

100 Years in the Making

The Detection of Gravitational Waves

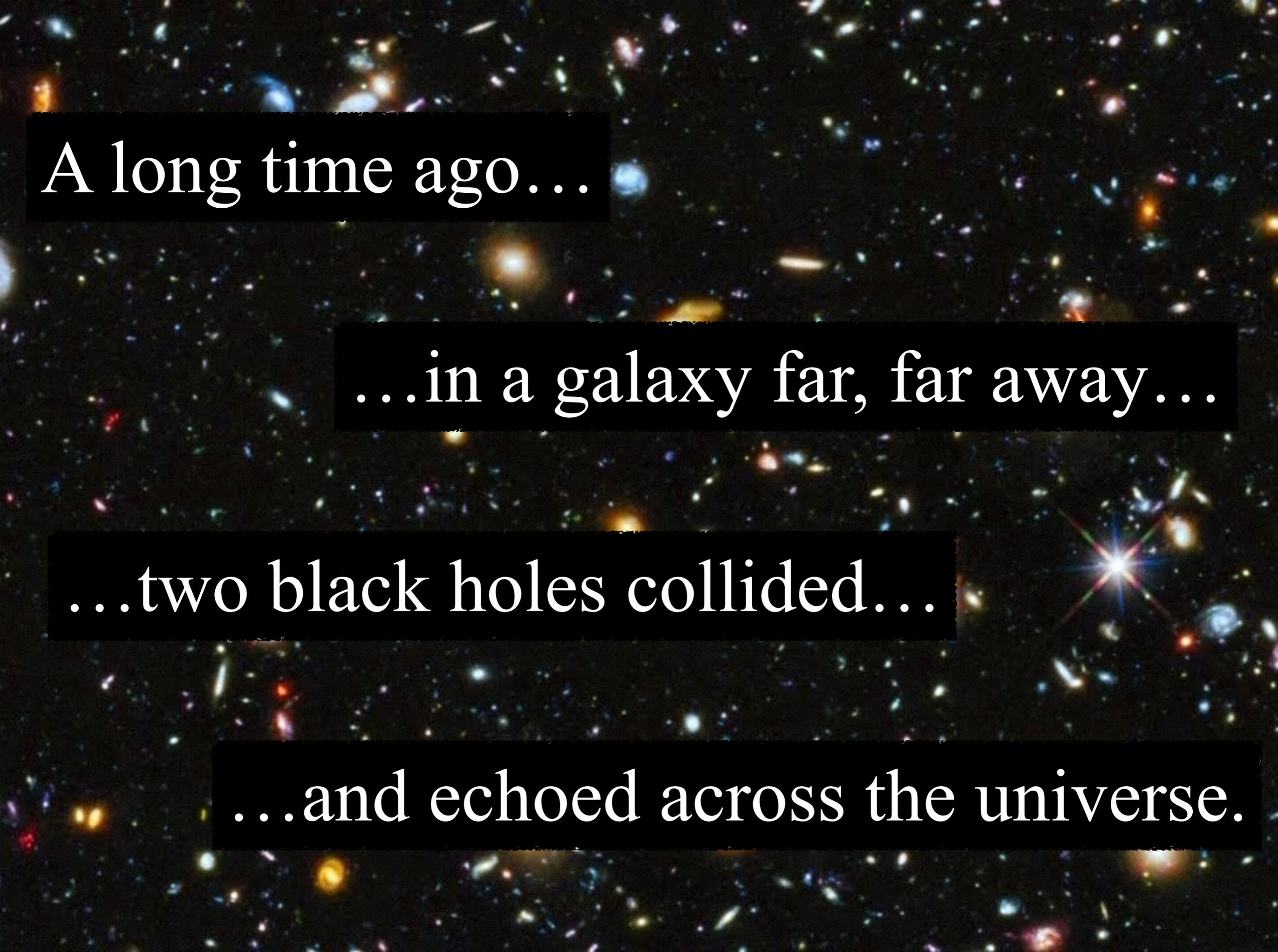
Zoheyr Doctor*

On behalf of the LIGO Collaboration

May 17, 2016

* Disclaimer: I am not a doctor.





A long time ago...

...in a galaxy far, far away...

...two black holes collided...

...and echoed across the universe.



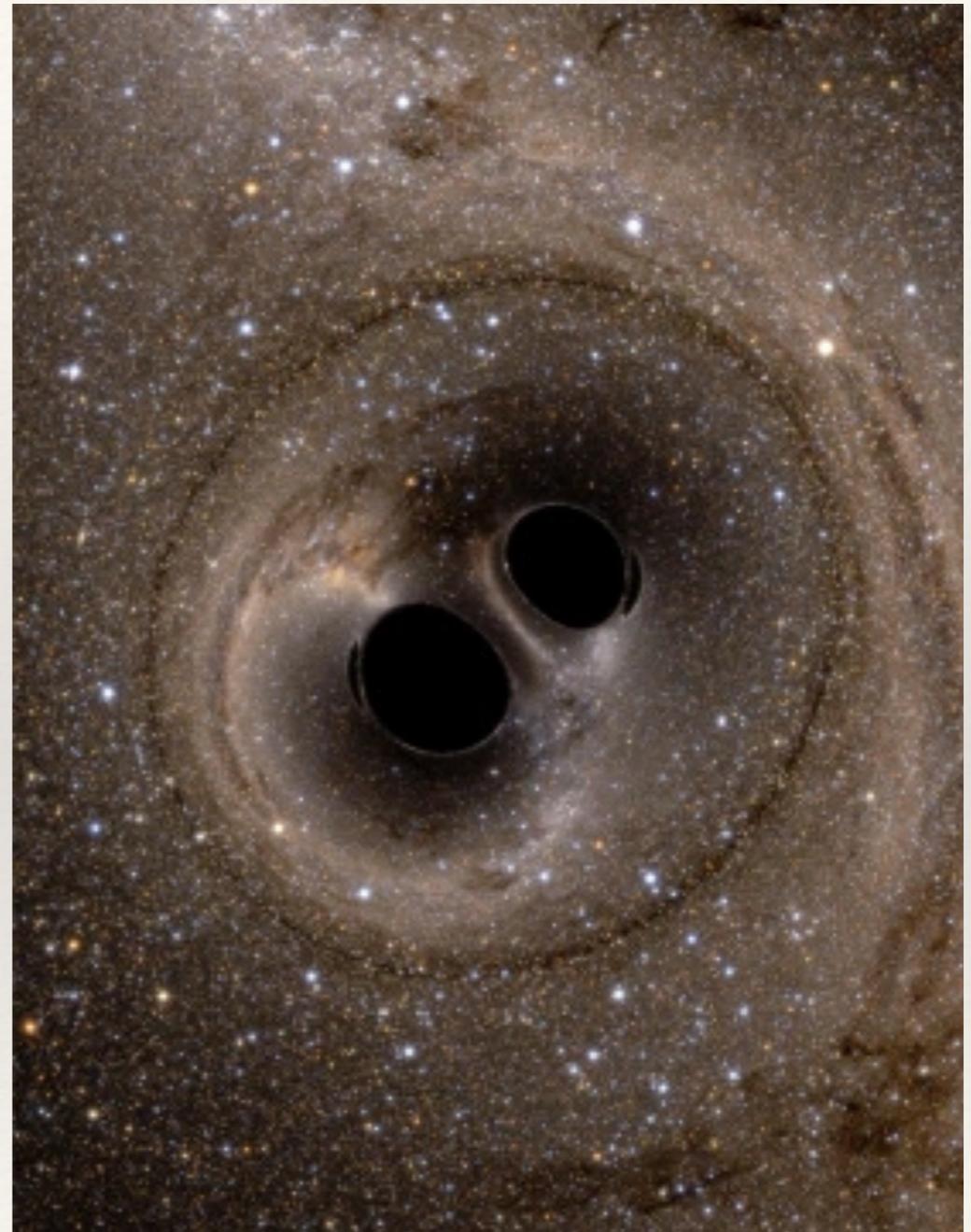
On September 14, 2015,
the Laser Interferometer
Gravitational-Wave Observatory
heard this echo.

The Punch Line

- On September 14, 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) measured gravitational waves originating from the collision of two black holes 1 billion light years away.
- This was the first direct detection of gravitational waves and black holes merging.
- A new field of astrophysics is born.

What is all the excitement about?

- Einstein's 100 year old (!) prediction of gravitational waves were finally observed.
- A new window into mind-bending phenomena in astrophysics
- A chance to gain a deeper understanding of the universe



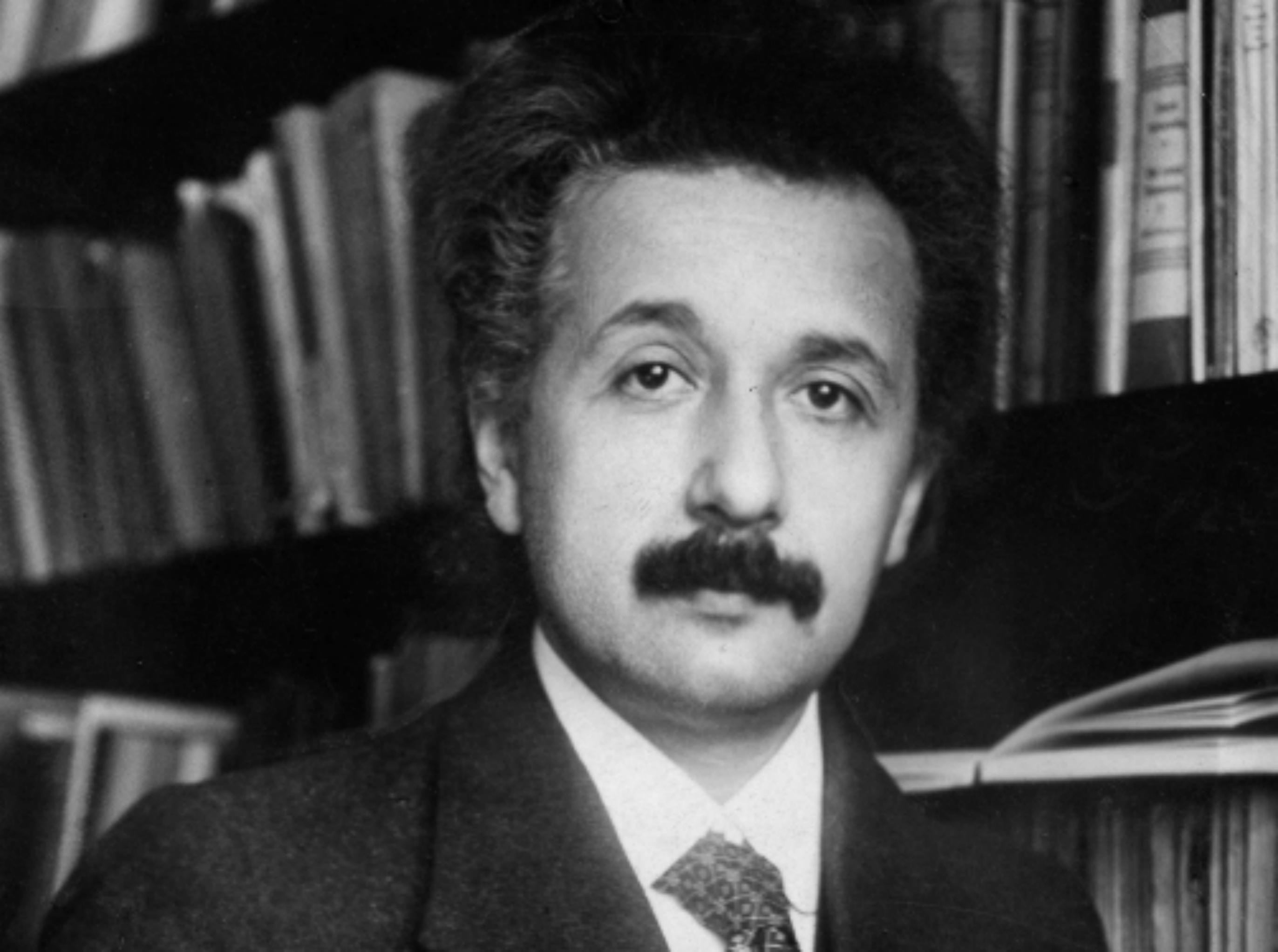
Roadmap

- ❖ Gravitational Waves
- ❖ Black Holes
- ❖ Laser Interferometer Gravitational-Wave Observatory (LIGO)



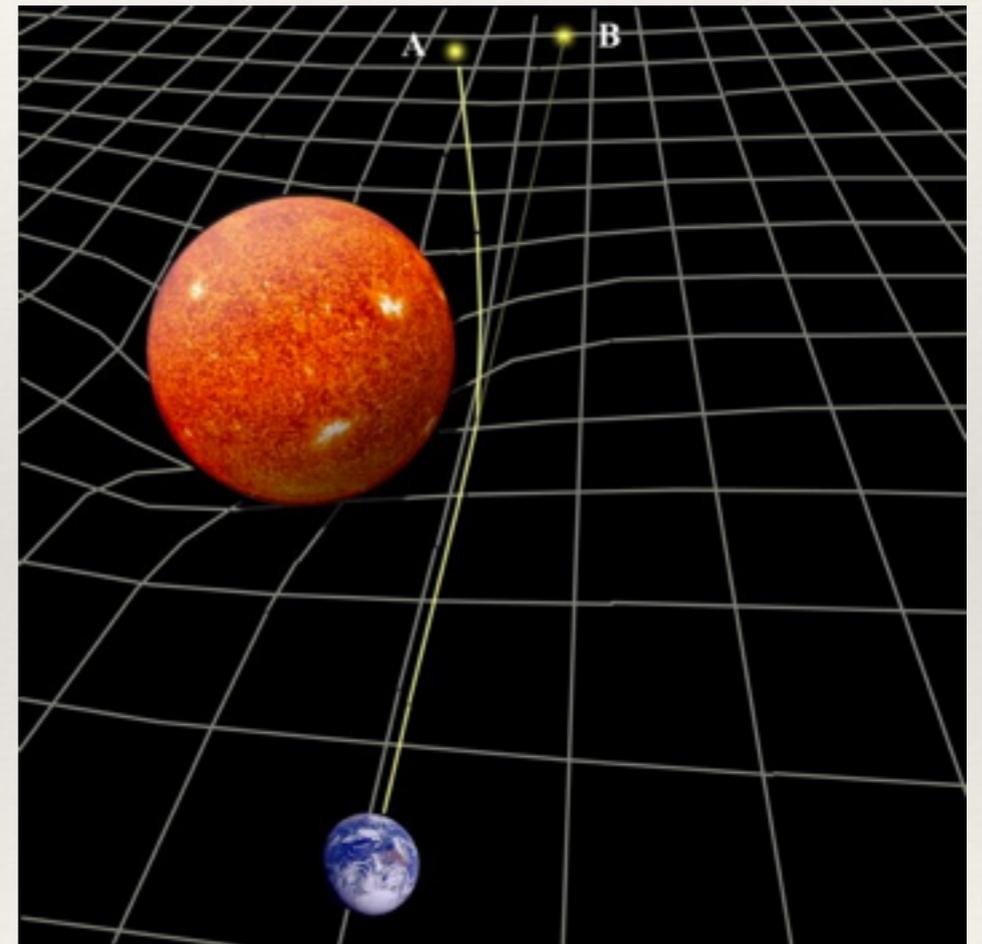
It all has to do with
GRAVITY

Newton got us to the moon.



1915: General Relativity

- Space and time are inextricably linked — “spacetime”
- Massive bodies distort spacetime.
- The bending of spacetime affects the movements of everything.
- Gravity is due to the curving of space-time, not a force as in Newton’s view.





“Spacetime tells matter how to move;
matter tells spacetime how to curve”

–John Archibald Wheeler



General relativity

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graph TD; A[General relativity] --> B[Gravitational Waves]; A --> C[Black Holes];
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Gravitational Waves

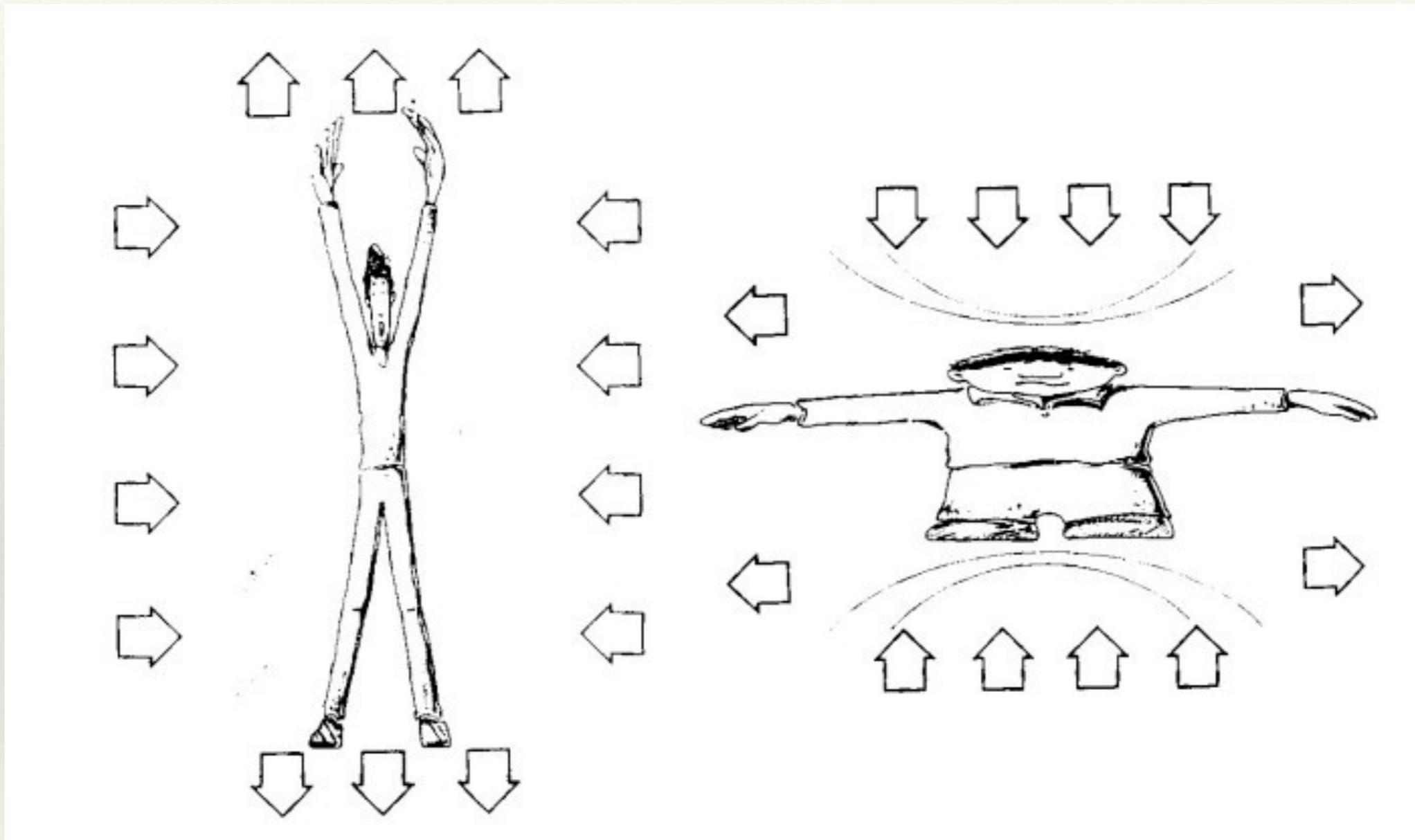
Black Holes

Gravitational Waves



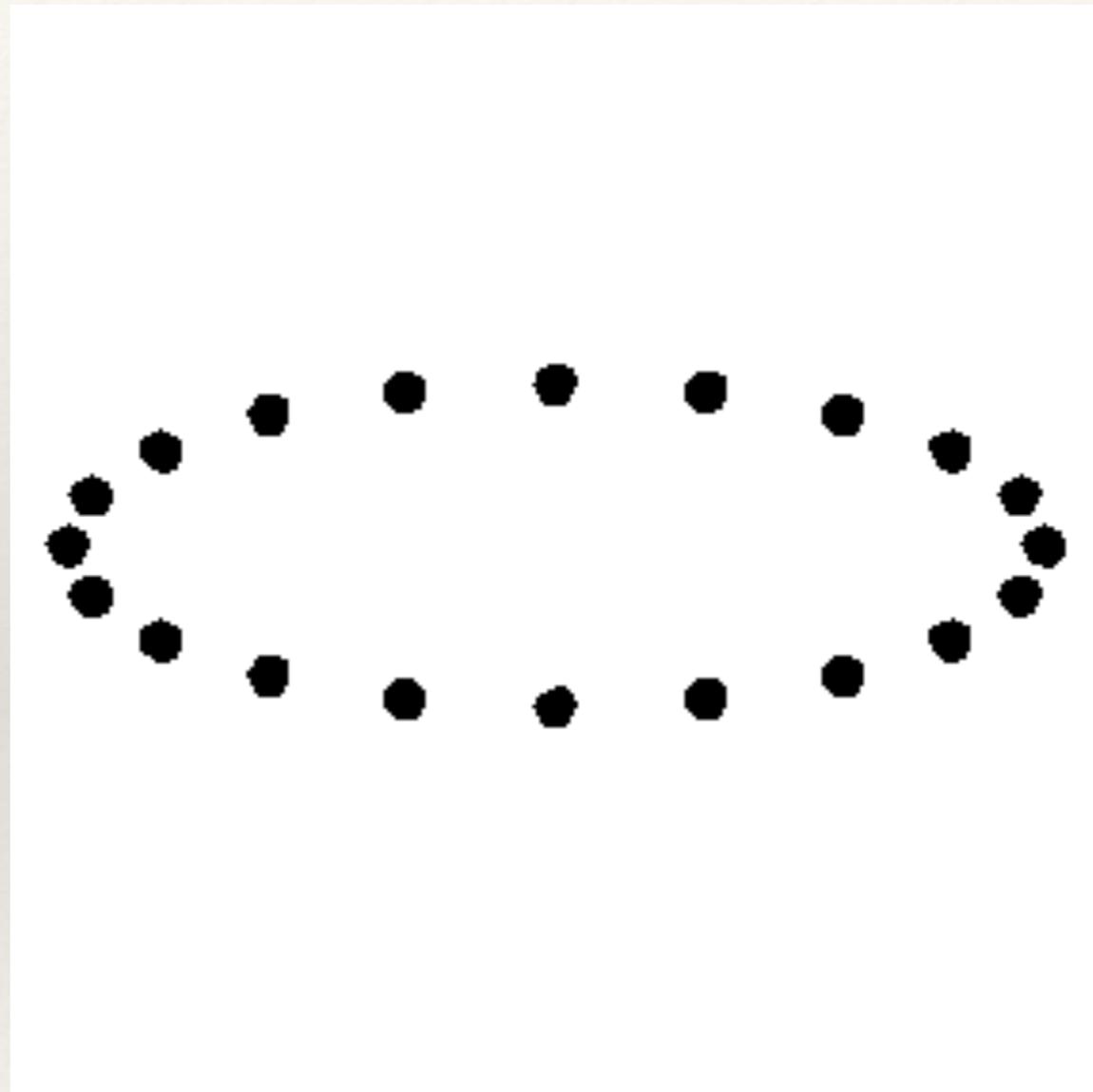
- Ripples in the fabric of spacetime

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”

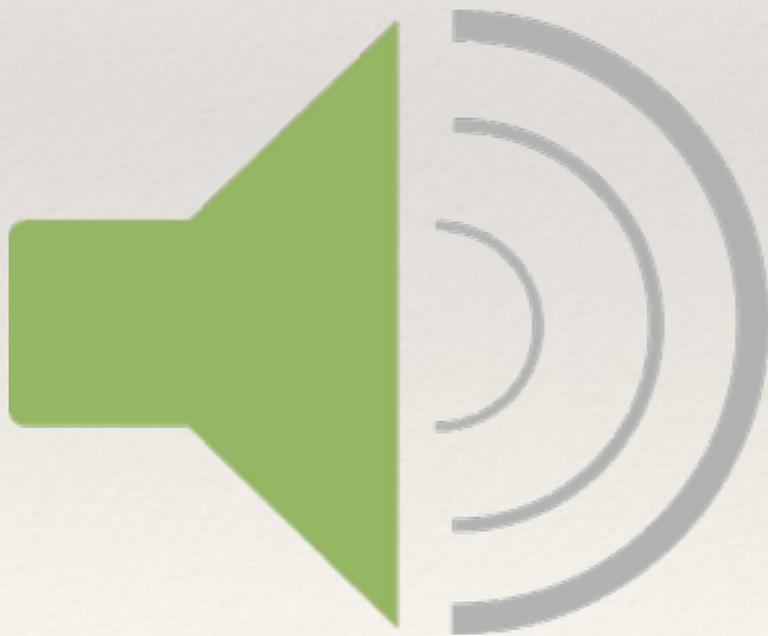
- Gravitational waves have a minuscule effect on matter they pass by.
- A “loud” gravitational wave would only change the distance between our sun and the next closest star (4.3 lightyears away) by the width of a human hair!



Detection Prerequisites

A “loud” source
of gravitational
waves

REALLY
precise
detector

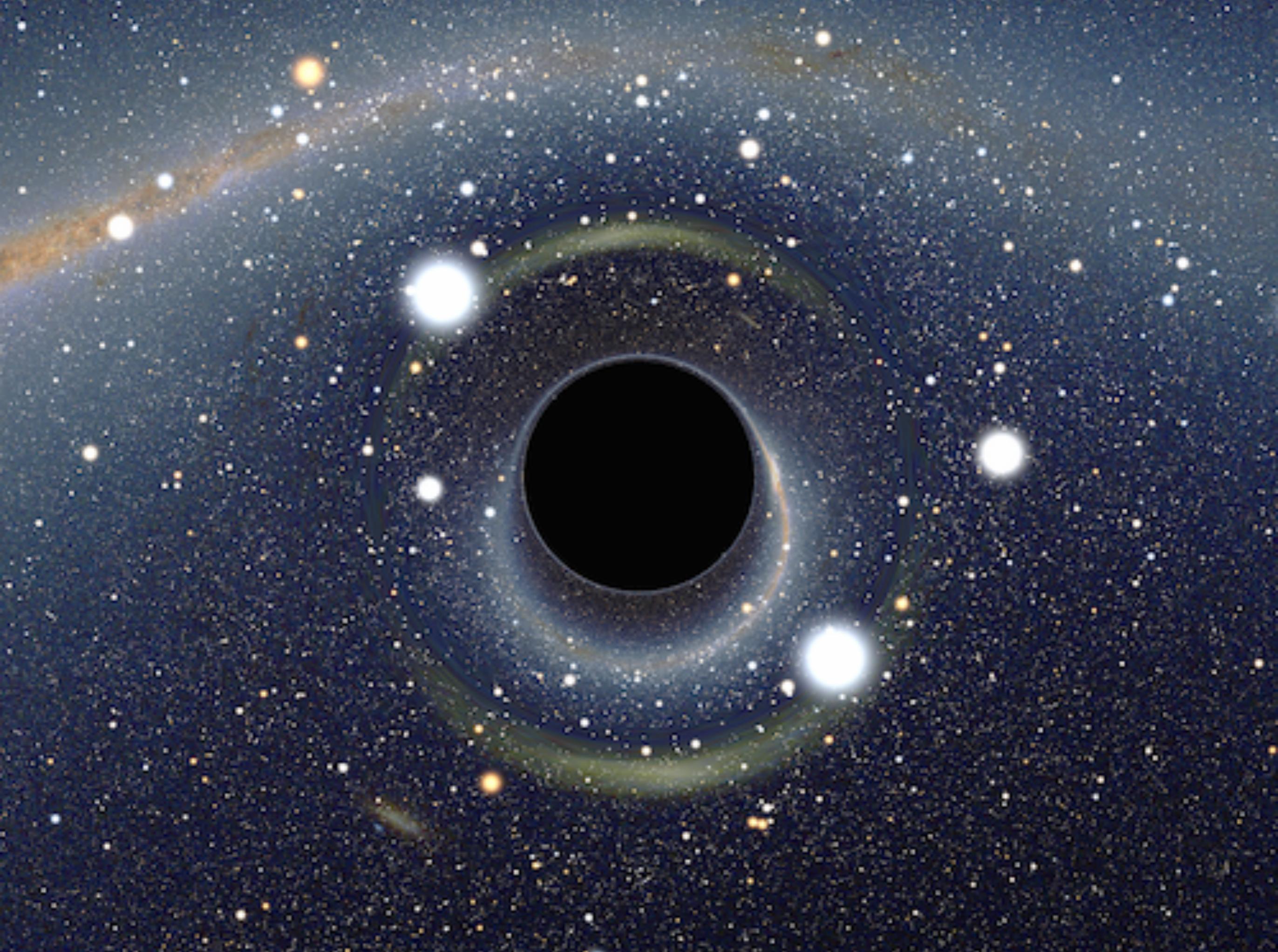


Black Holes

Spacetime can infinitely warp!

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

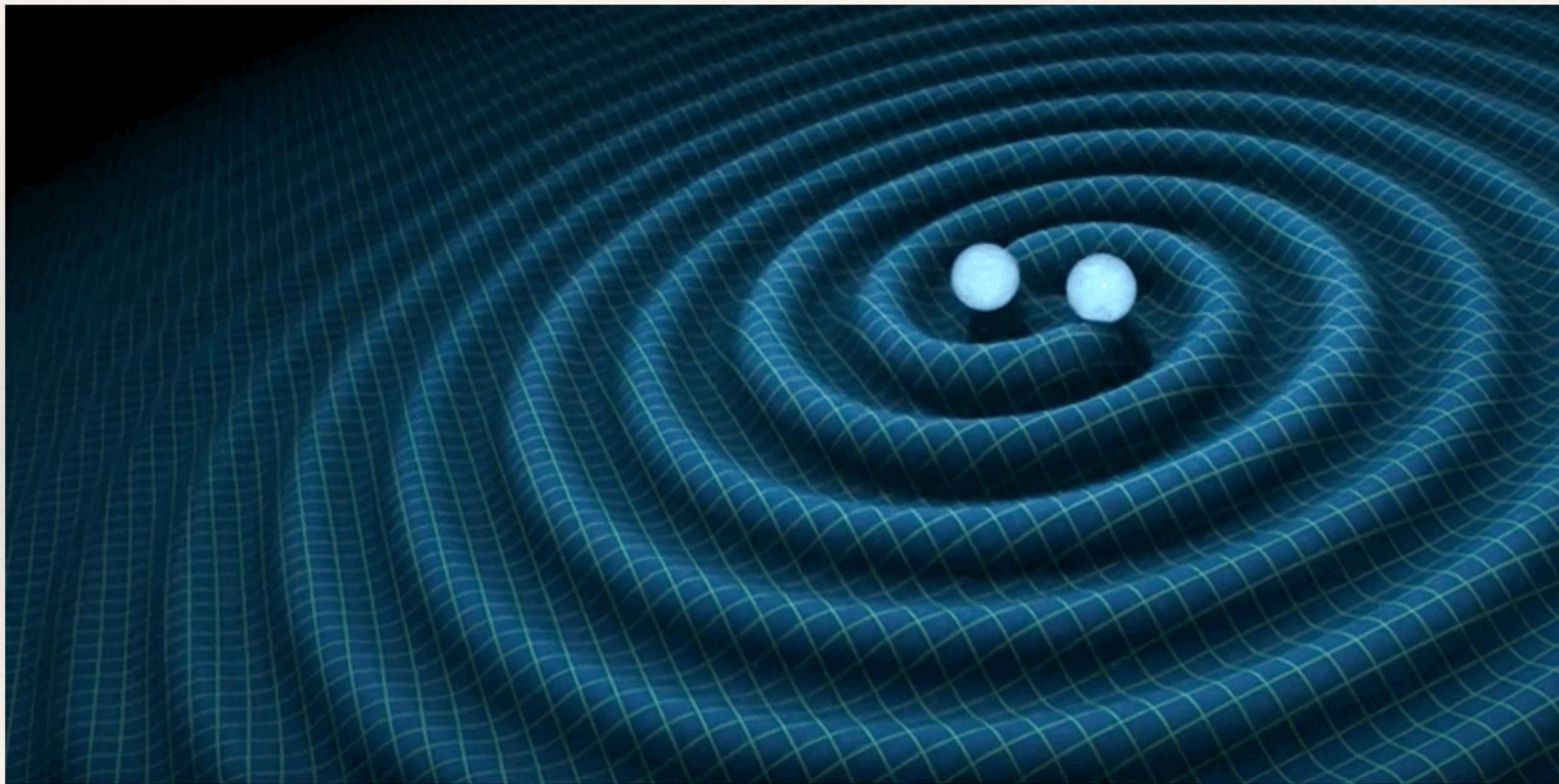






Two black holes orbiting each other
will produce gravitational waves!

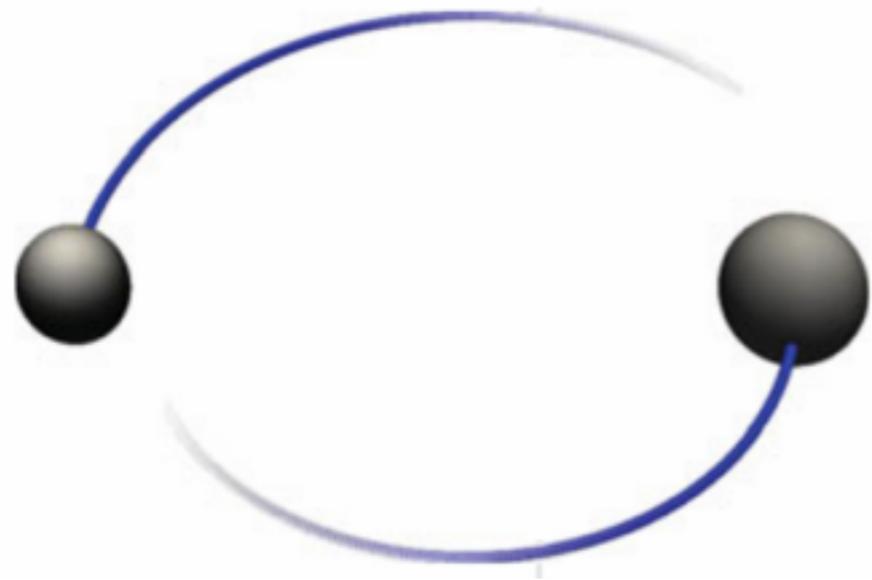
Gravitational Wave Production



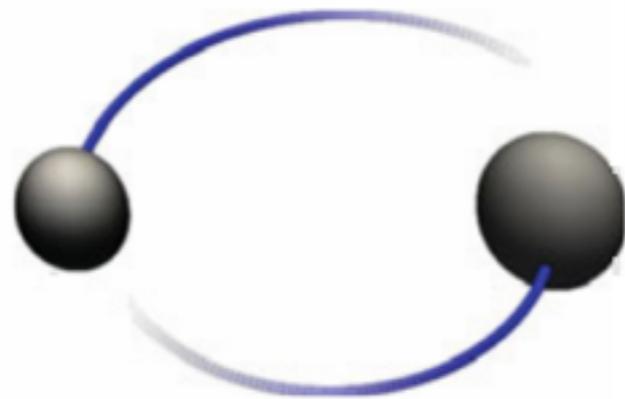


Characteristic Signal: Chirp

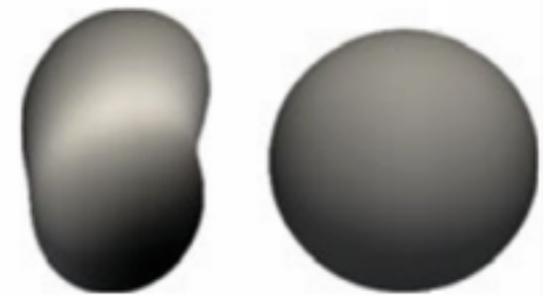
Inspiral



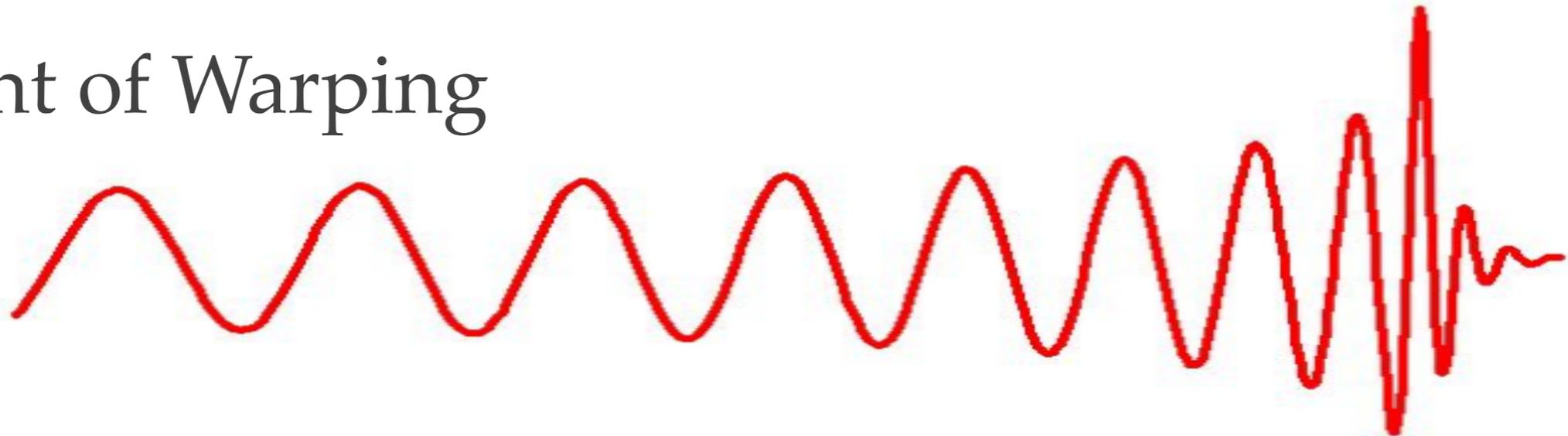
Merger



Ring-down

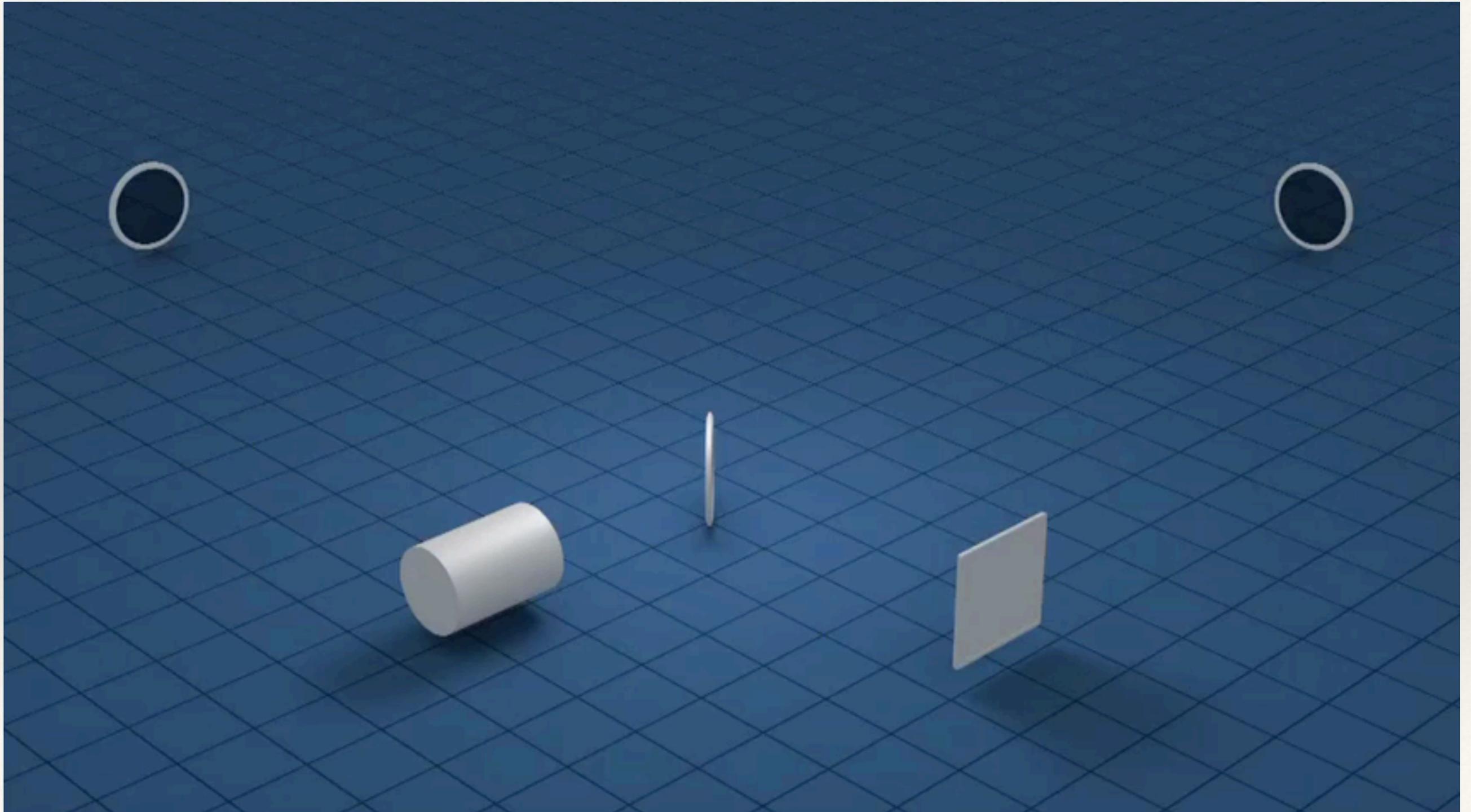


Amount of Warping



Time →

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

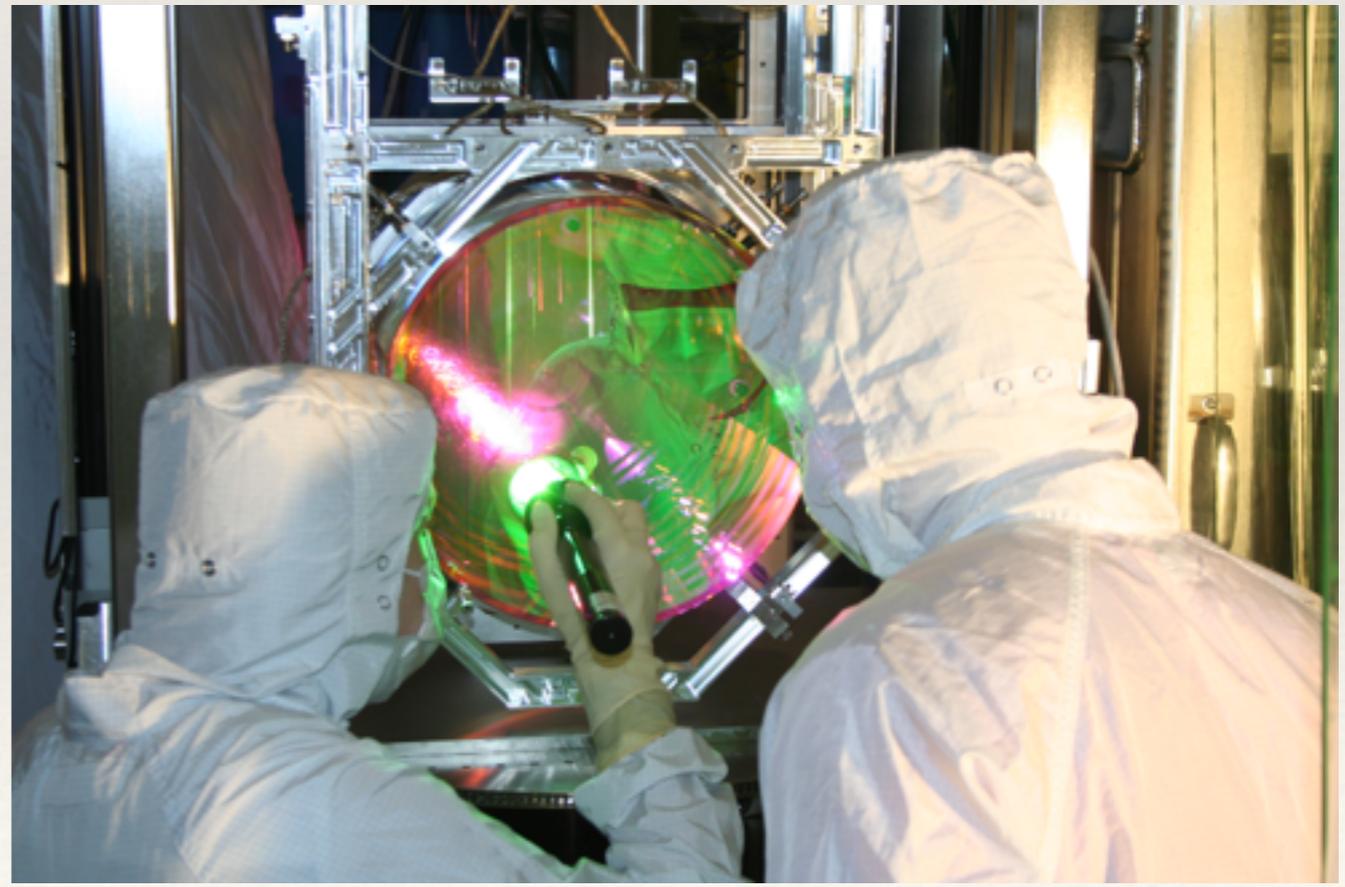
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Frederick J. Raab
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Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology





Multiple Interferometers

Use timing between two interferometers to find extraterrestrial signals

Two LIGO interferometers:

- Hanford, WA
- Livingston, LA



LIGO Scientific Collaboration

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





LIGO Scientific Collaboration

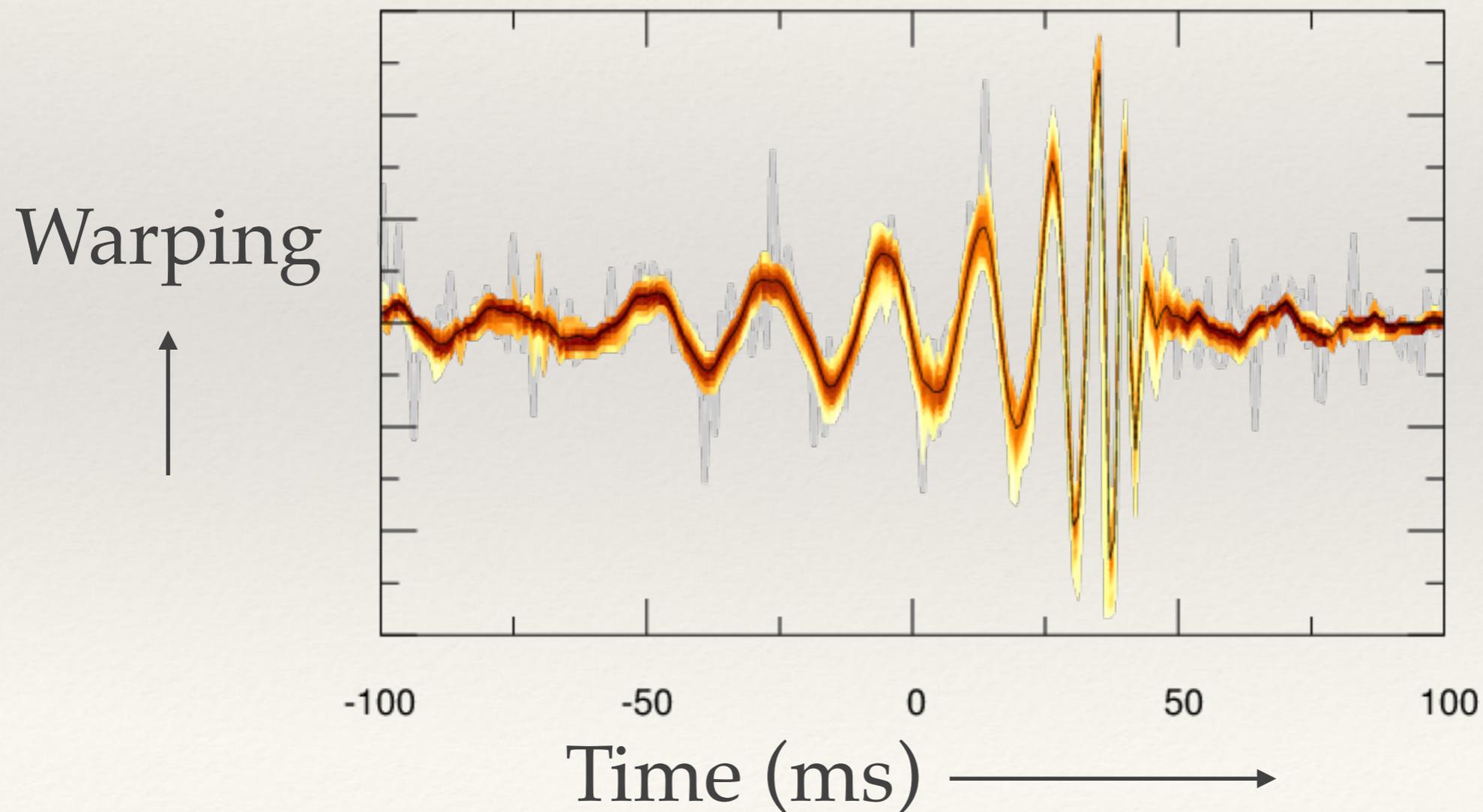


September 14, 2015



The Detection of Gravitational Waves

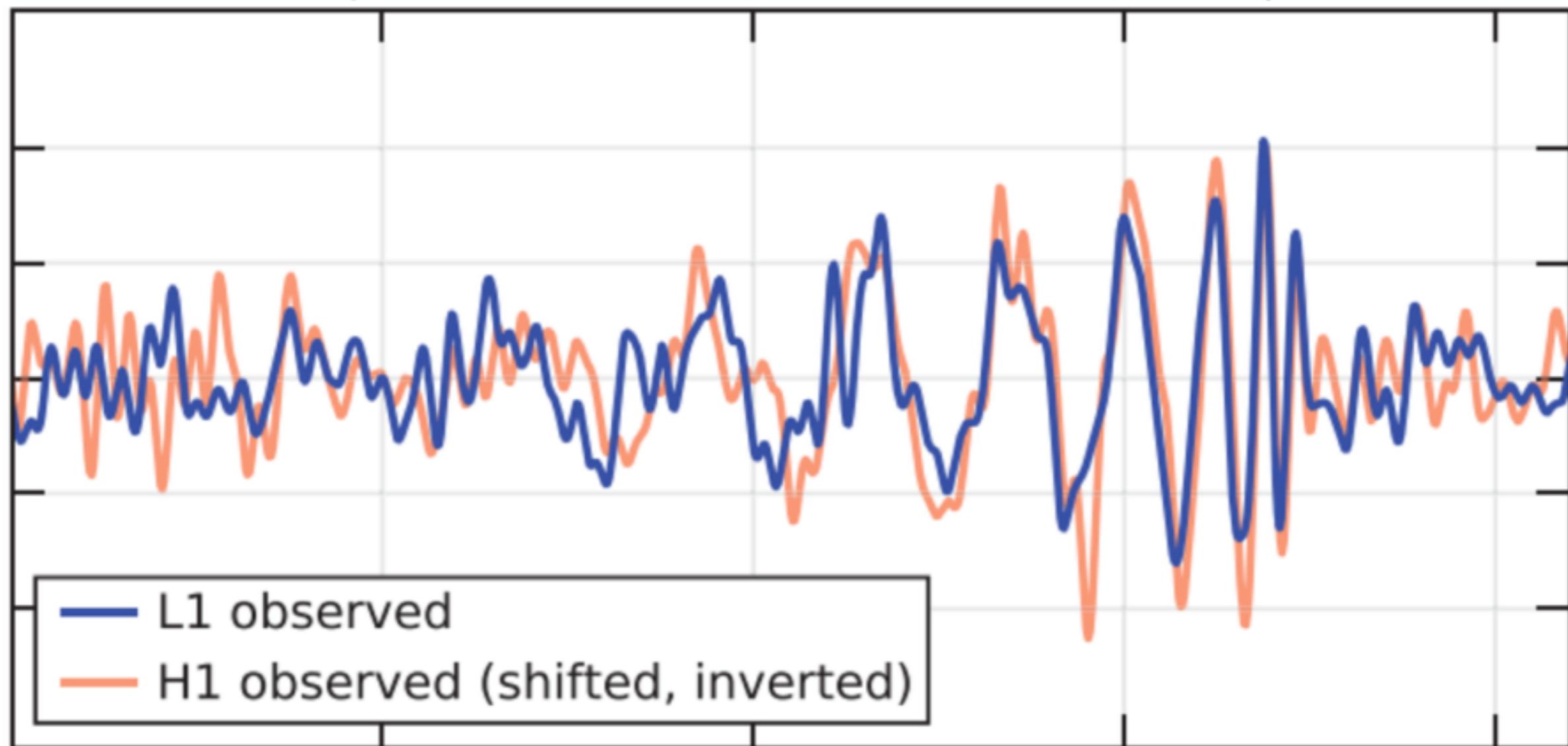
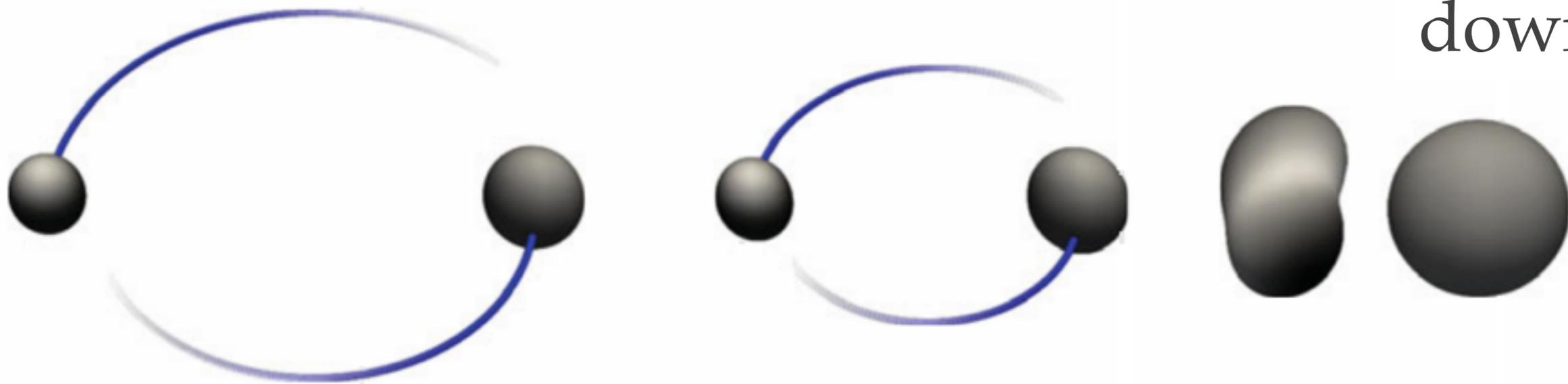
- ❖ LIGO sees chirp from merger of two black holes!



Inspiral

Merger

Ring-down



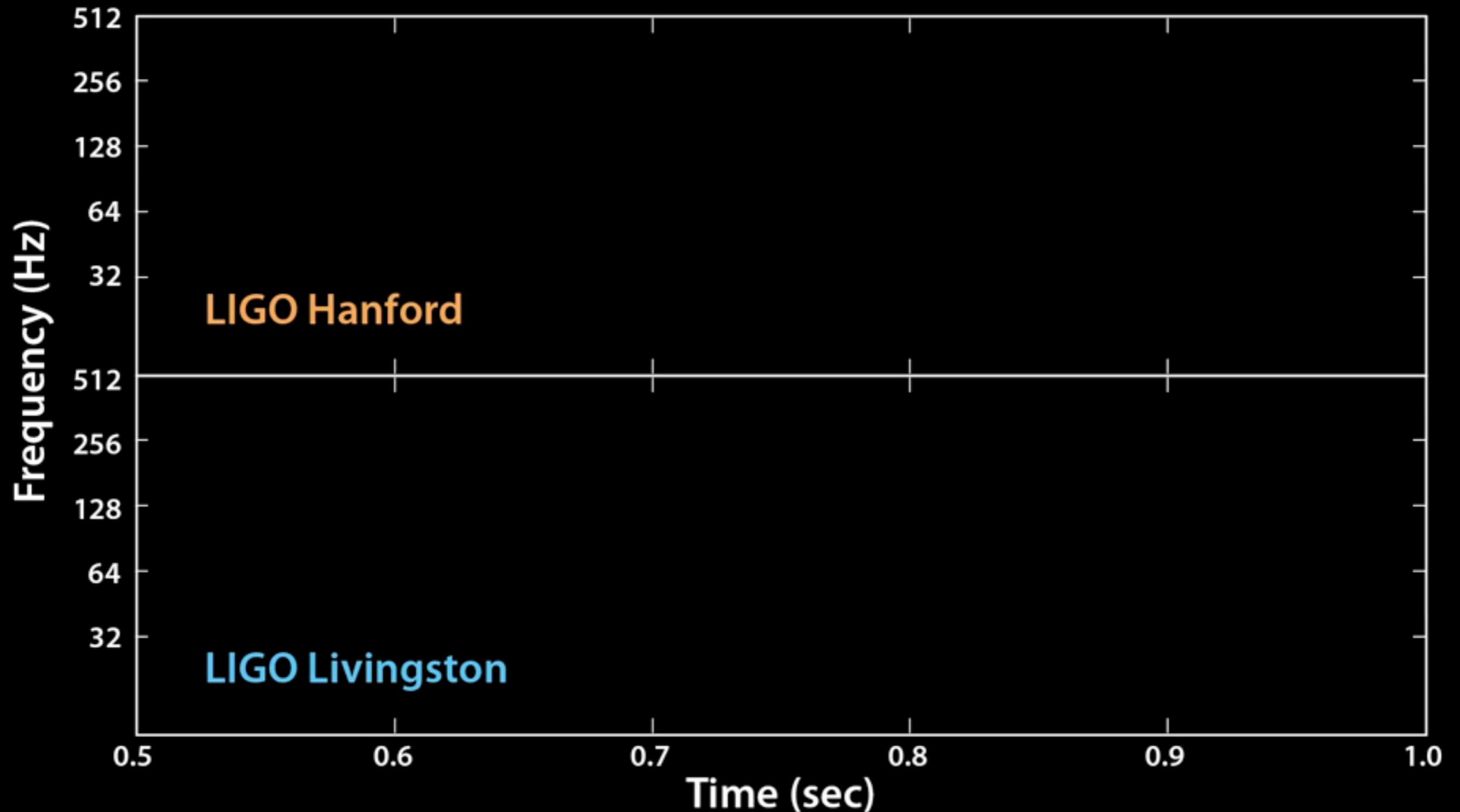
Two black holes crashing into each other at
over half the speed of light

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).

The sound of 2 black holes colliding



The Announcement: Feb. 11, 2016



Streamed all over the world,
including University of Chicago



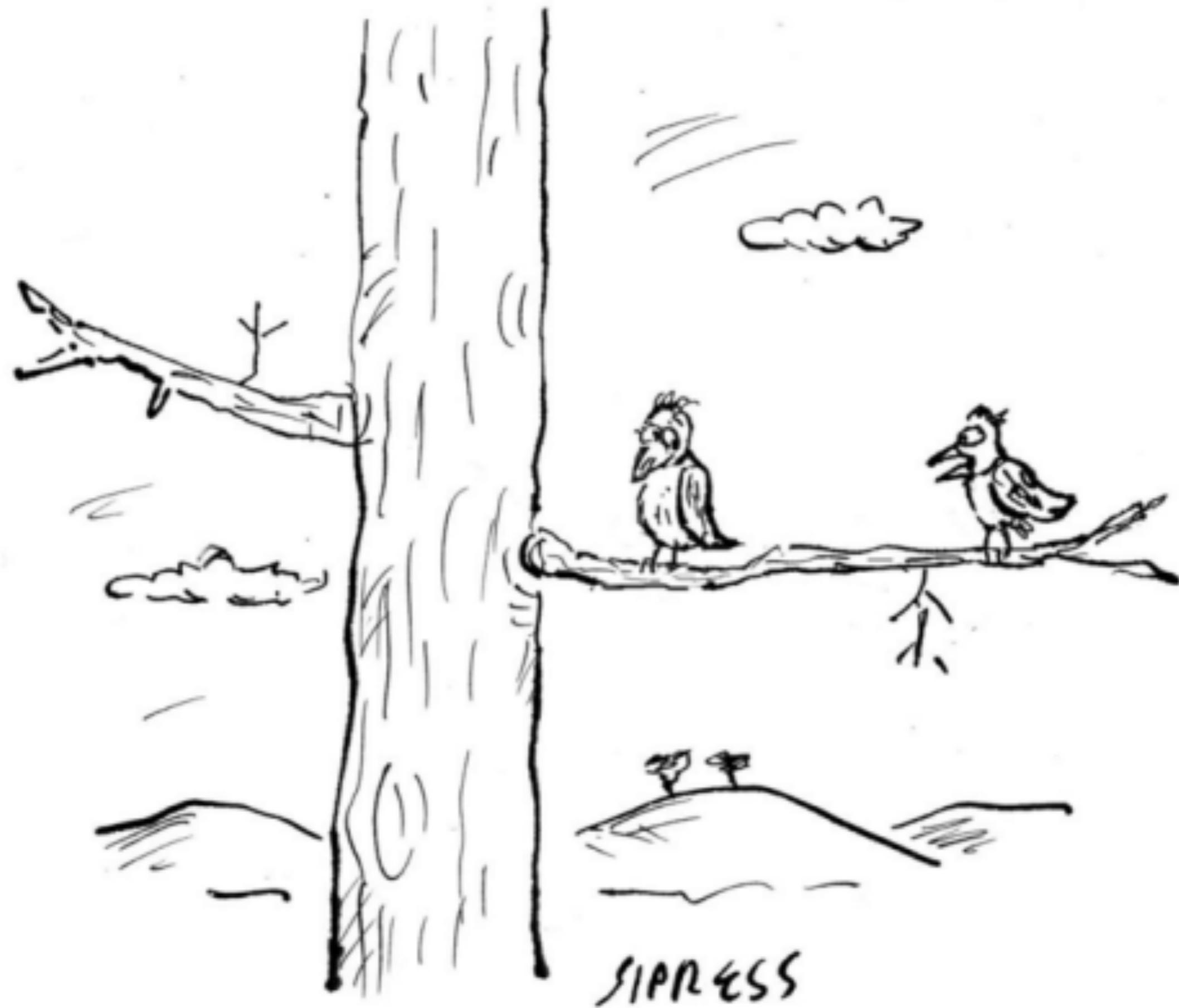
UChicago LIGO Group

Hsin-Yu Chen

Daniel Holz

Zoheyr Doctor

Ben Farr



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

"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.

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\$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.

Long in Clinton's Corner, Blacks Notice Sanders

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-

Courted Hard in South Carolina, Loyalists Listen Closely

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 Semnara, Richard Pérez-Peña and Kirk Johnson.

PRINCETON, Ore. — They im-

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

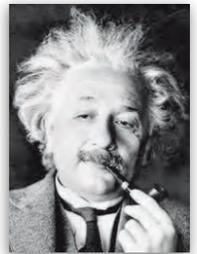
An Echo of Black Holes Colliding a Billion Light-Years Away

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-



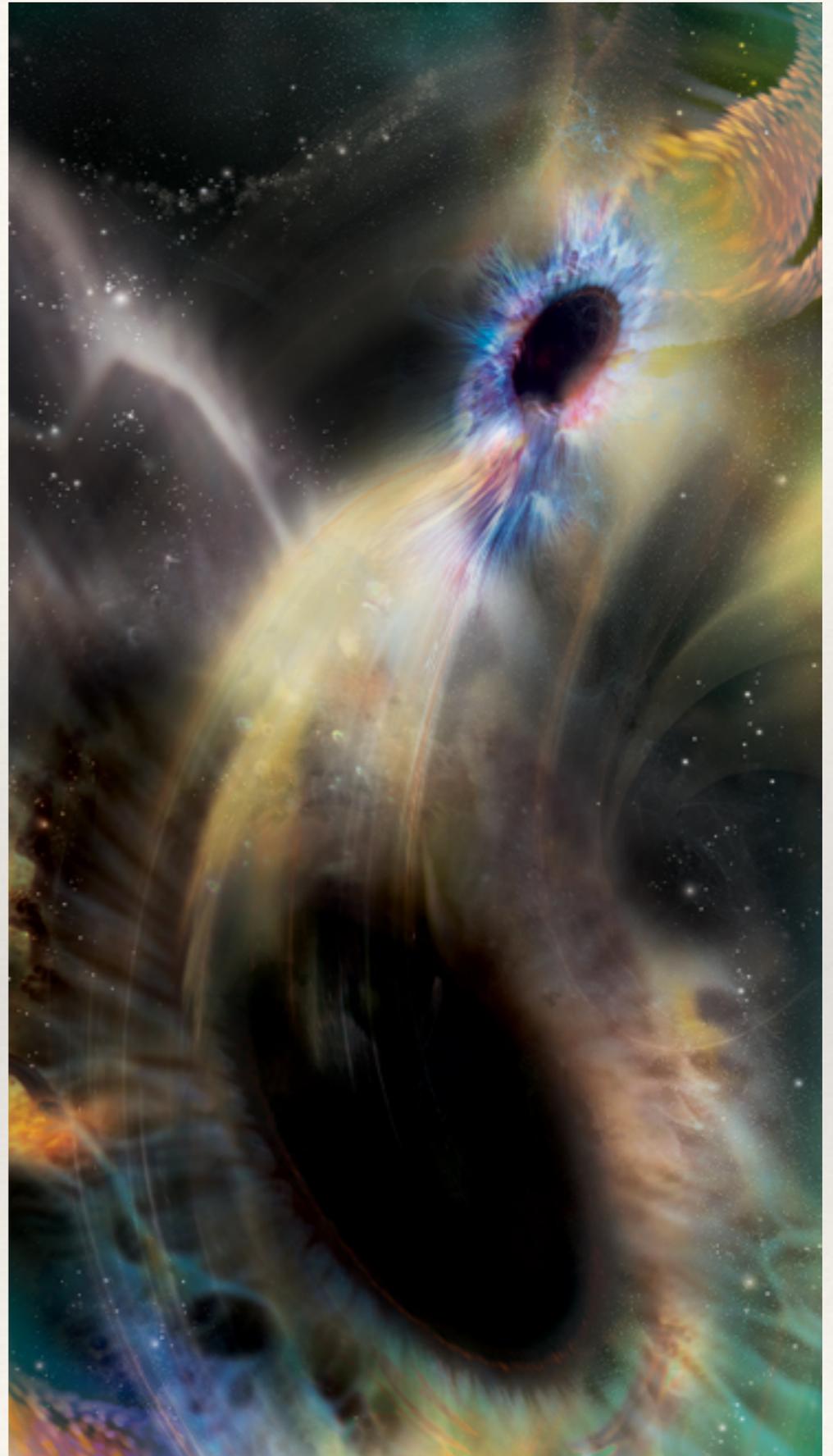




Future Possibilities

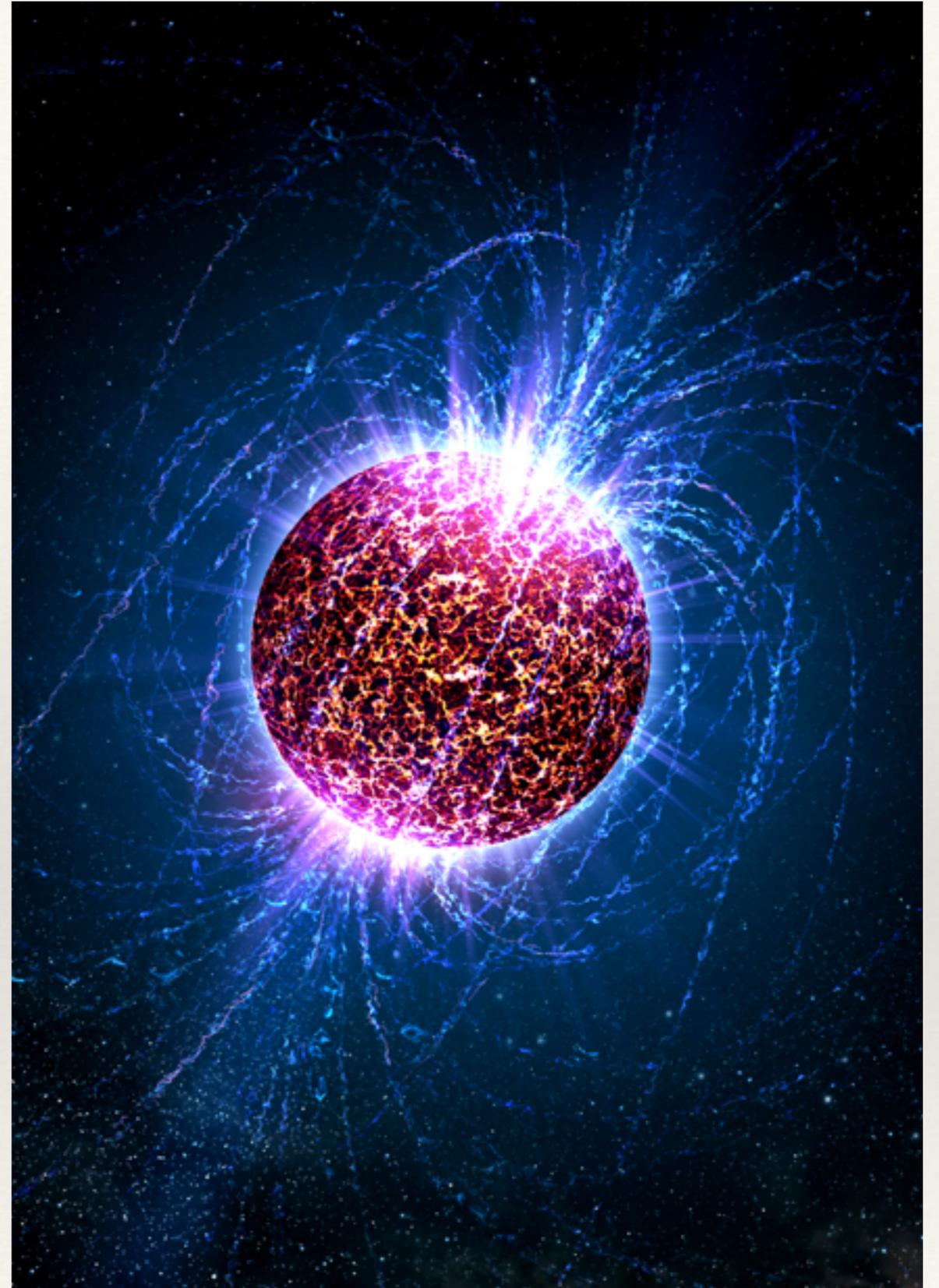
More Black Holes

- Only first 16 days out of 50 days of data analyzed
- Increased sensitivity later this year



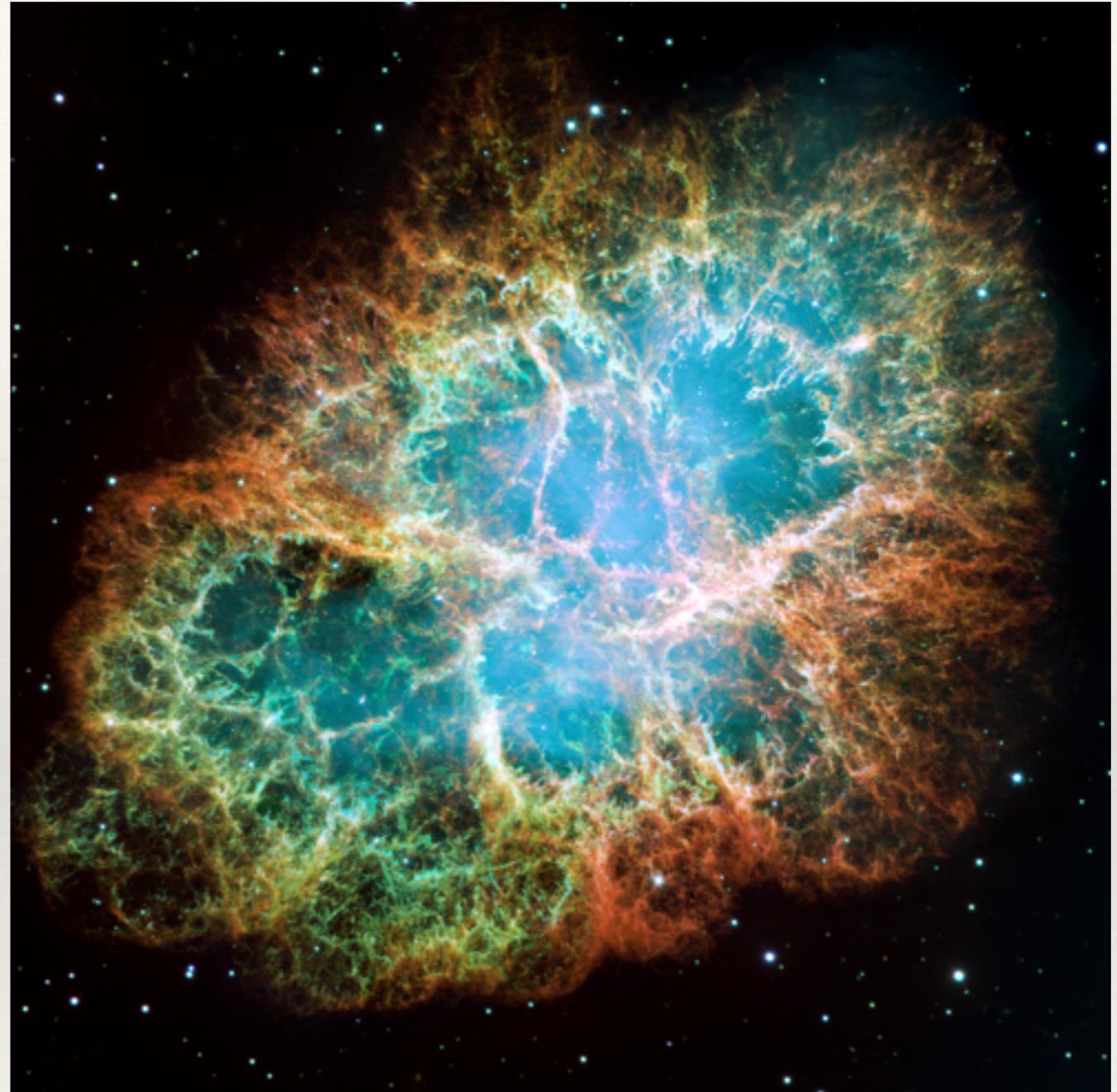
Merging Neutron Stars

- Made of just neutrons!
- Second densest objects in the universe after black holes
- Neutron star merger expected to produce flashes
telescopes may be able to see

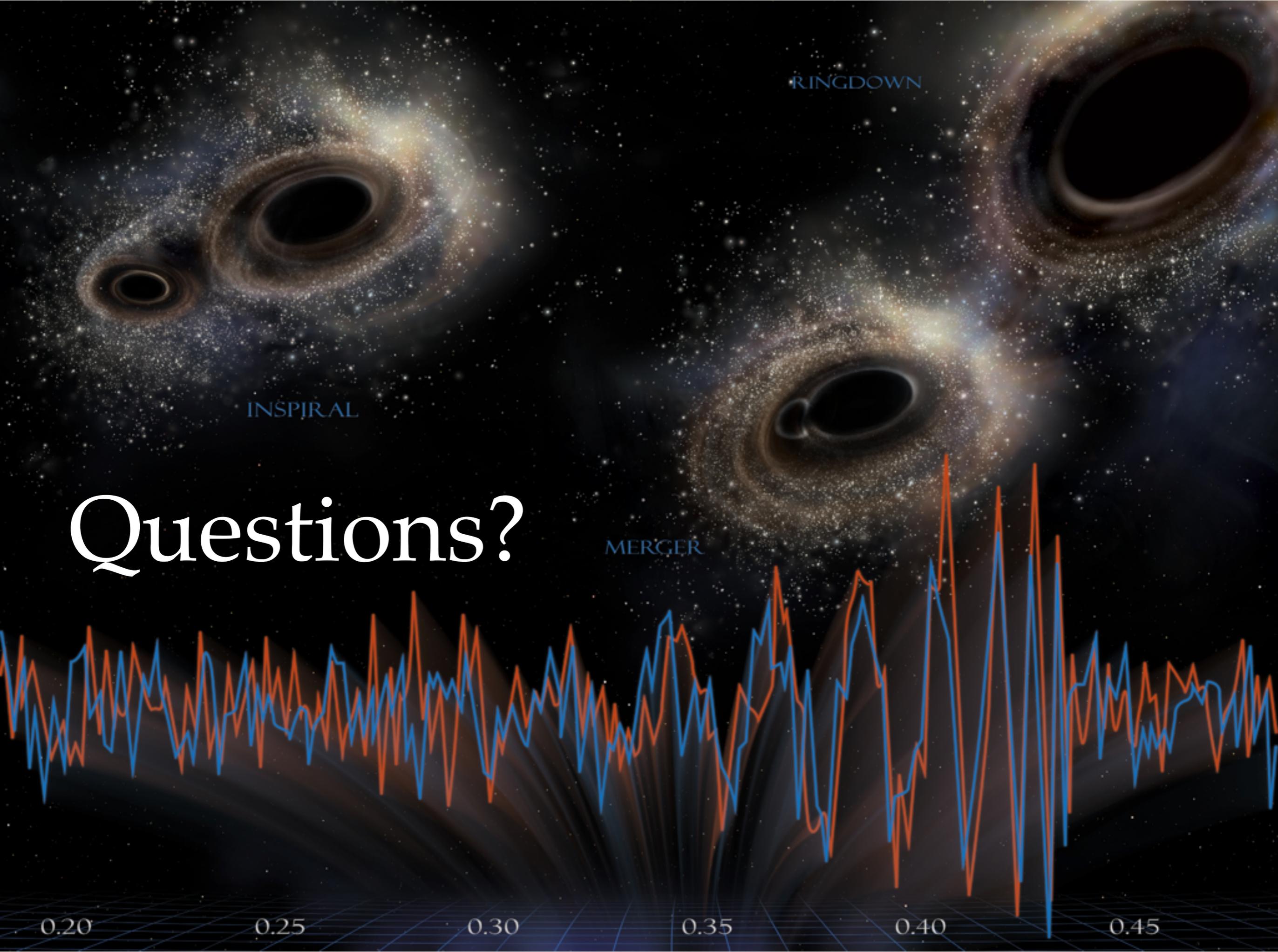


Supernovae

- Explosion of a massive star
- Could detect if it happens in our galaxy



Maybe we'll find something
unexpected...



RINGDOWN

INSPIRAL

MERGER

Questions?

0.20 0.25 0.30 0.35 0.40 0.45