Colorado State University
Hillsdale College
Northwestern
UF University of Florida
Universität Hamburg Der Forschung | Der Lehre | Der Bildung
GEO 600
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
Swinburne University of Technology
CITA | ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique theorique
The University of Mississippi
NASA Goddard Space Flight Center

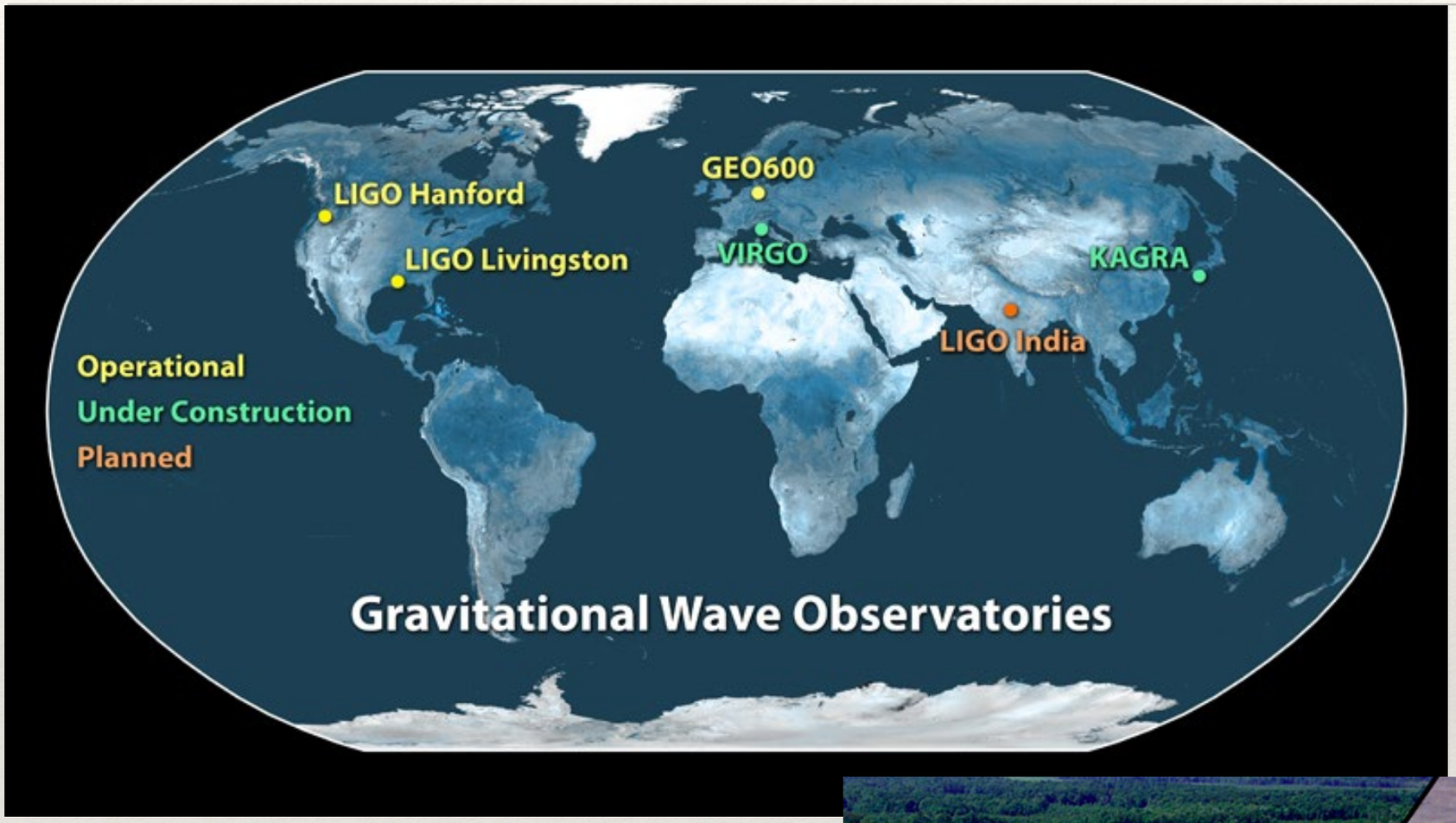
UChicago LIGO Group



Robert Wald, Amanda Farah, Reed Essick, Daniel Holz, Maya Fishbach, José Maria Ezquiaga

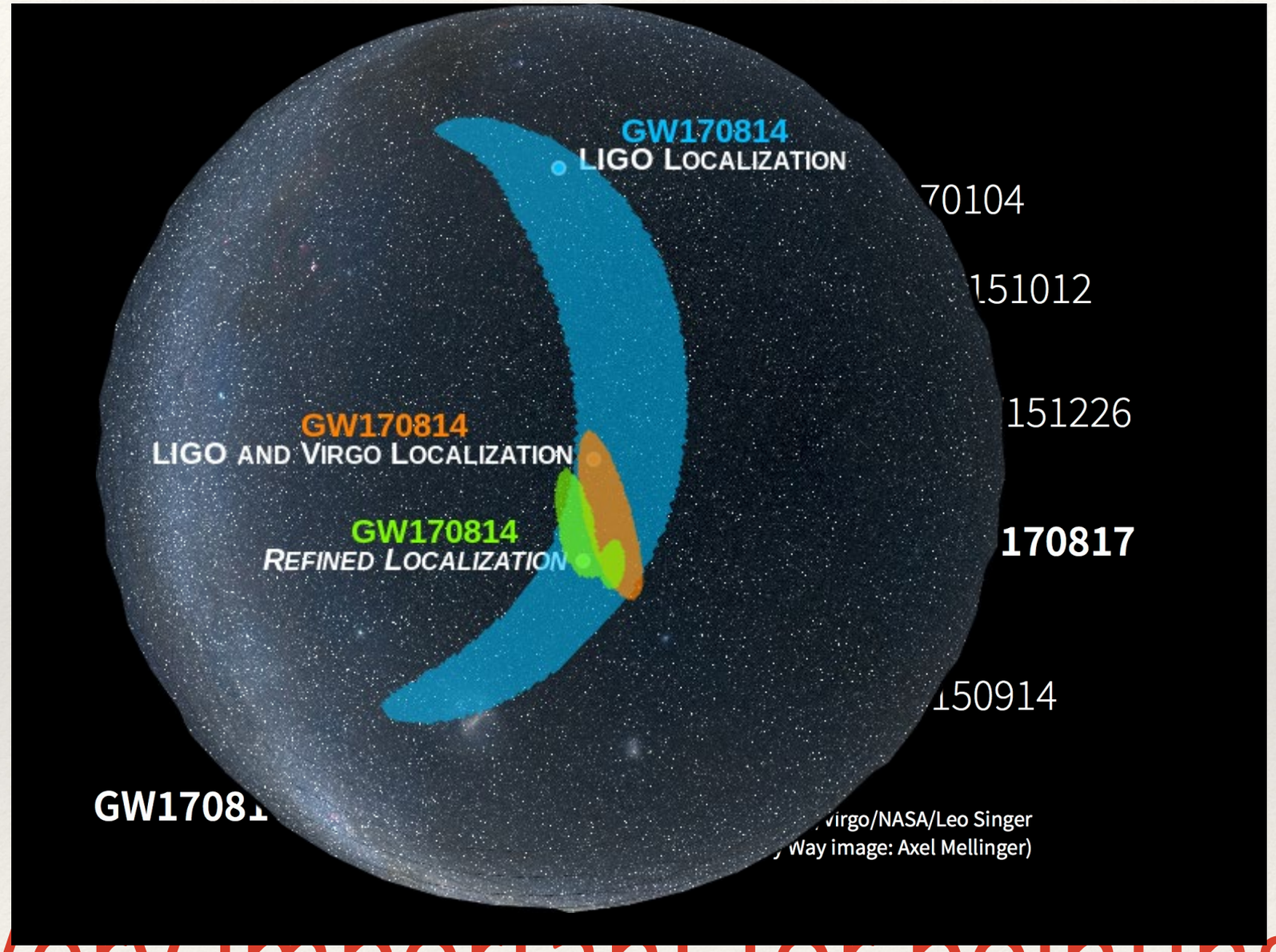
Past members: Hsin-Yu Chen, Ben Farr, Zoheyr Doctor, Phil Landry

A network of interferometers



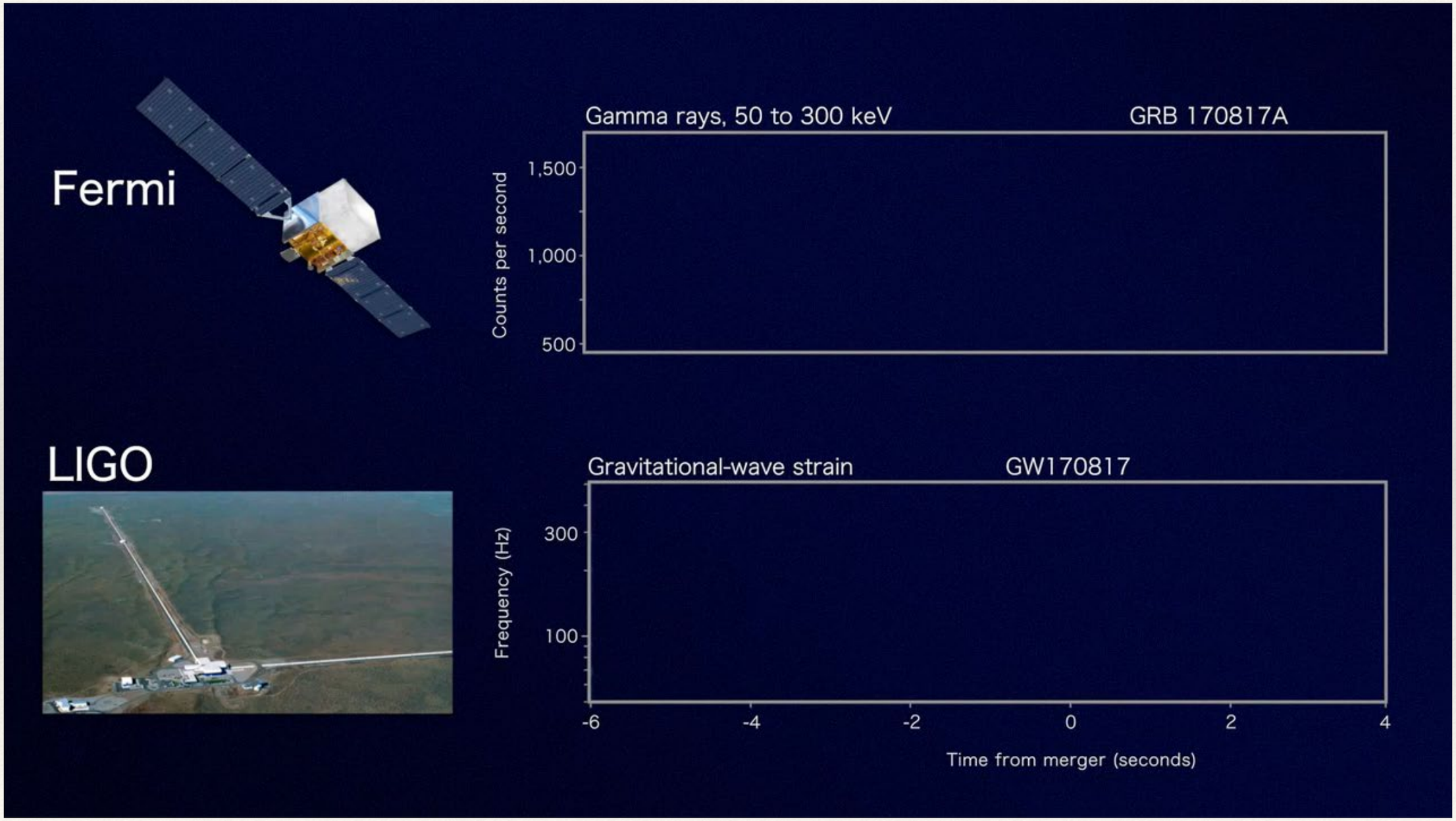
The two LIGO detectors

With 3 detectors, we can localize sources

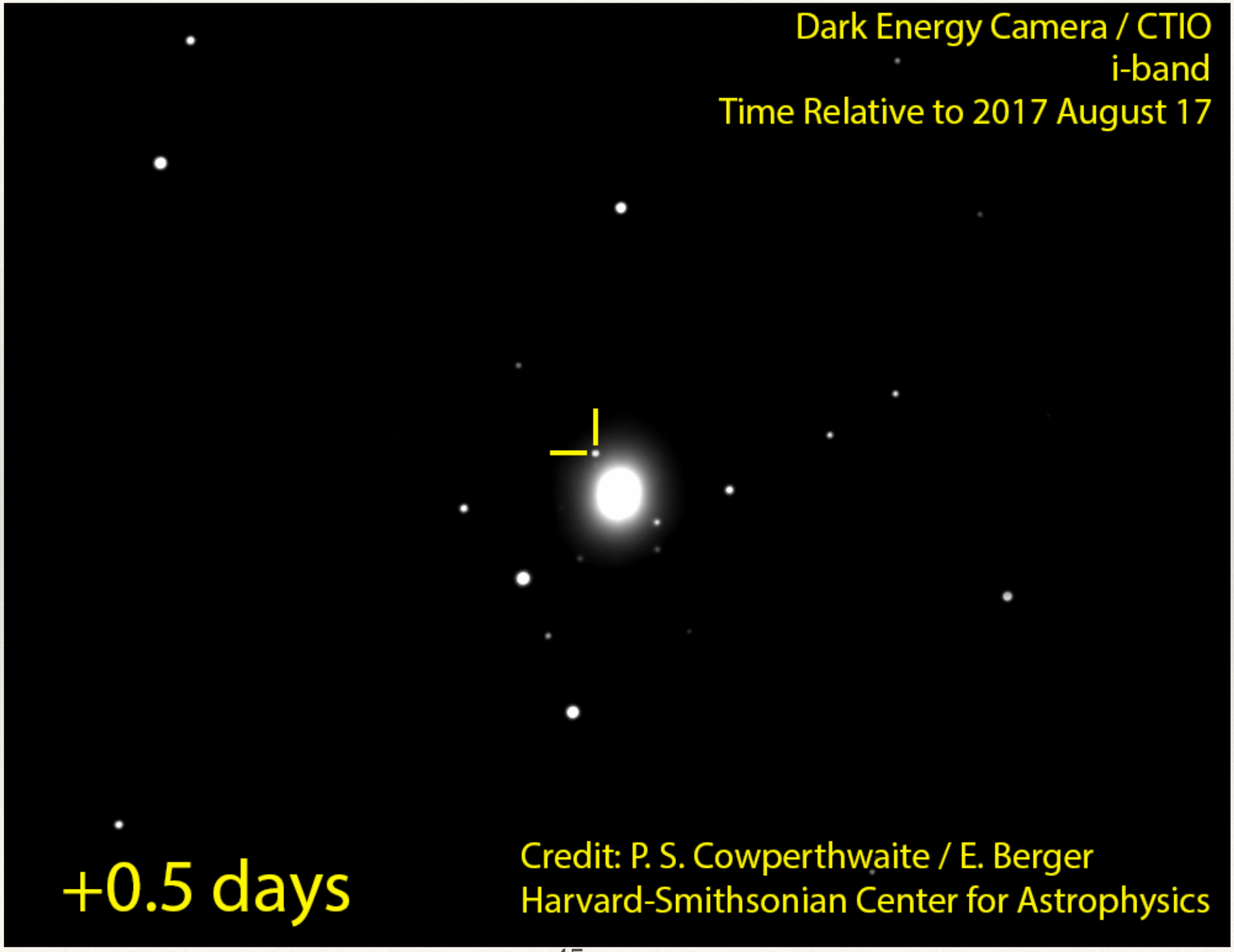


Very important for pointing telescopes!

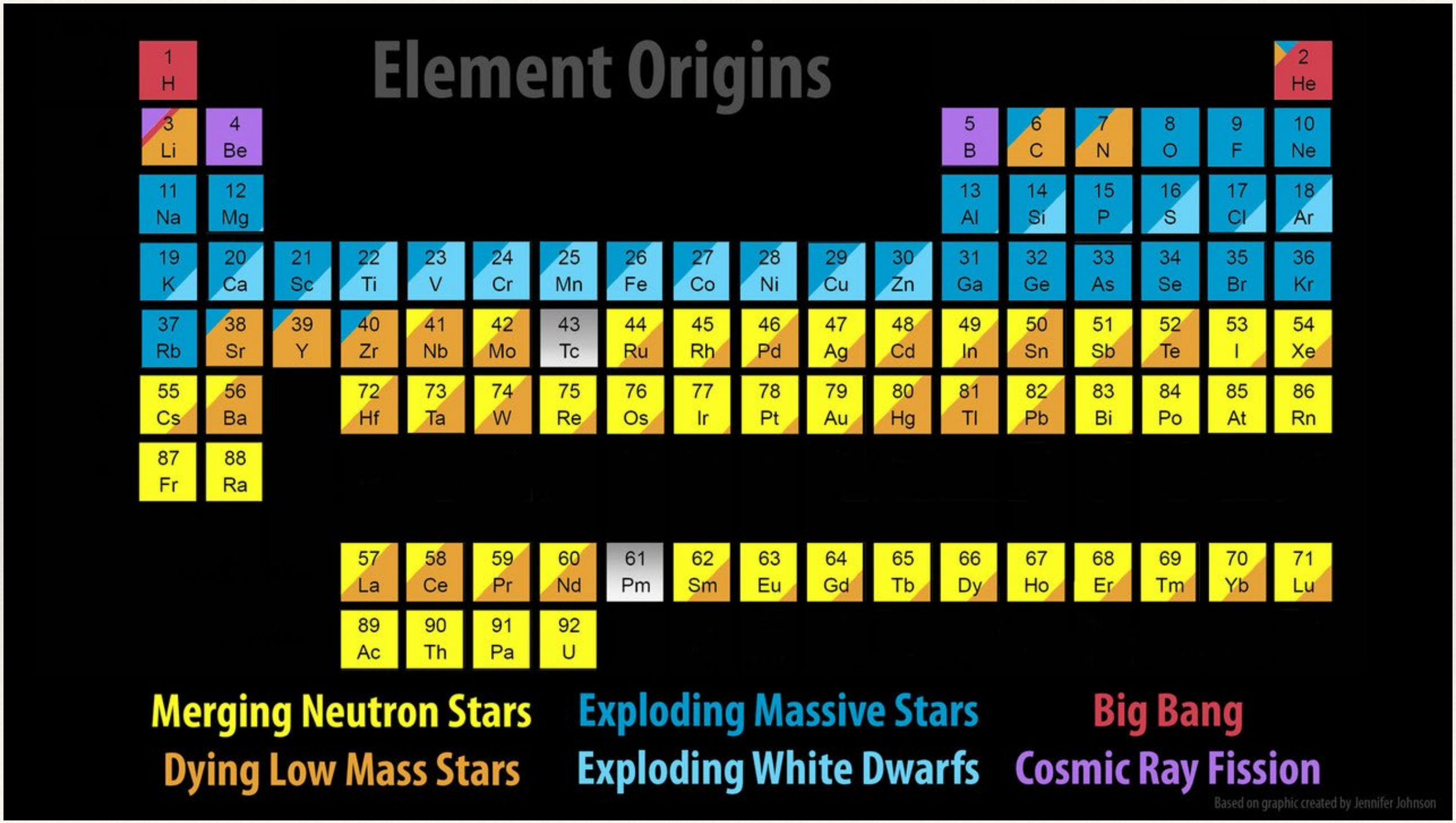
Neutron star collisions produce flashes of light



Neutron star collisions produce flashes of light

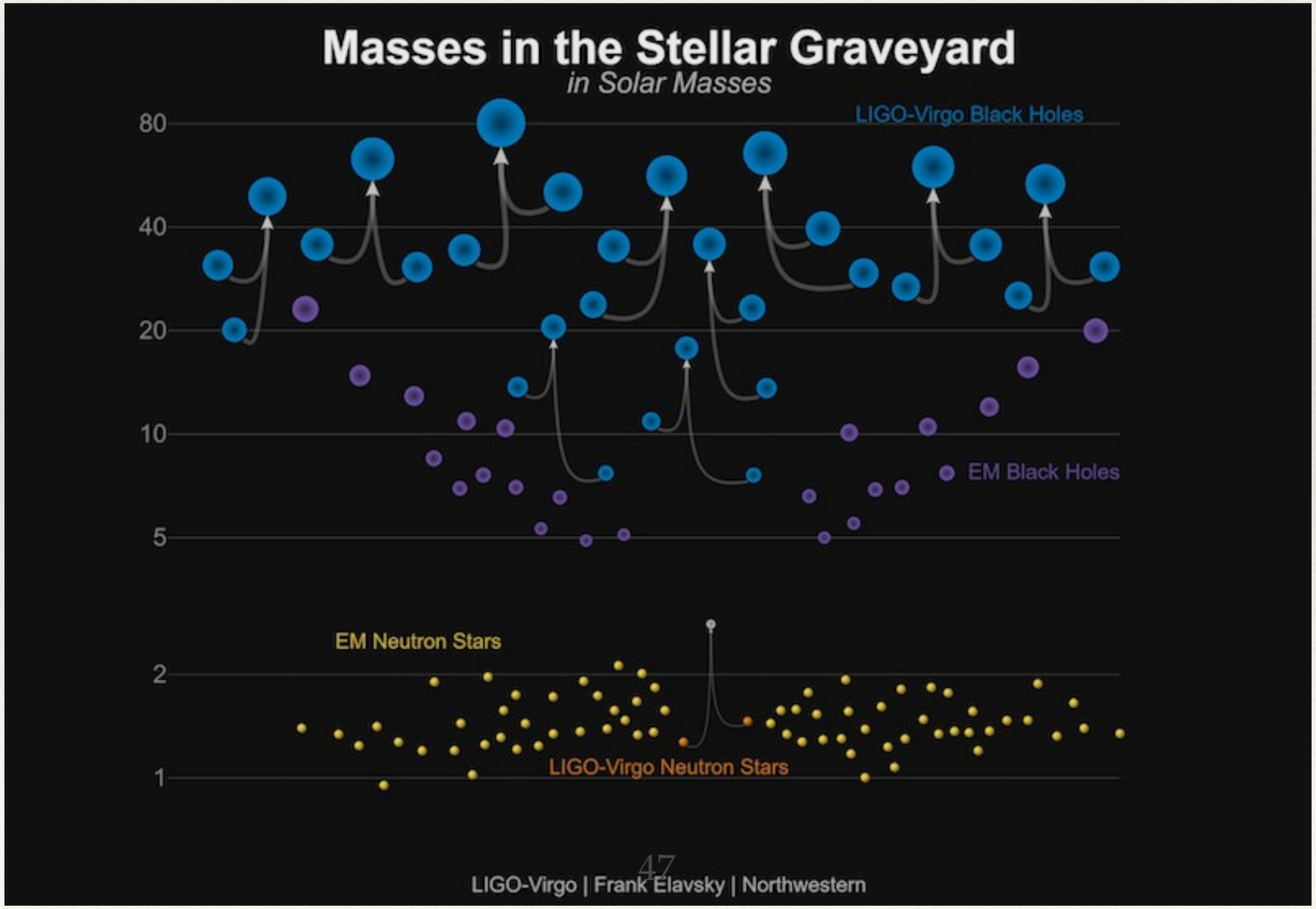


Neutron star collisions produce heavy elements



With LIGO and Virgo, we have already detected:

- 10 black hole mergers
- 1 neutron star merger



LIGO and Virgo are currently in our third observing run!

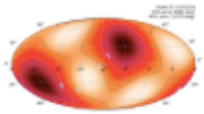
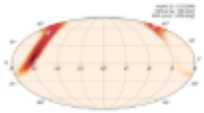
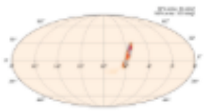
GraceDB — Gravitational-Wave Candidate Event Database

HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION

LIGO/Virgo O3 Public Alerts

Detection candidates: 33

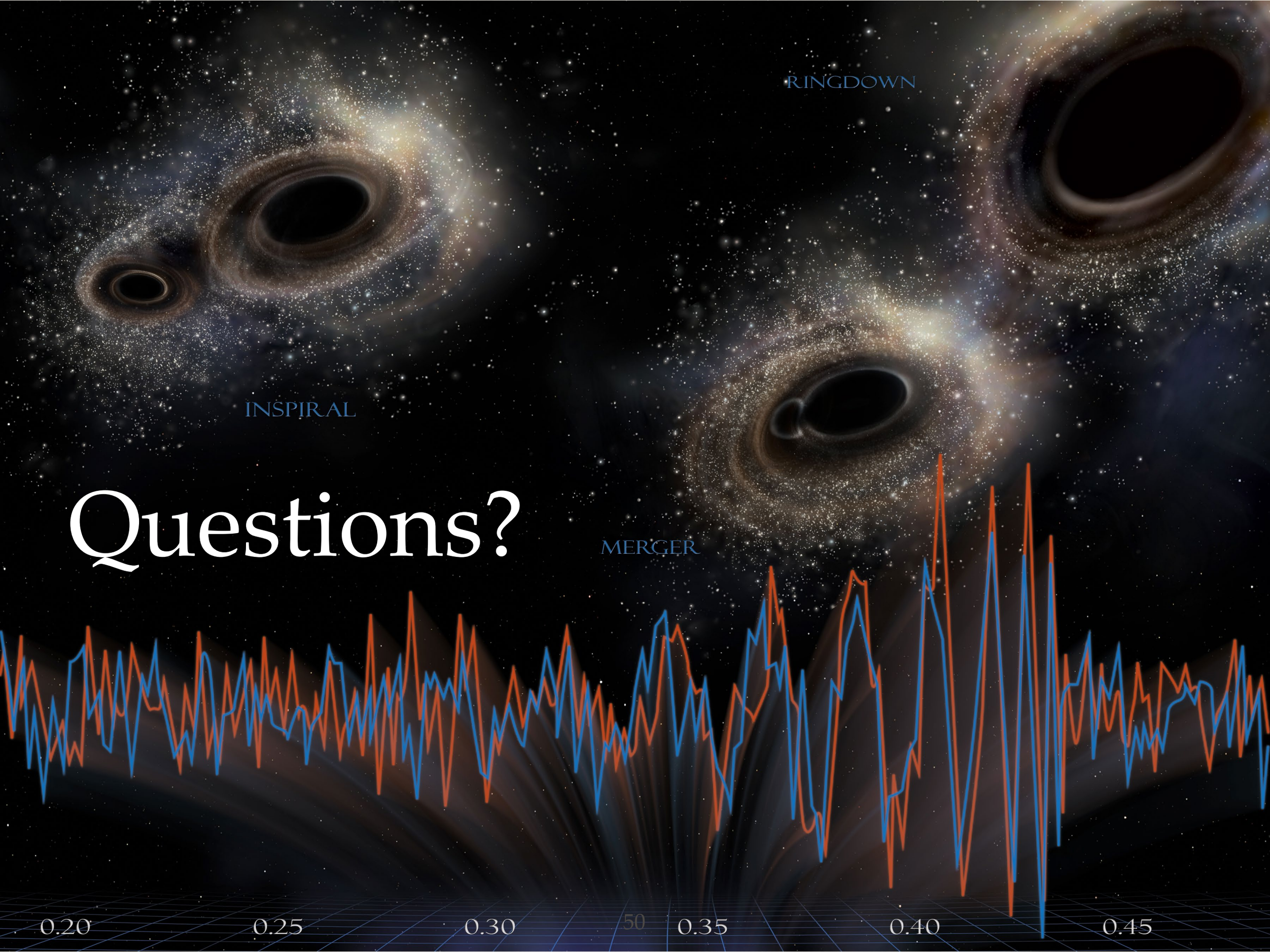
SORT: EVENT ID (A–Z) ▼

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190930t	NSBH (74%), Terrestrial (26%)	Sept. 30, 2019 14:34:07 UTC	GCN Circulars Notices | VOE		1 per 2.0536 years	
S190930s	MassGap (95%), Terrestrial (5%)	Sept. 30, 2019 13:35:41 UTC	GCN Circulars Notices | VOE		1 per 10.534 years	
S190928c		Sept. 28, 2019 02:11:45 UTC	GCN Circulars Notices | VOE	No public skymap image found.	1 per 4.7092 years	RETRACTED
S190924h	MassGap (>99%)	Sept. 24, 2019 02:18:46 UTC	GCN Circulars Notices | VOE		1 per 3.5493e+10 years	

Alerts are public!

What's next?

- More black holes and neutron stars! (There is still a lot to learn!)
- Supernovae? (Exploding stars)
- Pulsars? (Spinning neutron stars)
- Gravitational waves from the beginning of the universe??



Questions?