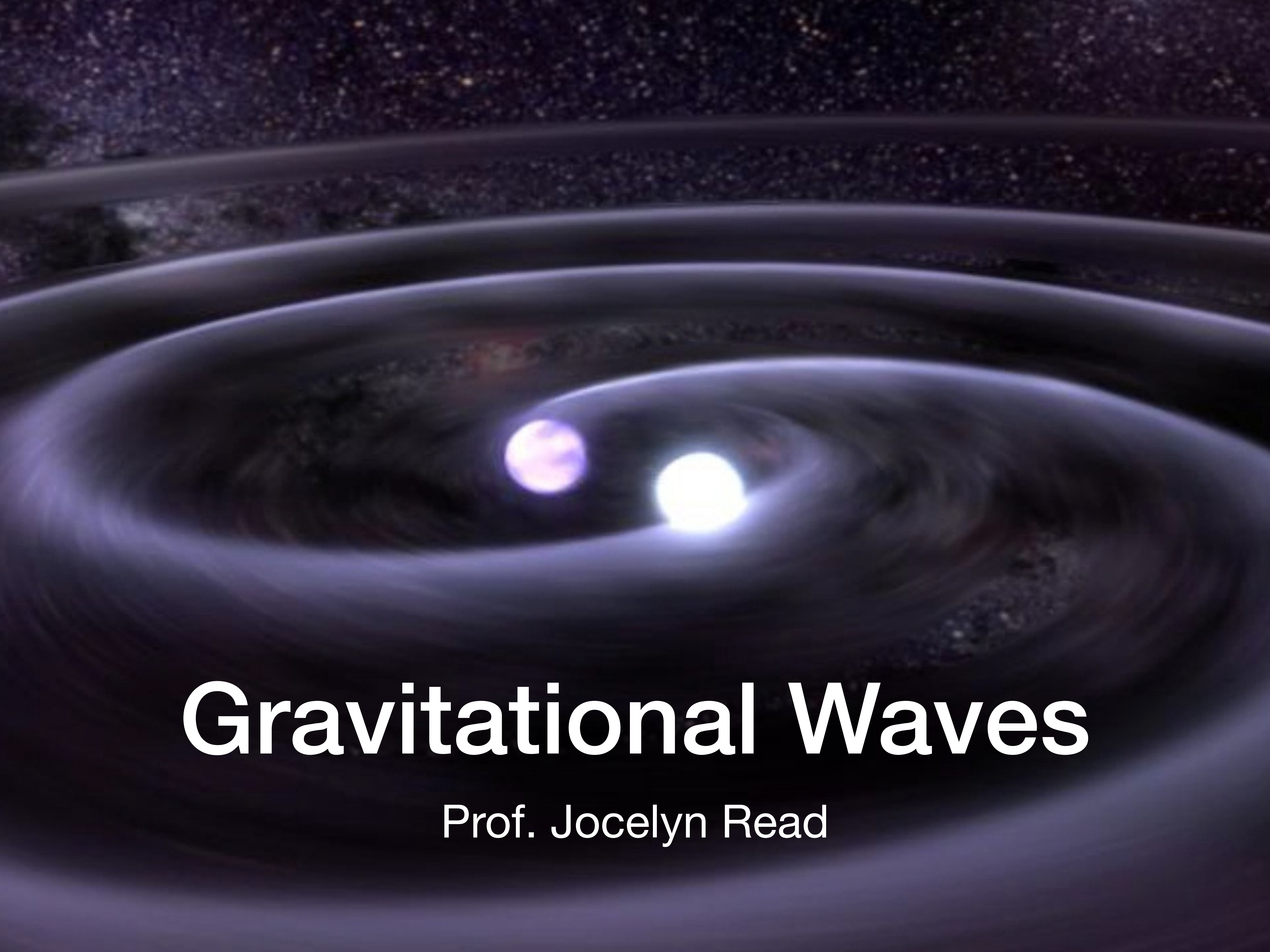


Gravitational Waves

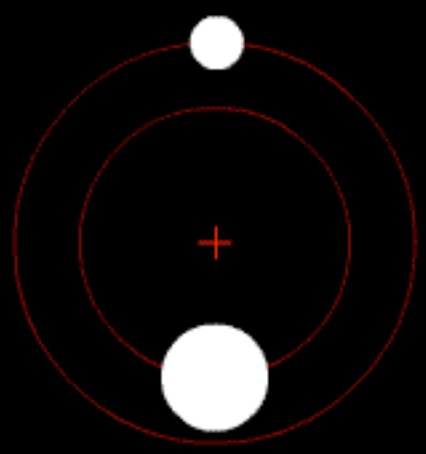
Prof. Jocelyn Read

Gravity

Earth and Its Moon
as seen from NASA's Mars Reconnaissance Orbiter, Nov. 20, 2016

Gravity in our Solar System

Newton: Falling and orbiting are explained by the same gravitational force



All masses attract each other:

$$F = G\frac{m_1 m_2}{r^2}$$

NASA's New Horizons spacecraft observes Pluto and it's largest moon, Charon, as it approaches. Jan 25—Jan 31, 2015

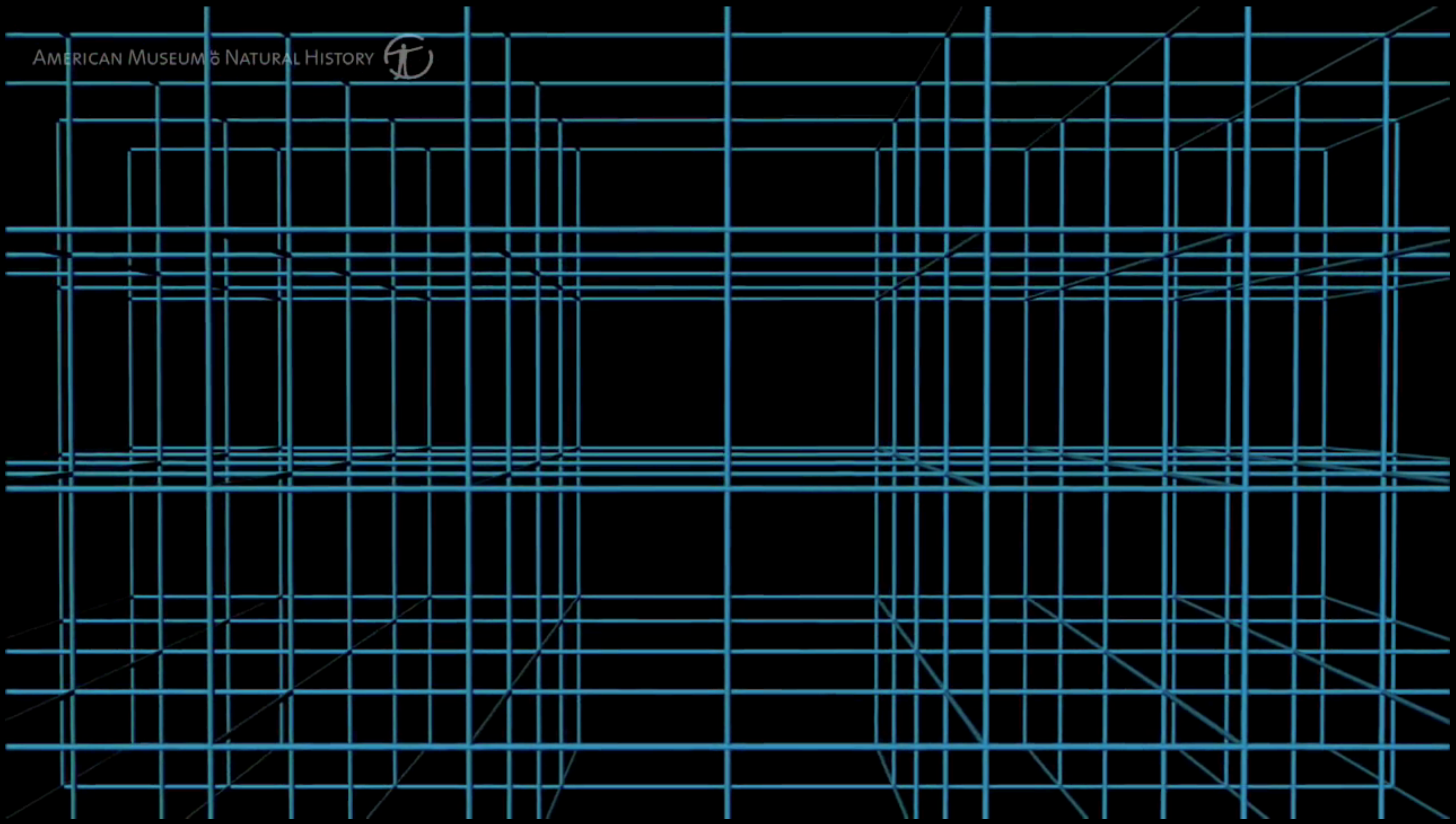
NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

$$F = G M m / r^2$$

If you make an object smaller in size, but keep the mass the same, the gravitational effects get stronger

General Relativity

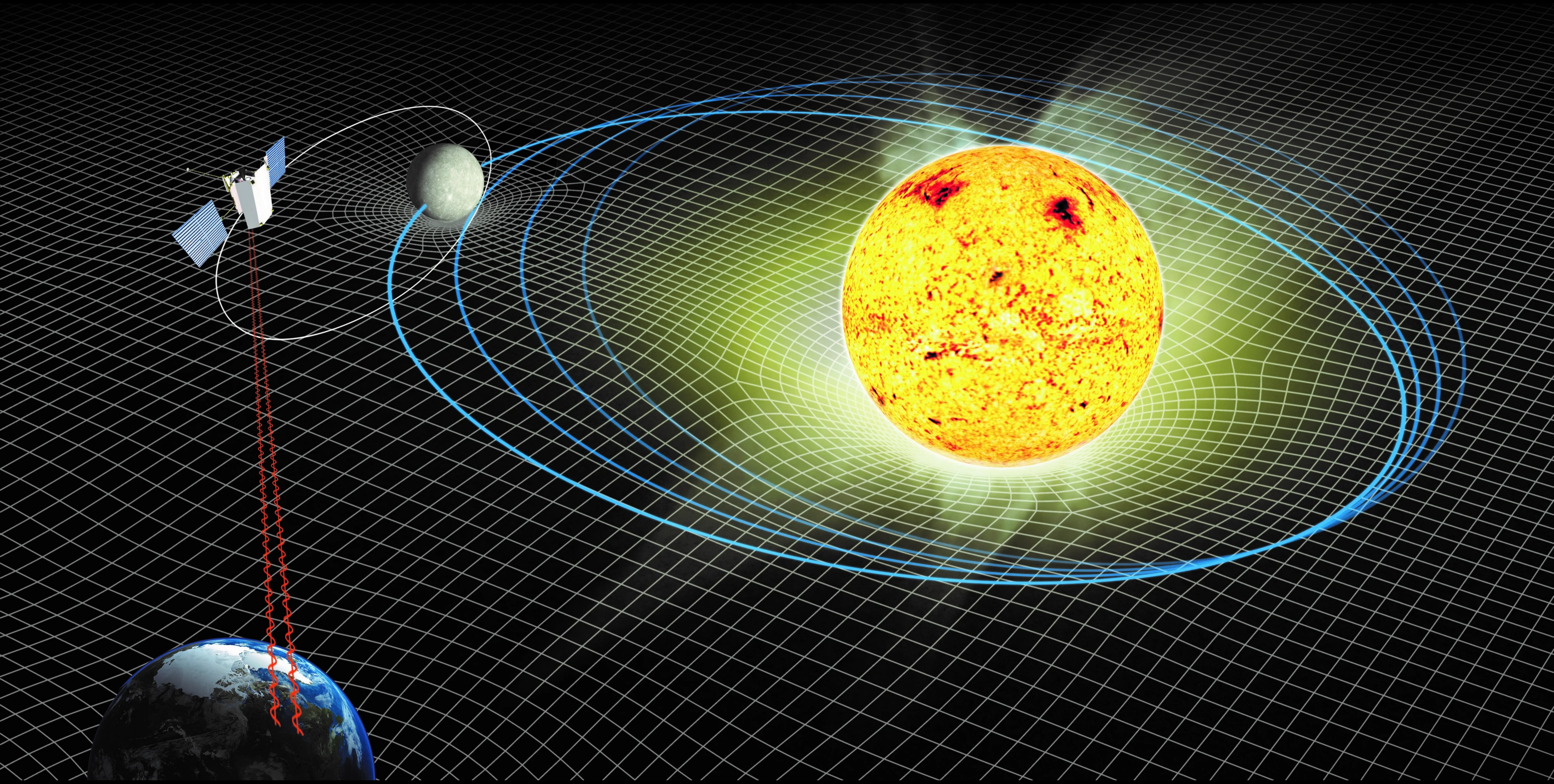
"Matter tells space-time how to curve and space-time tells matter how to move."
- John A. Wheeler



American Museum of Natural History
"Gravity: Making Waves"

Mercury orbits our Sun

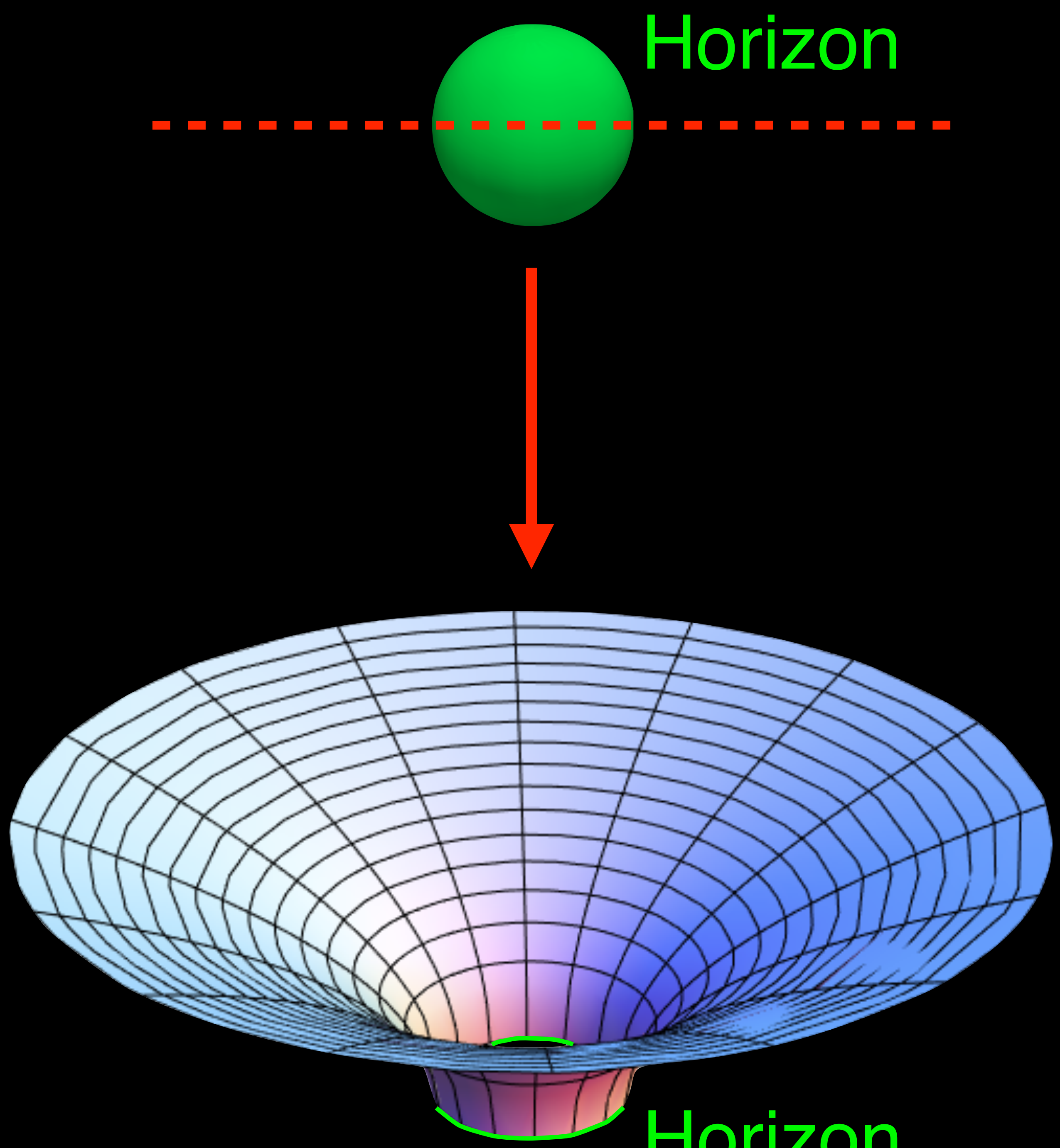
Orbital precession: GR fits, Newton doesn't



https://solarsystem.nasa.gov/news/296/

Black holes: extremes of space-time curvature

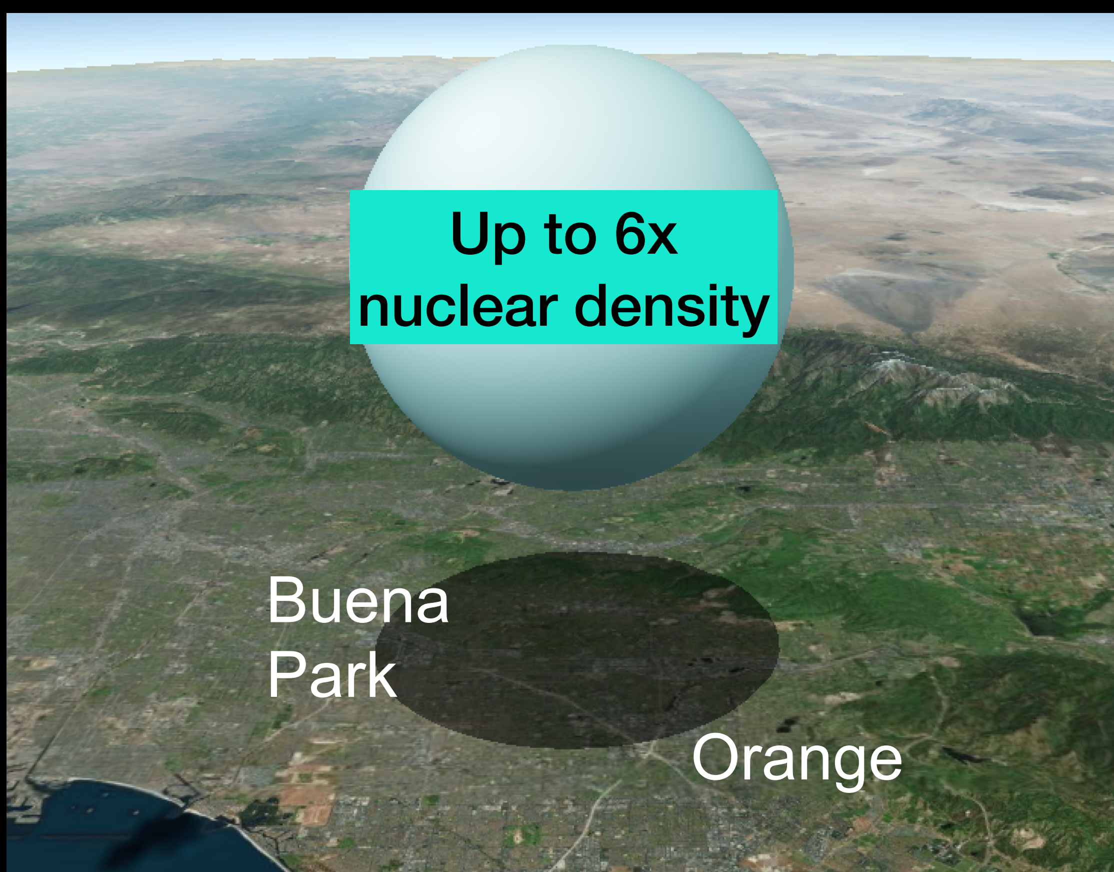
- *Stellar-mass* formed when the massive stars collapse
- *Supermassive* found in the centers of galaxies
- Gravity so strong...
  - Nothing can escape from within the horizon (surface)
  - *Singularity* inside horizon



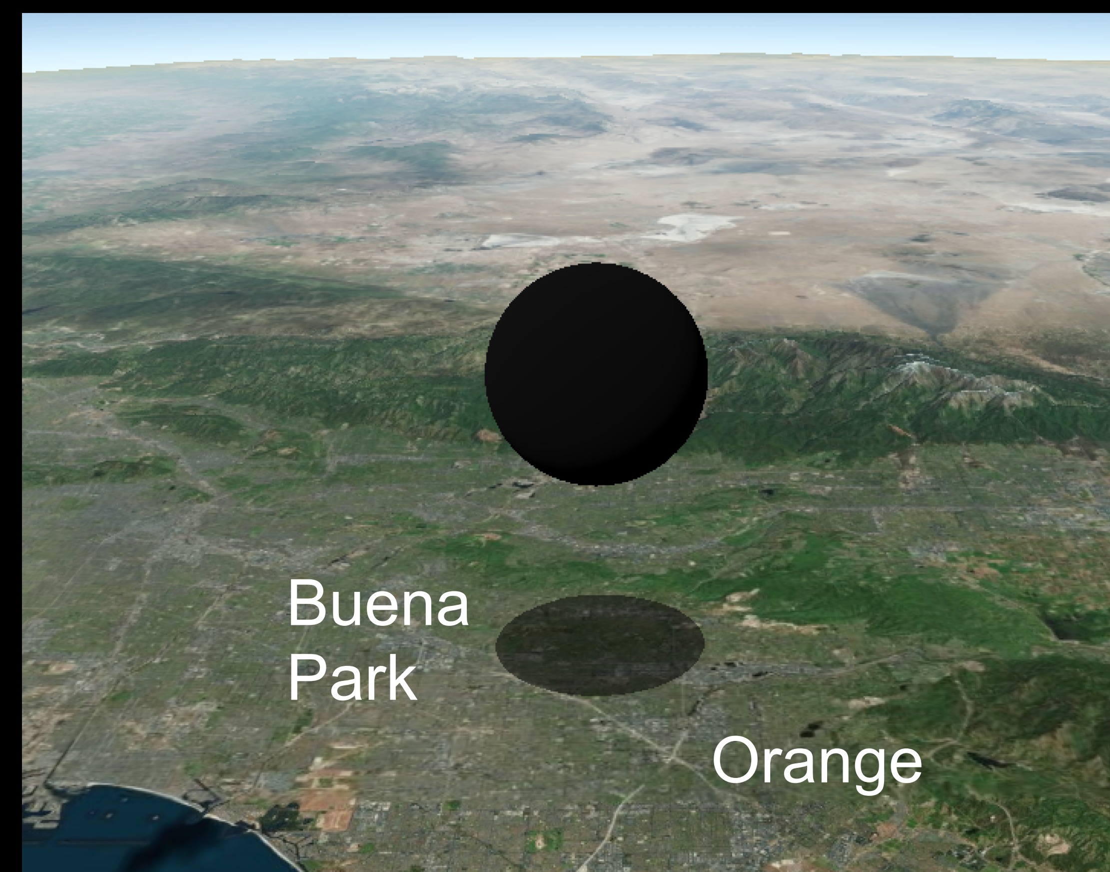
Images from Wikipedia

Compact objects: lots of mass in a small volume

Neutron star: Mass = 1-2 ☀
Radius ≈ 10 - 13 km



(small) Black hole: Mass = 2 ☀
Radius = 6 km

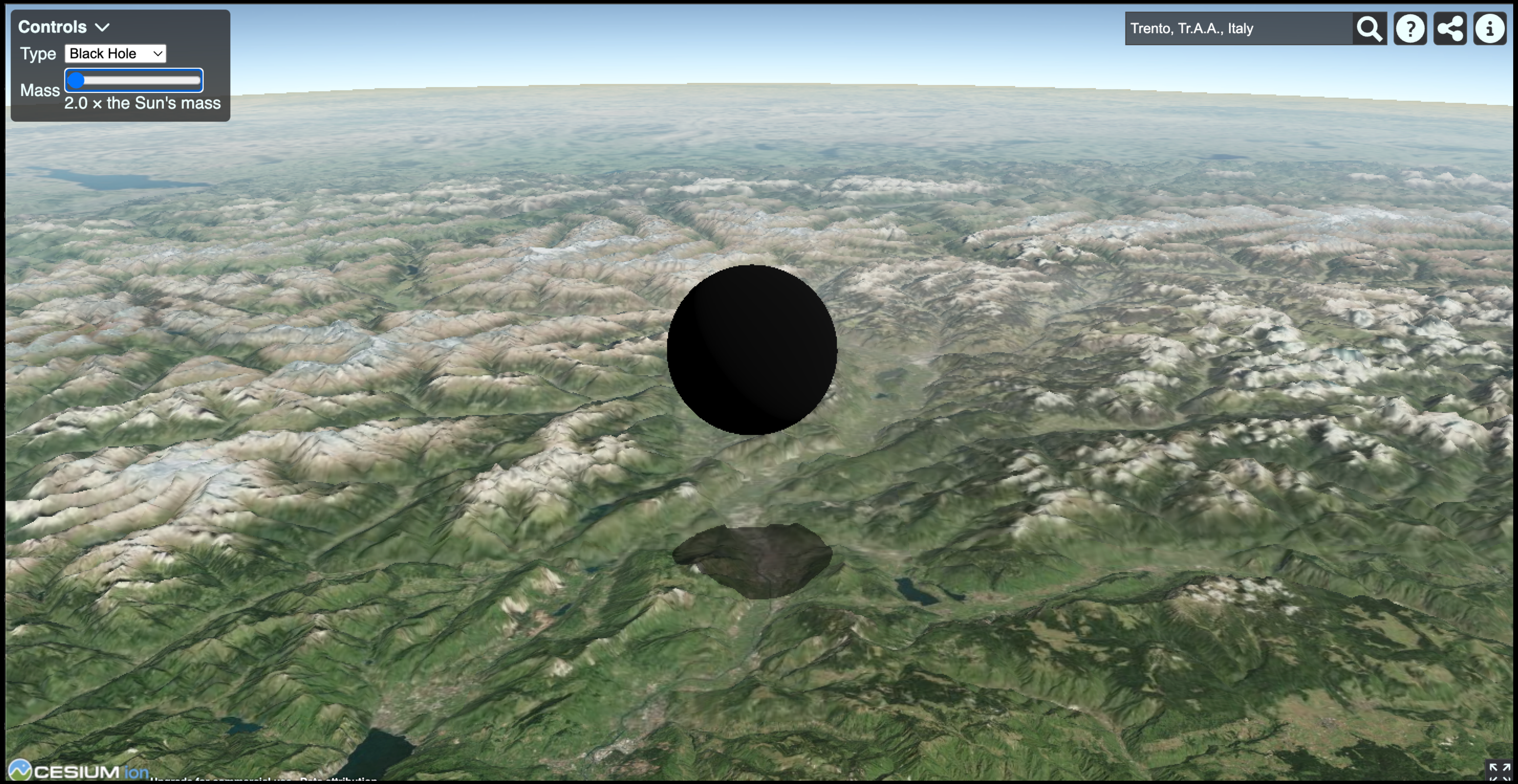


https://ns-in-my-city.daniel-wysocki.info/

Black hole sizes

2.0 $M_\odot$ Black hole

$(R_S = 2GM/c^2)$

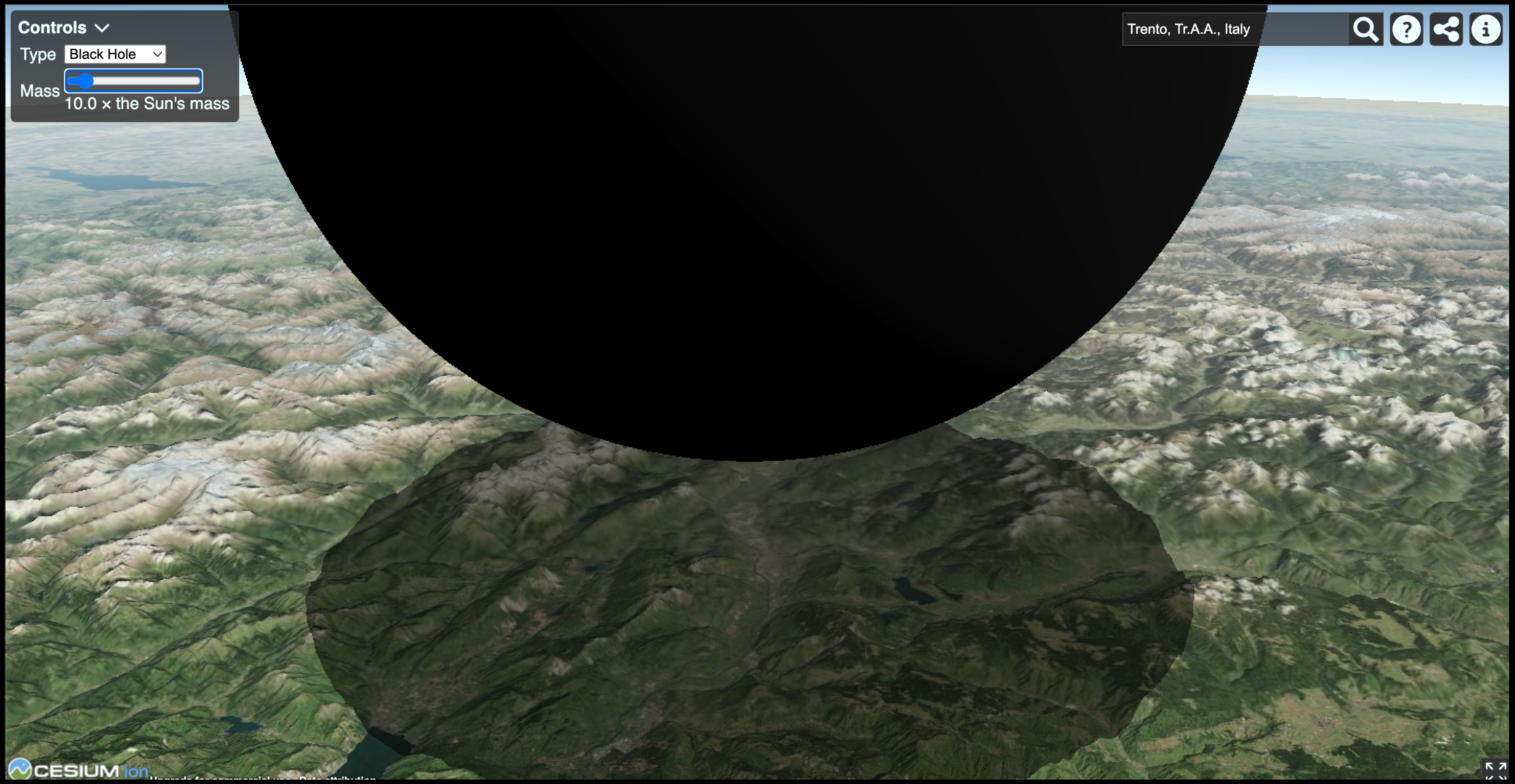


ttps://ns-in-my-city.daniel-wysocki.info/

Black hole sizes

10 $M_\odot$ Black hole

$(R_S = 2GM/c^2)$



The Crab Nebula: supernova observed in 1054

X-ray: NASA/CXC/SAO/F.Seward; Optical: NASA/ESA/ASU/J.Hester & A.Loll; Infrared: NASA/JPL-Caltech/Univ. Minn./R.Gehrz

6.5 billion solar mass black hole

Supermassive black hole at the center of the galaxy M87

Event Horizon Telescope Collaboration

The star S2 orbits the Milky Way’s central black hole Sagittarius A*

Orbital precession: GR fits, Newton doesn’t

https://www.eso.org/public/news/eso2006/

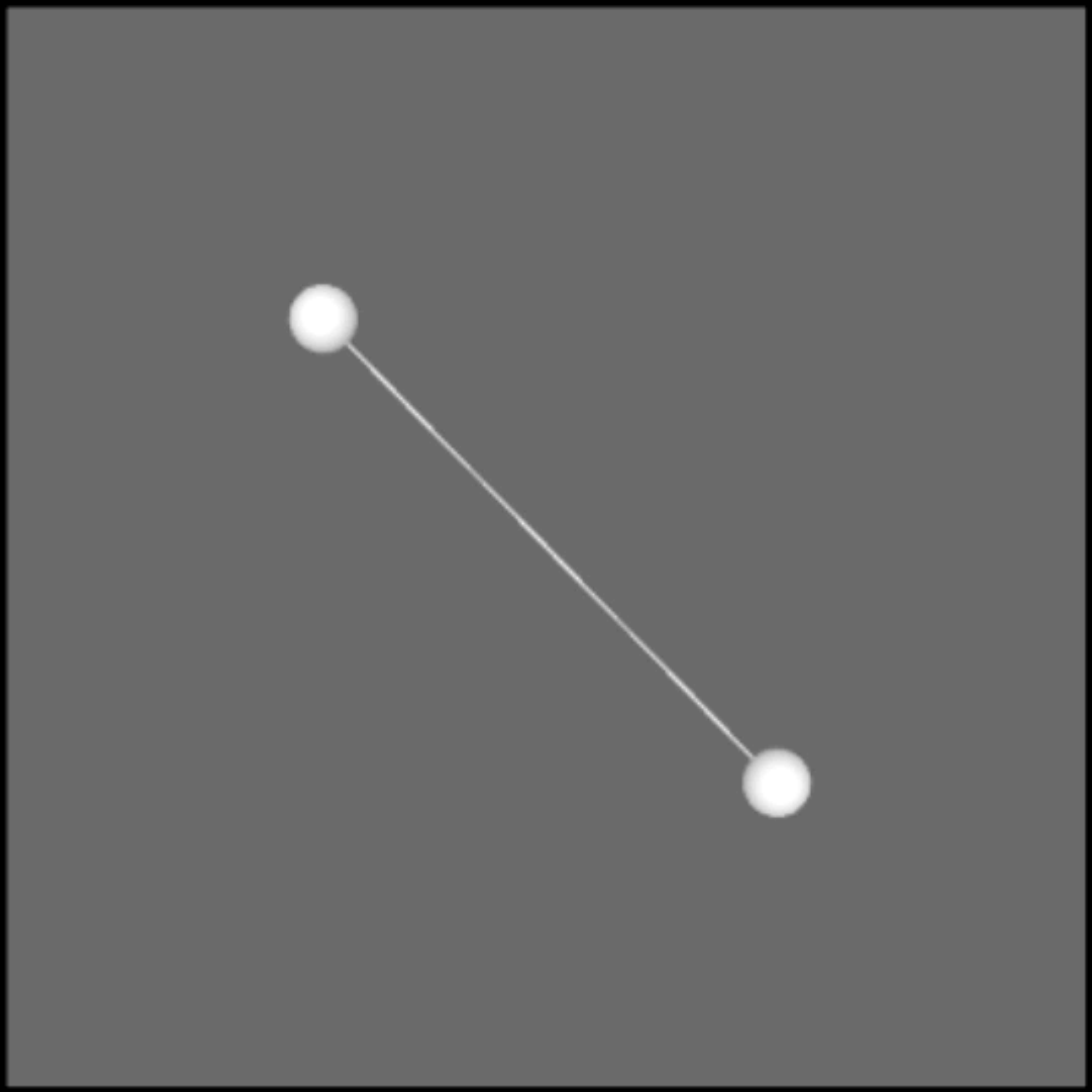
Mass in Motion

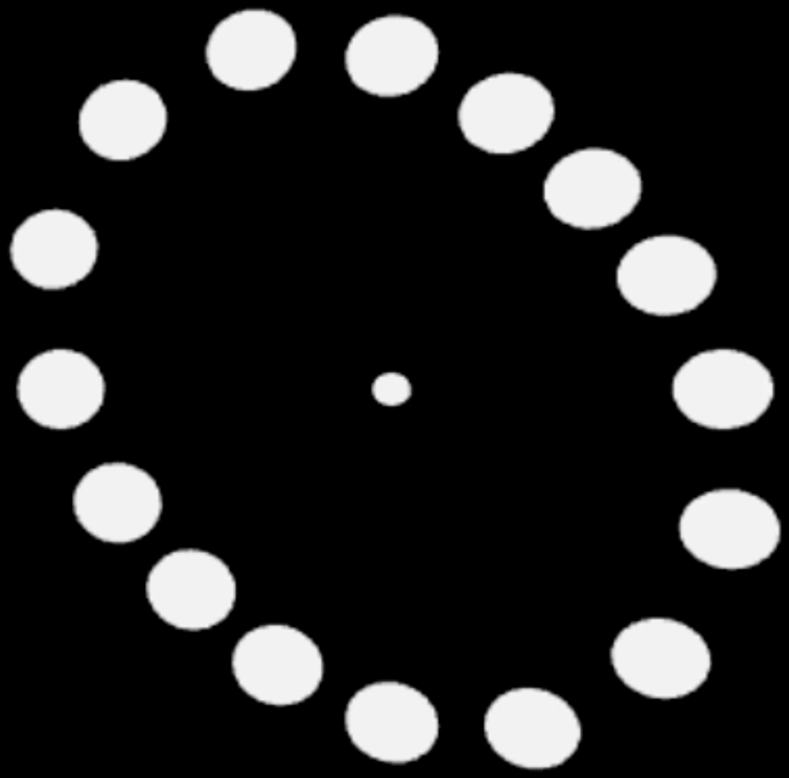
- Newtonian Gravity: “Action at a distance”
  - Instantly feel the new position of a moving object
- General Relativity:
  - Changes in curved spacetime ripple out at the speed of light

Moon passing Earth
as seen from NASA’s DSCOVR spacecraft (NASA/NOAA)
at the L1 Point between the Earth and the Sun, 5 light seconds from Earth

Two objects orbit, gravitational pull *changes*

At your observing location, a ring of particles stretches and squeezes in response





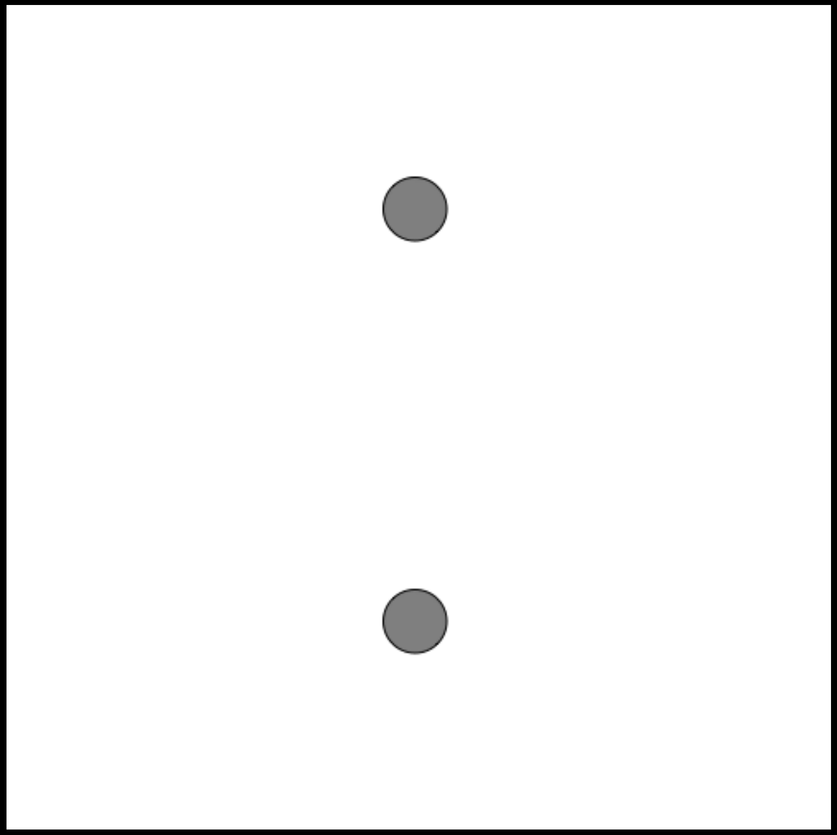
Demo by Eric Flynn, CSUF

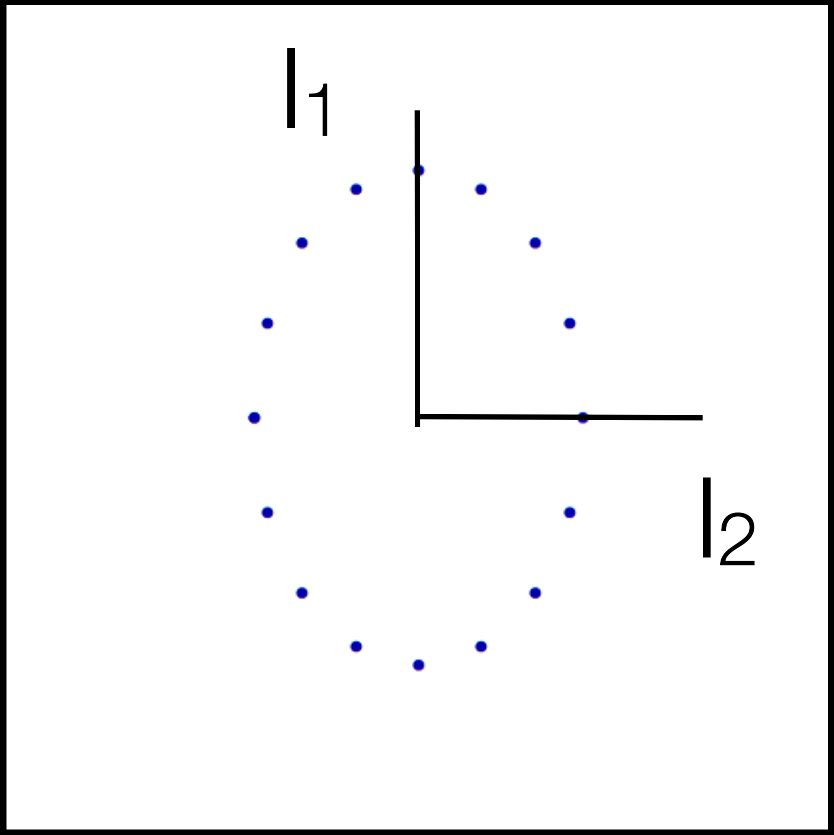
Which of the following would emit zero gravitational waves?

Hint: would the gravitational pull you feel change?

A. A spinning spherical star
B. The earth orbiting the sun
C. A professor wildly waving her hands
D. All of the above would emit gravitational waves

How many stretch/squeeze cycles are there during the time the stars take to make a full orbit?





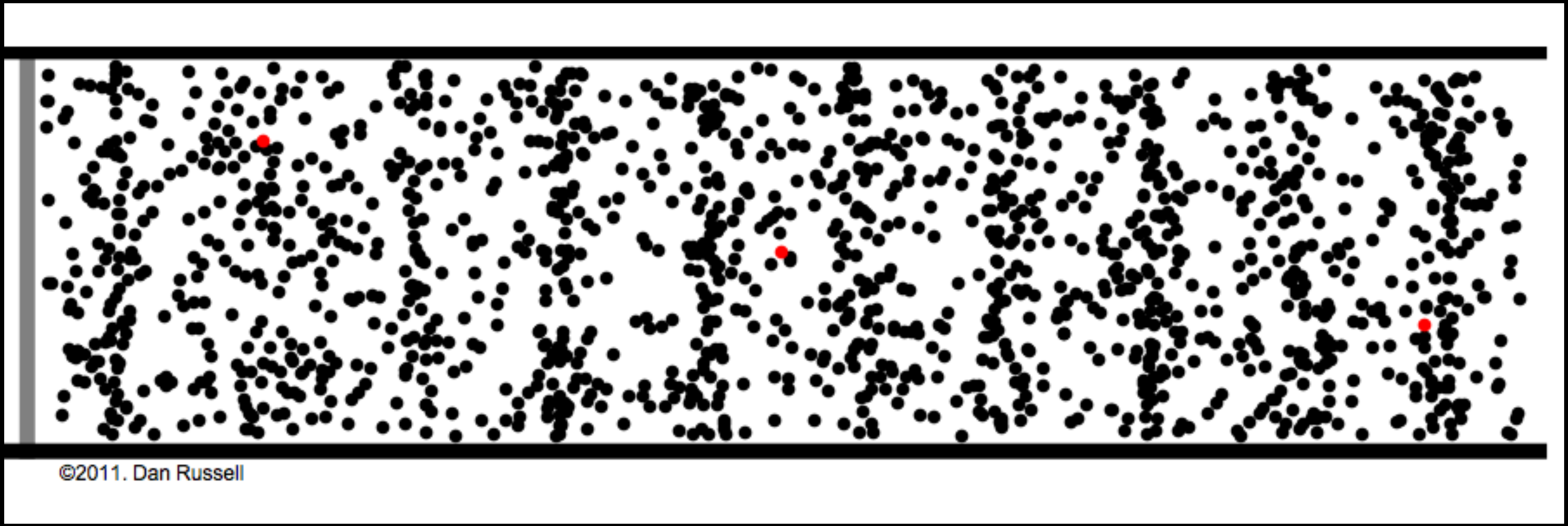
A. One

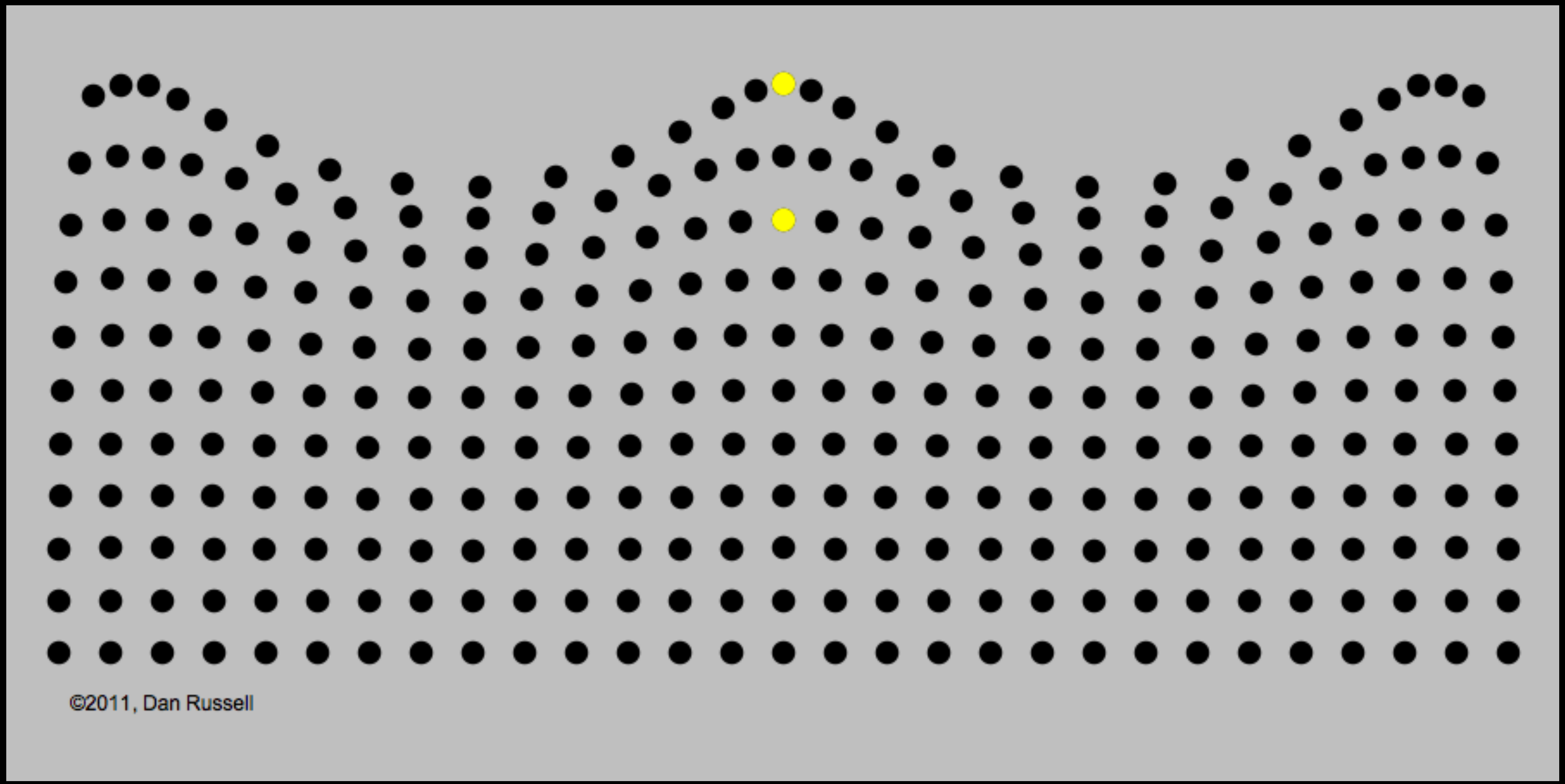
B. Two

C. Half

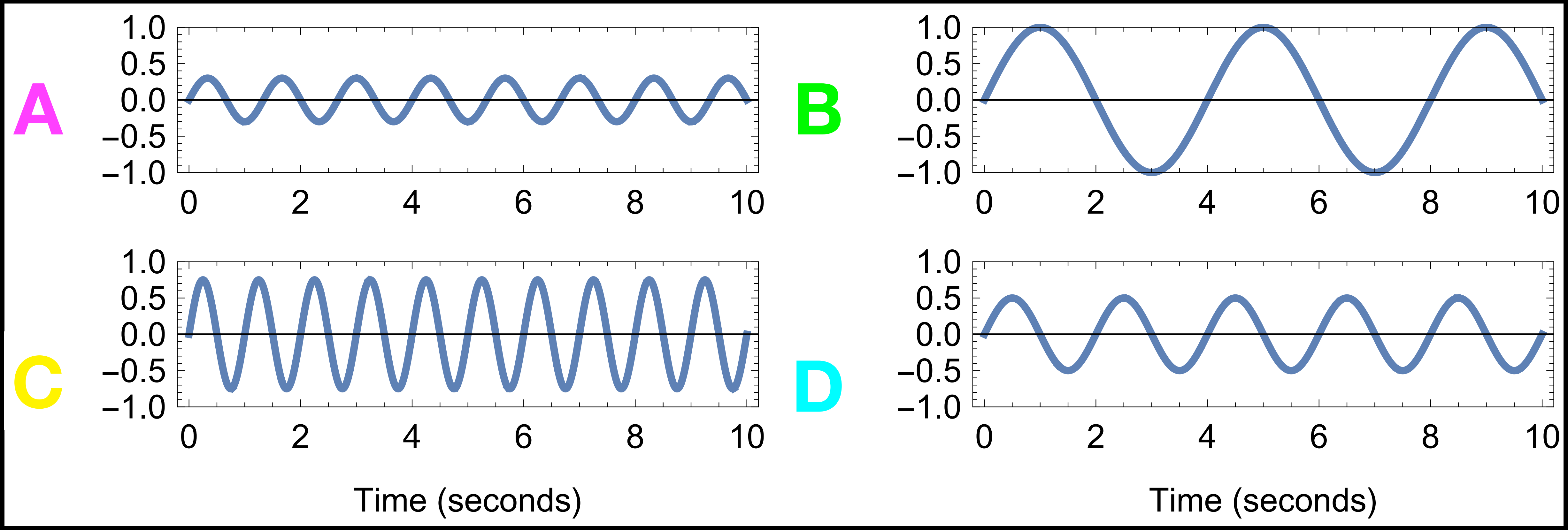
D. Four

Waves



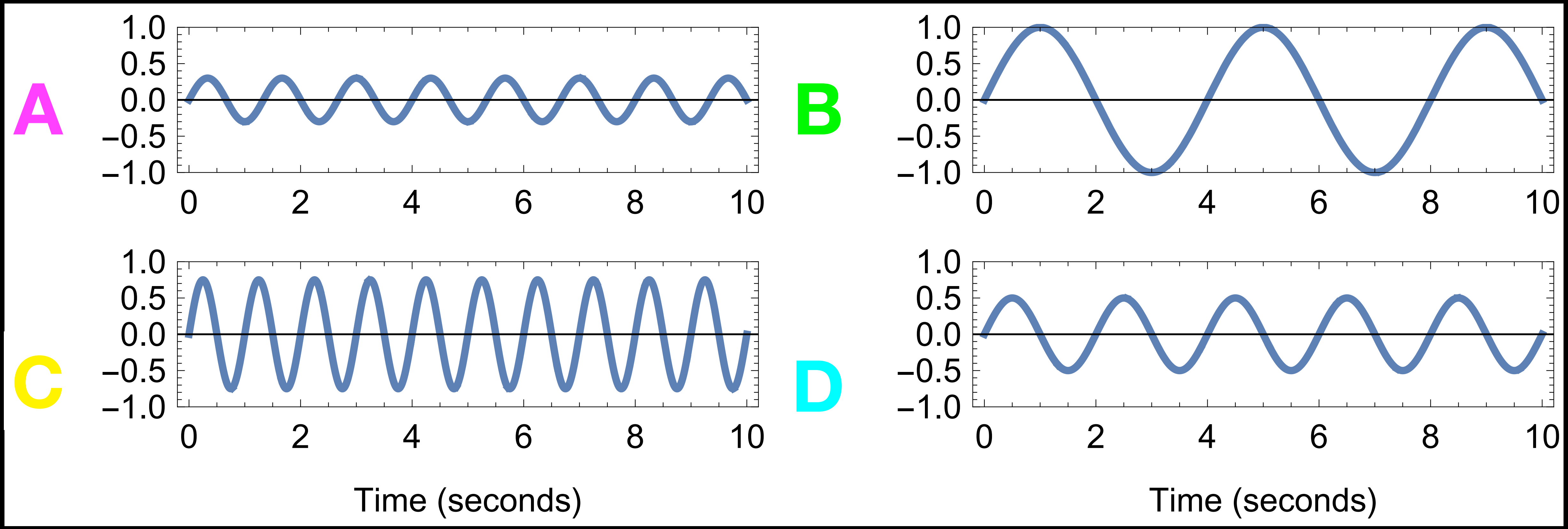


- Consider the following four waves, plotted over time:



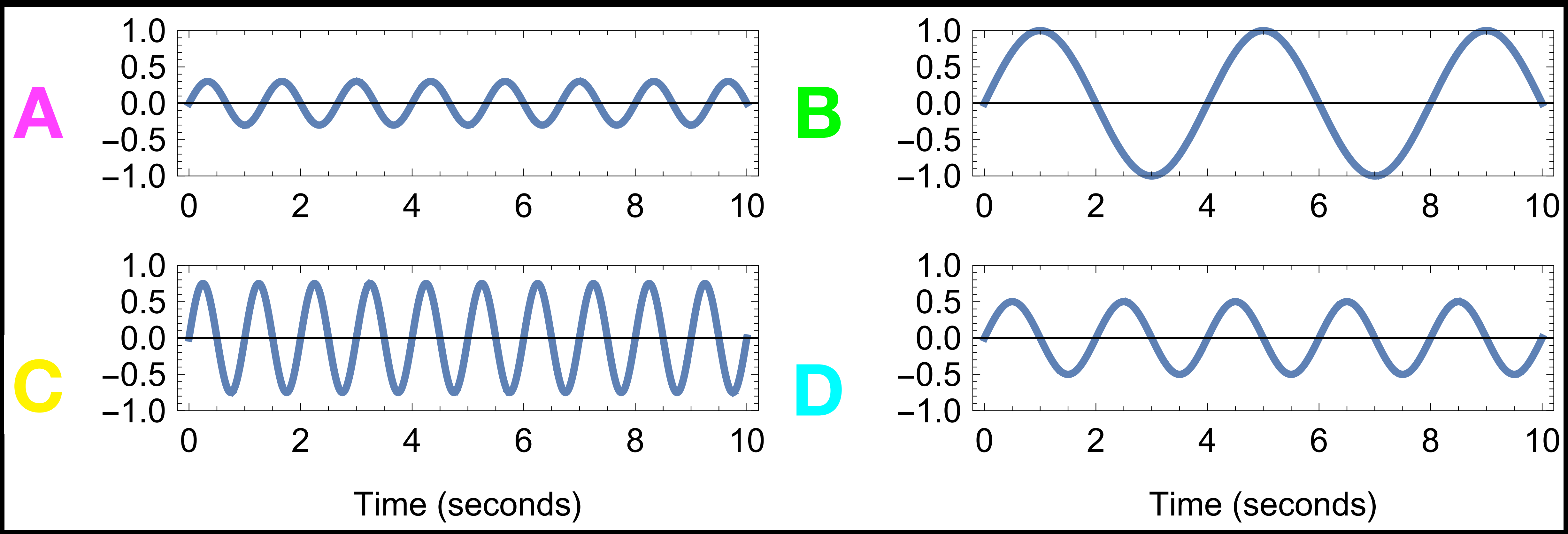
- Which has the largest amplitude?

- Consider the following four waves, plotted over time:



- Which has the shortest period *(time taken for one wave cycle)*?

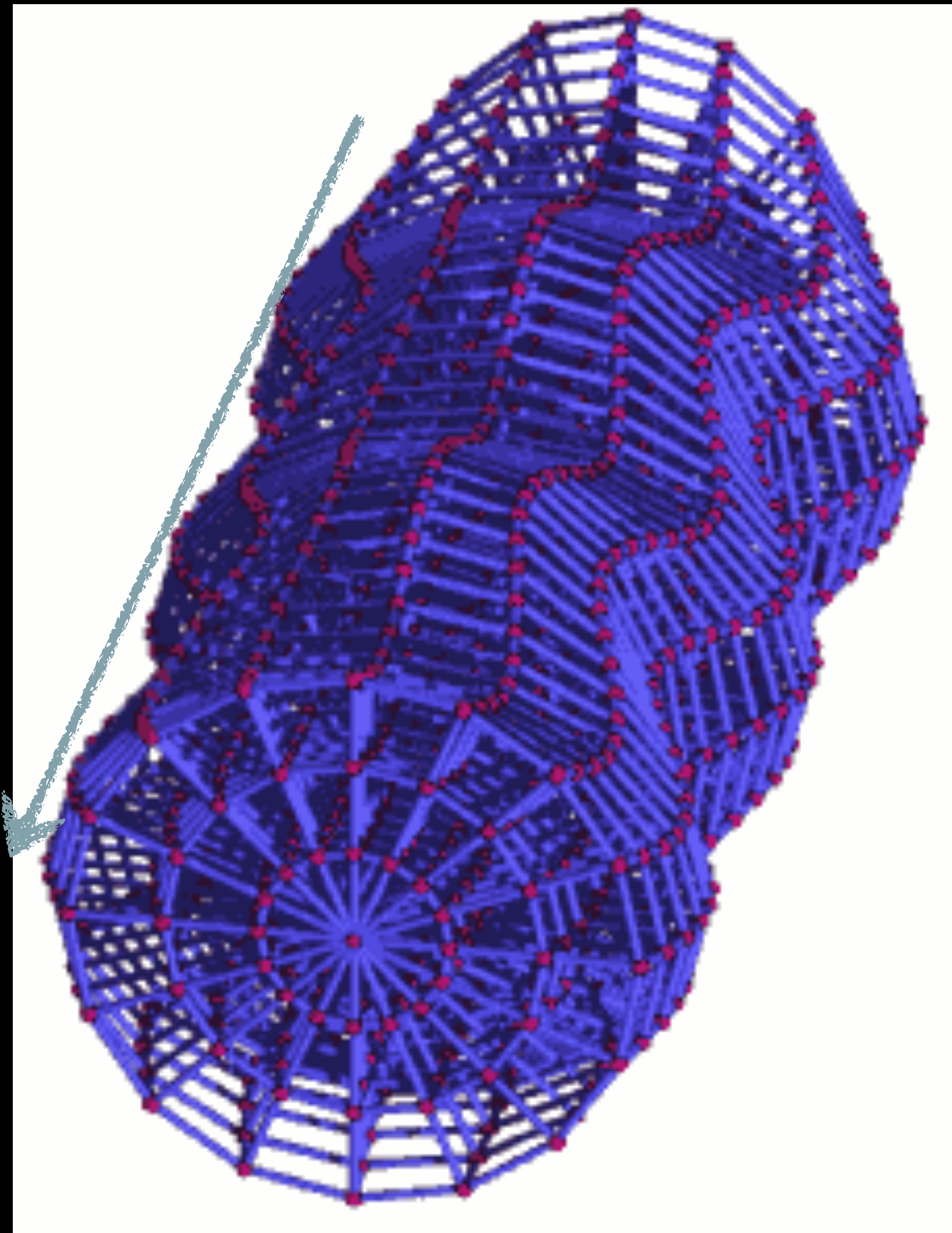
- Consider the following four waves, plotted over time:



- Which has the highest frequency *(number of wave cycles observed in a given amount of time)*?

Gravitational wave

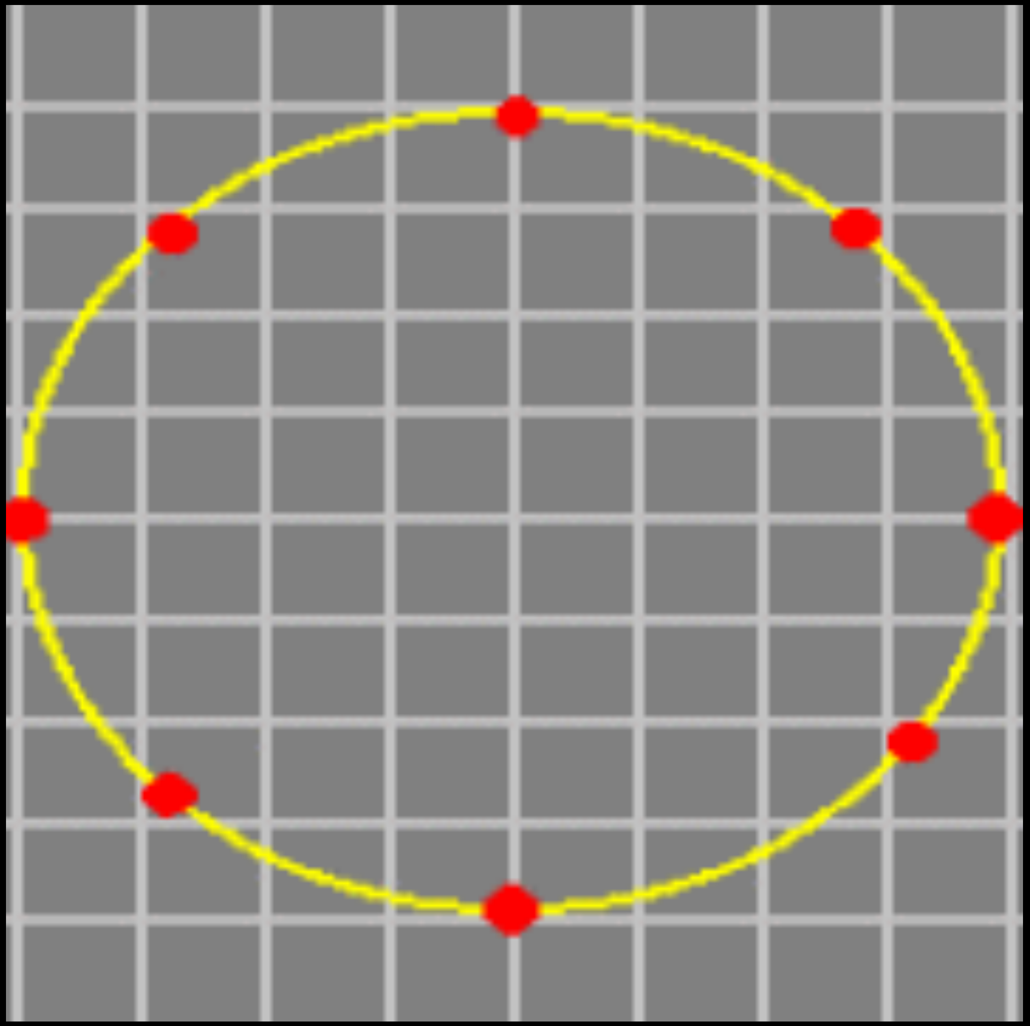
- Stretching and squeezing distances between objects
- Traveling at the speed of light

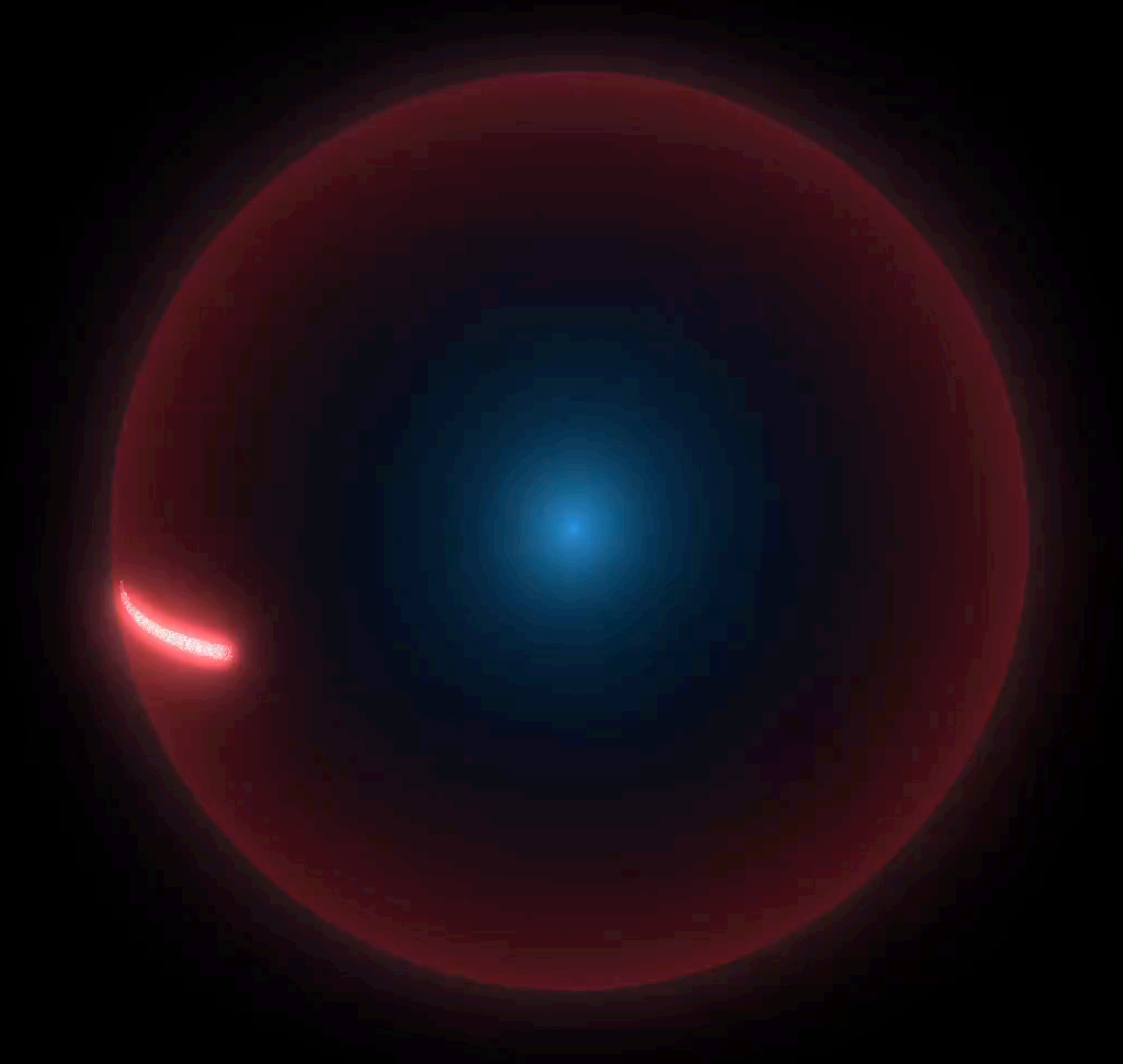


Animation from http://www.einstein-online.info/spotlights/gravWav

Effects of gravitational waves

- Cause the distance between objects to change
- Fractional change shown 10%
- Fractional change from gravitational waves arriving at Earth 0.000000000000000000001%



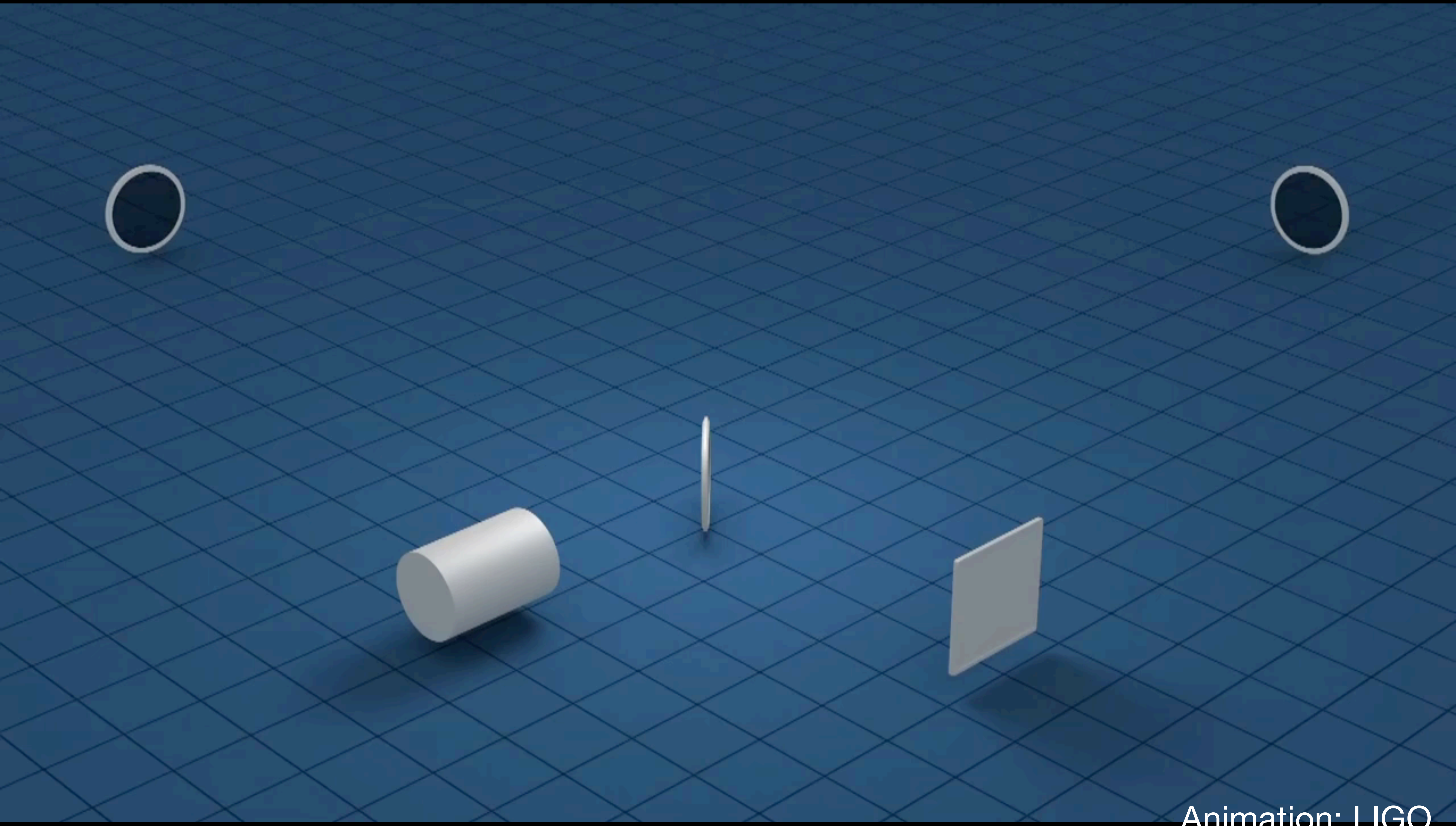


Animation: LIGO

If a gravitational wave and a pulse of light were both emitted at the same time from a cataclysmic event in a distant galaxy, which wave would get to earth first?

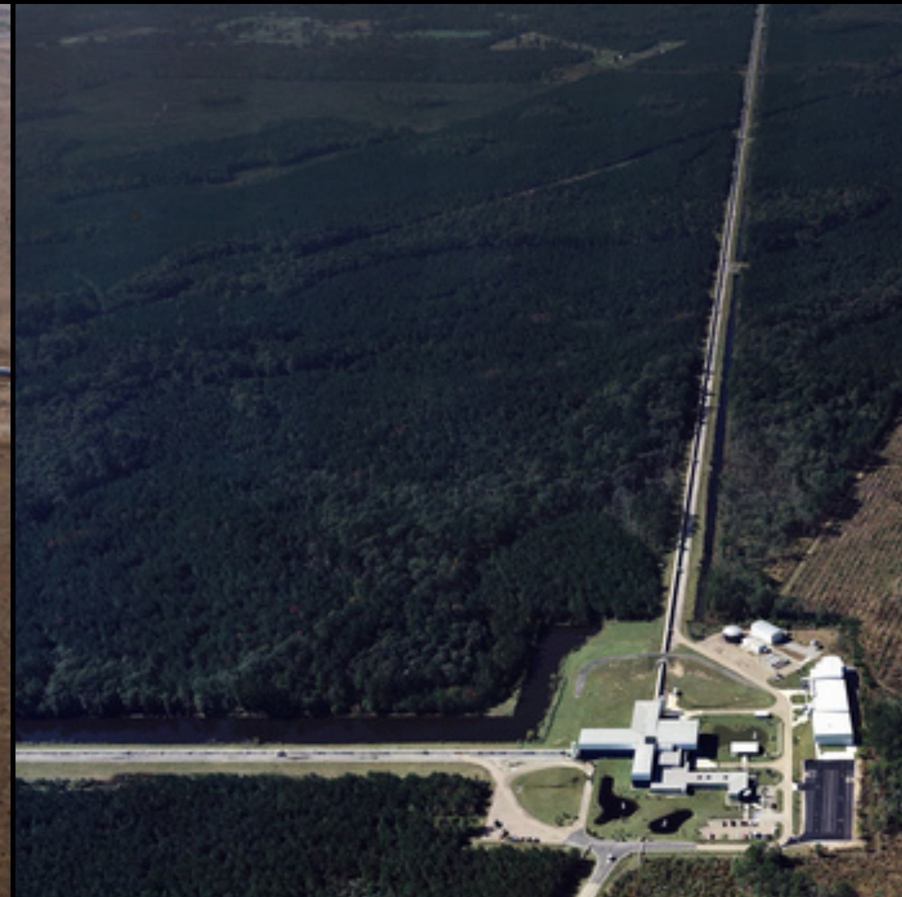
A. Gravitational Wave
B. Light
C. Both would reach earth at the same time

Measuring gravitational waves



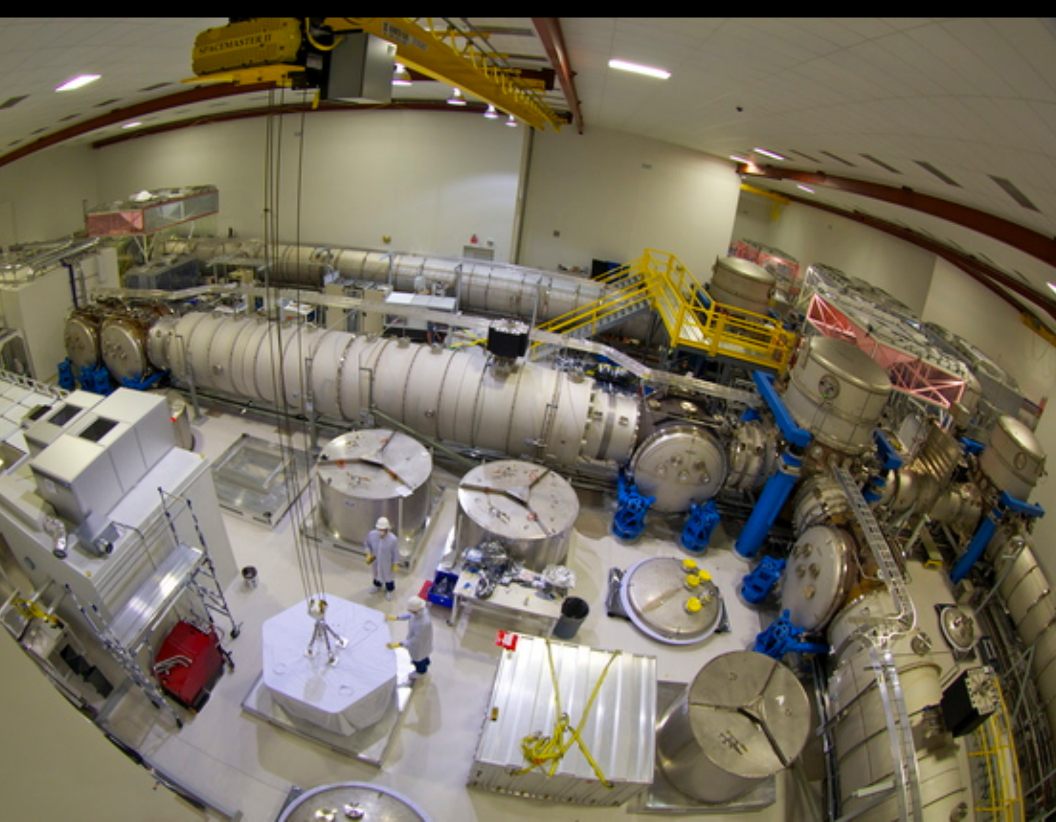
Animation: LIGO

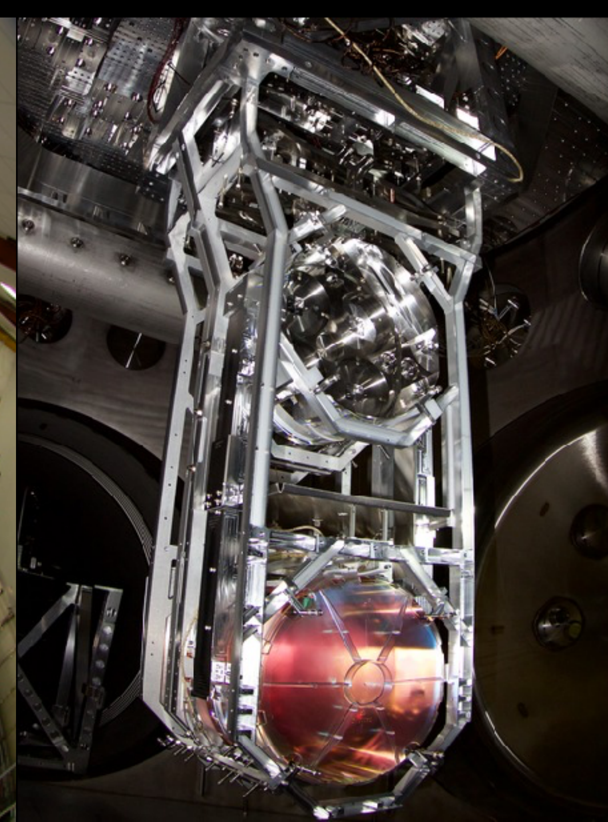
LIGO Hanford, Washington
2015+



LIGO Livingston, Louisiana
2015+

Virgo, Italy
2017+



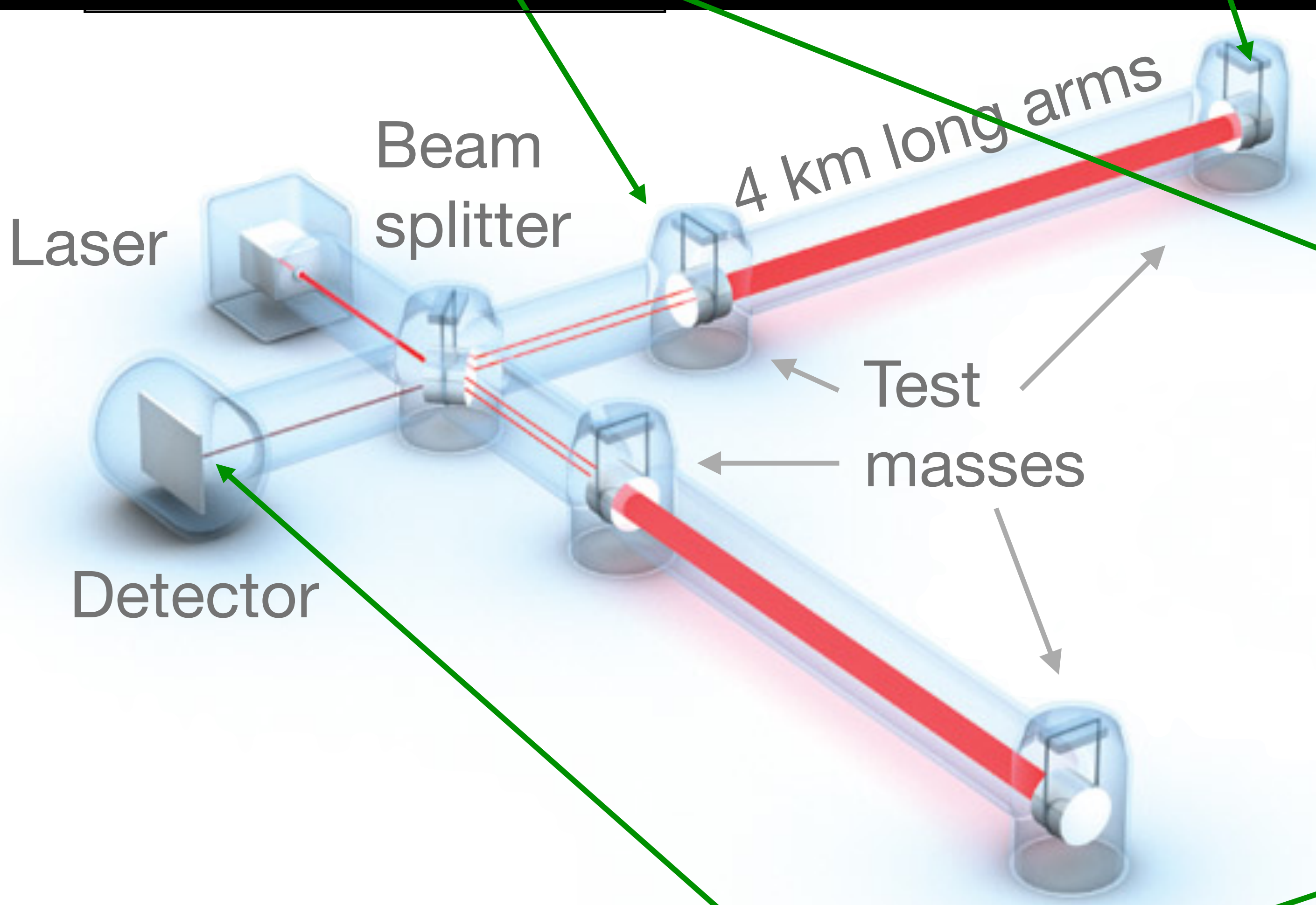


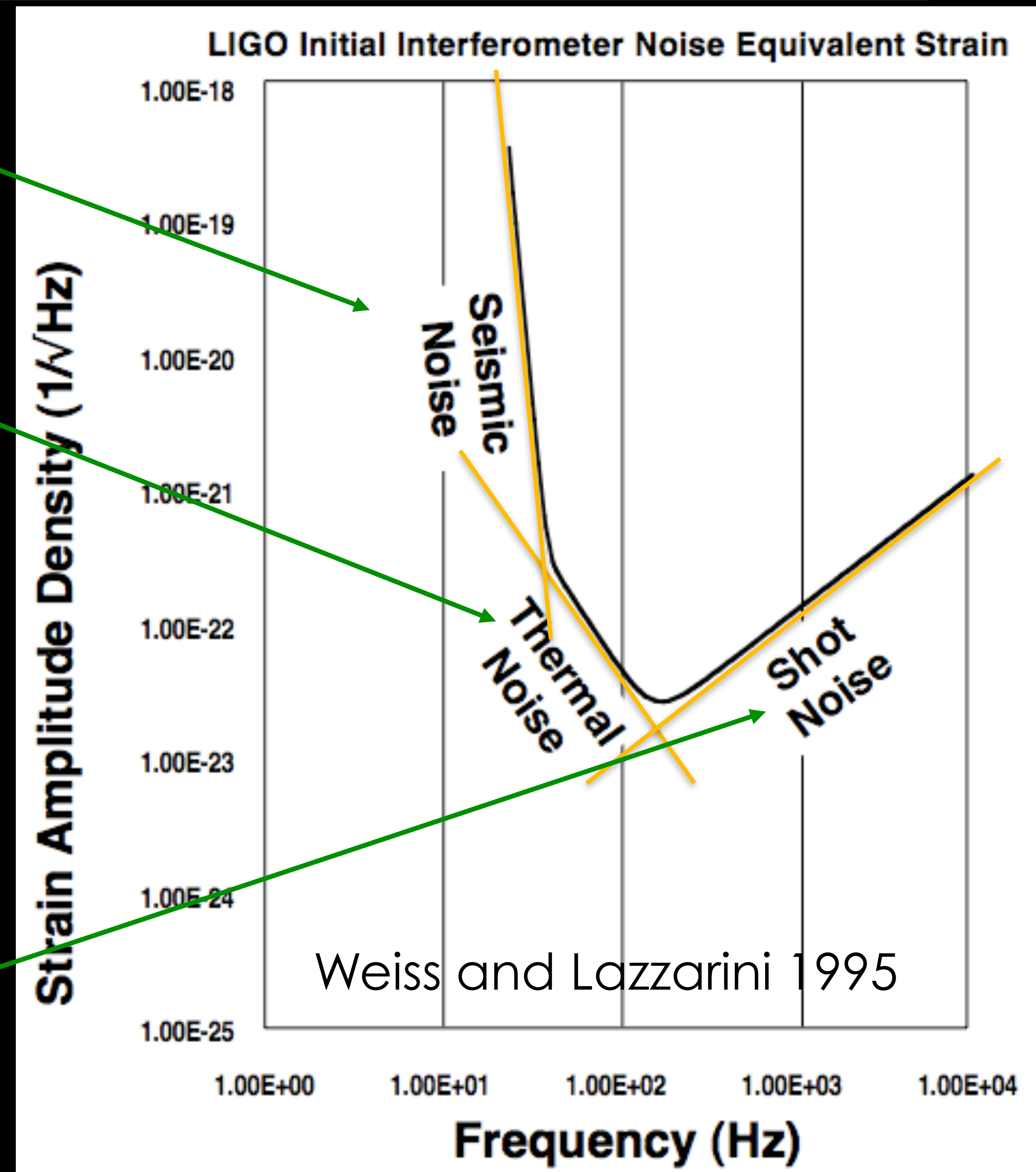
Ground-Based gravitational-wave observatories

Competing sources of mirror motion

Thermal K_BT motion of molecules in mirrors

Seismic motion of ground shakes mirrors

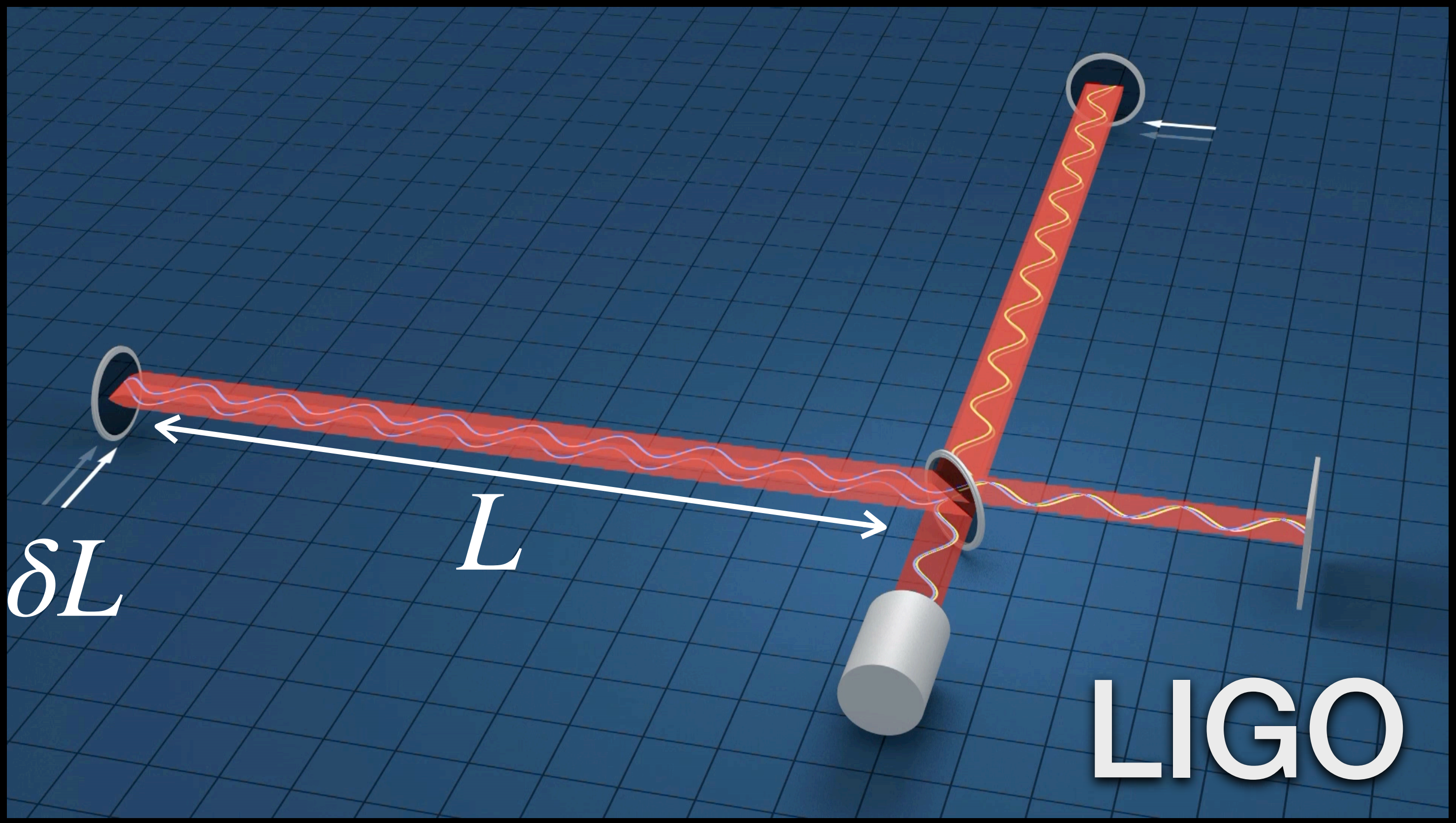




Photons arrive in a statistical pitter patter

Slide courtesy Josh Smith, CSUF

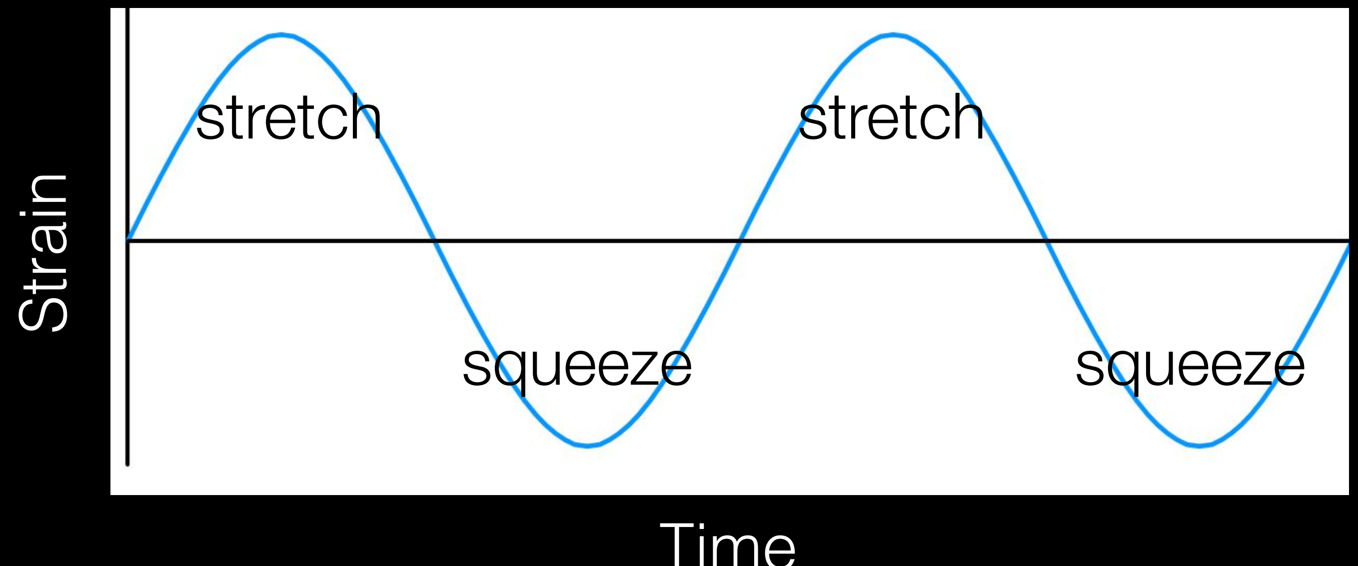
Plotting gravitational waves



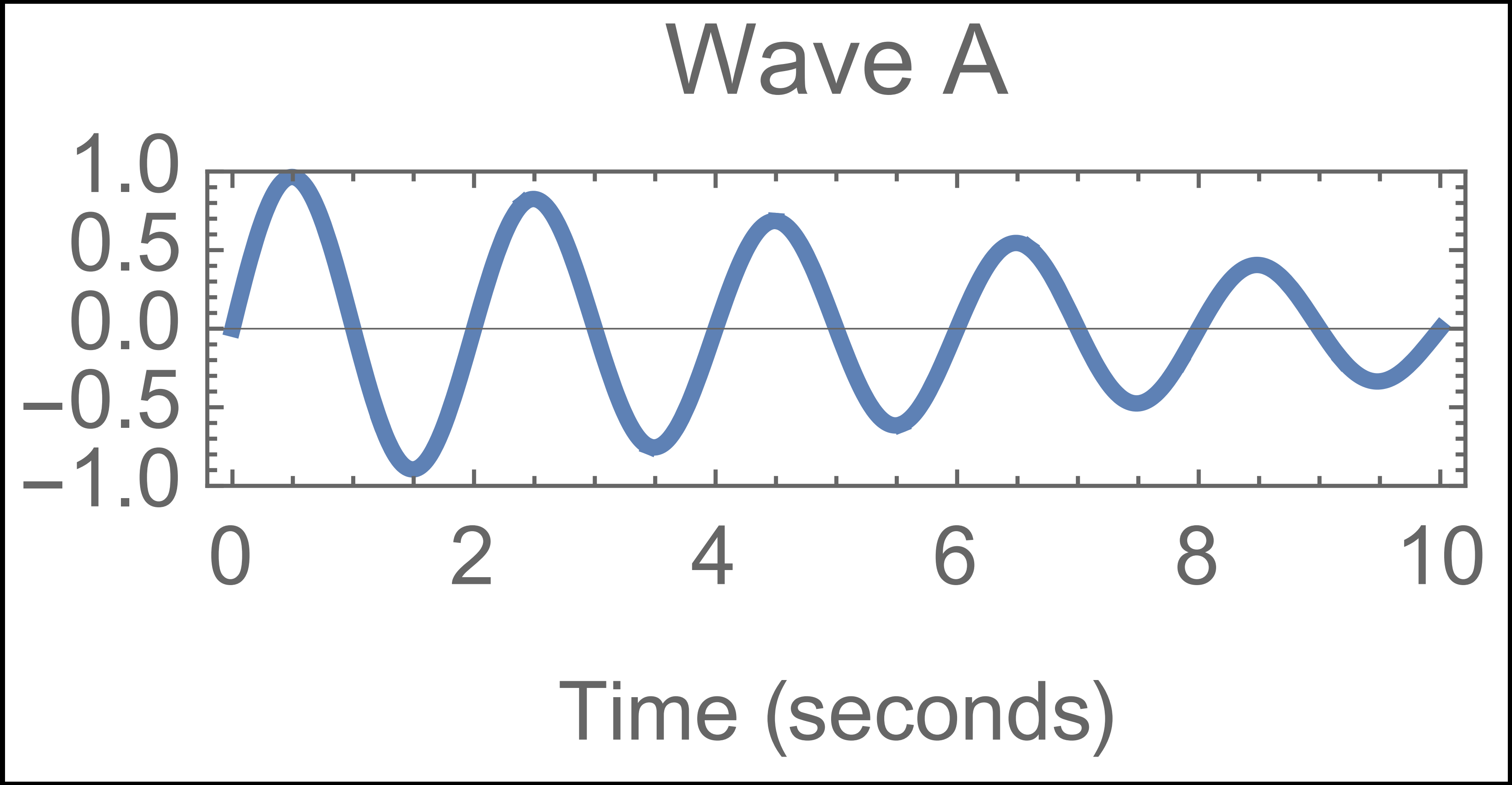
Gravitational-wave *strain*

$$h_+ \sim \frac{L_1 - L_2}{L}$$

$$\frac{\text{Change in length}}{\text{original length}}$$



- This wave is changing with time. What is changing, and how?



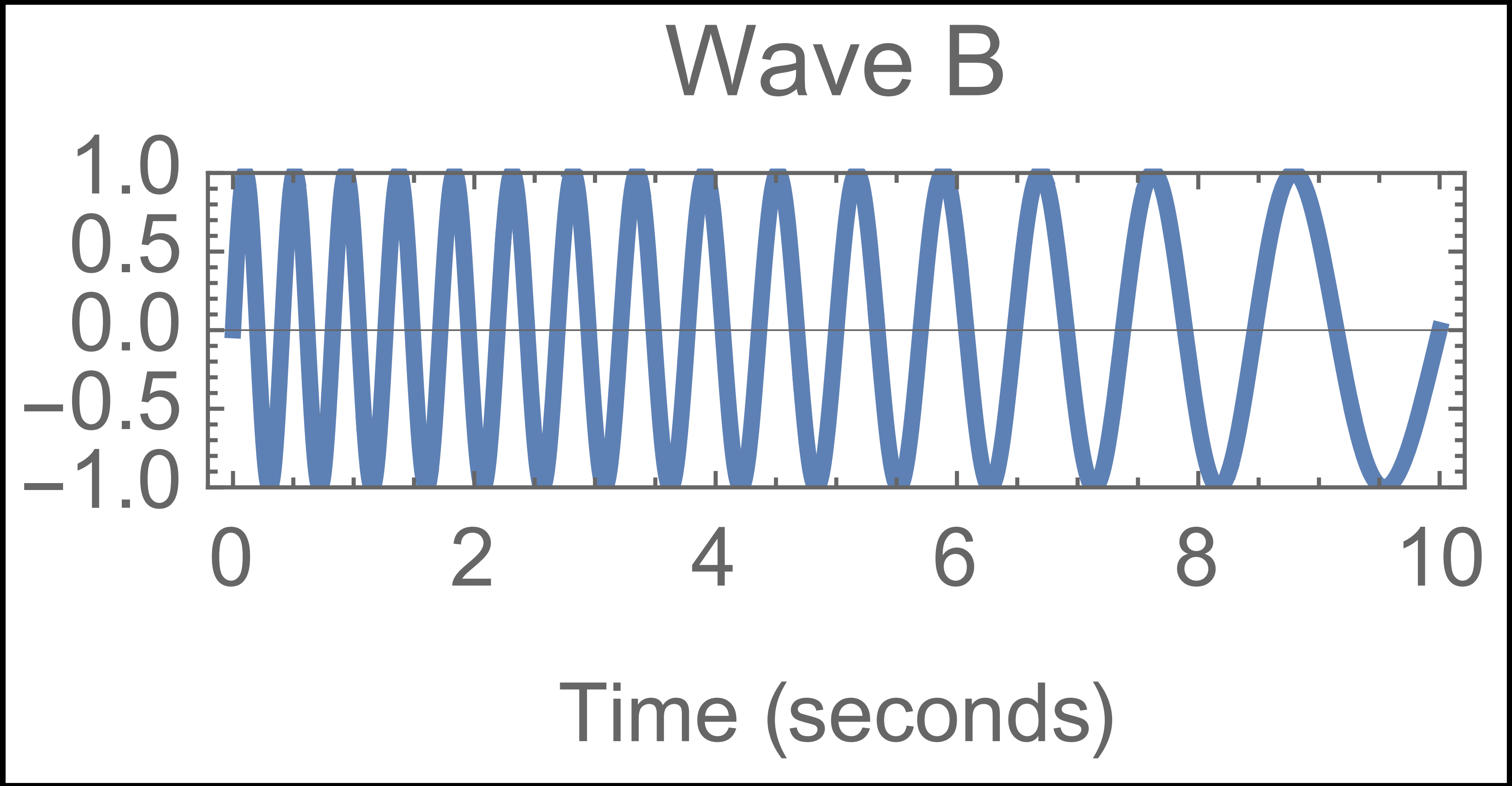
A. Amplitude is increasing

B. Amplitude is decreasing

C. Frequency is increasing

D. Frequency is decreasing

- This wave is changing with time. What is changing, and how?

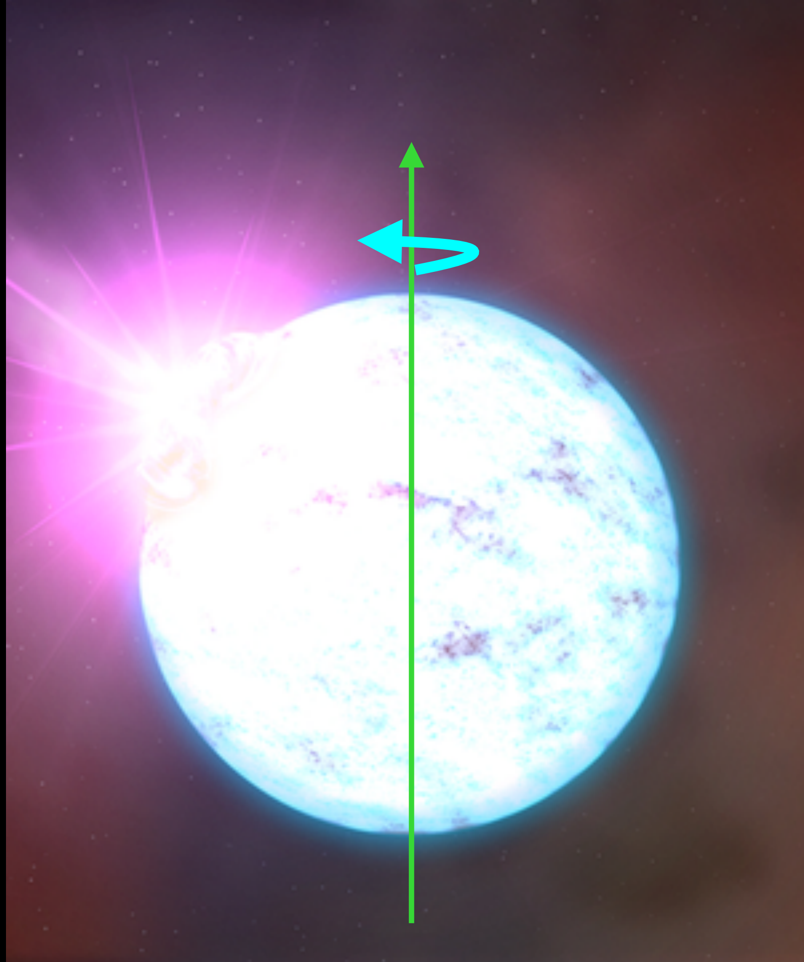


A. Amplitude is increasing

B. Amplitude is decreasing

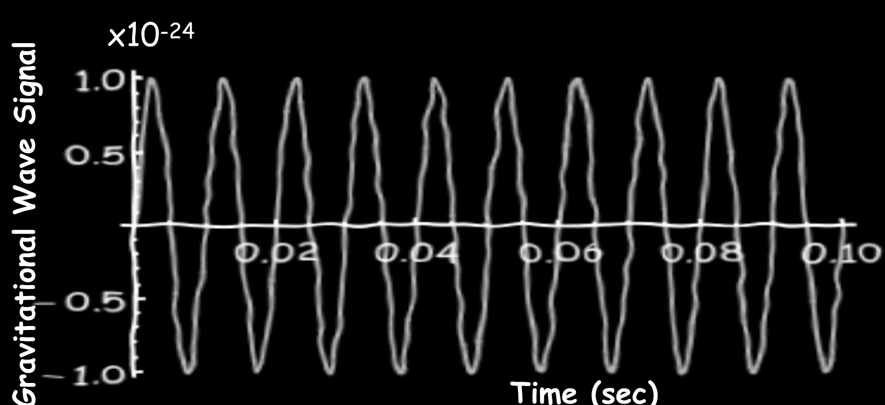
C. Frequency is increasing

D. Frequency is decreasing



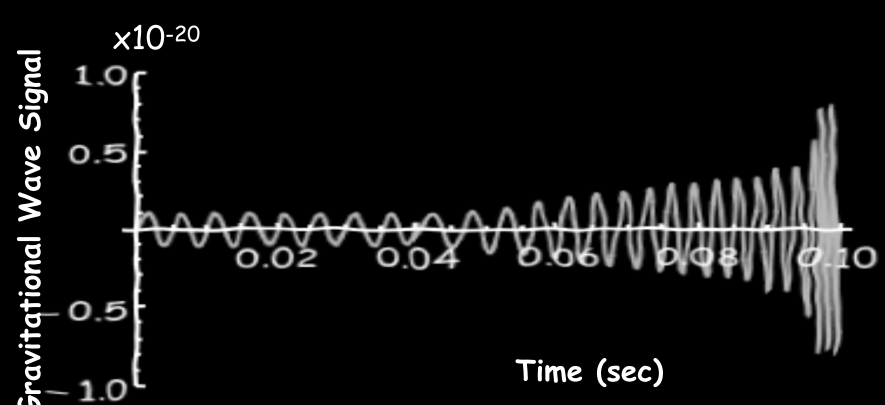
A neutron star is *spinning at a steady rate*. A heavy mountain on its surface is carried around by the star's rotation. What GW pattern is produced?

A.



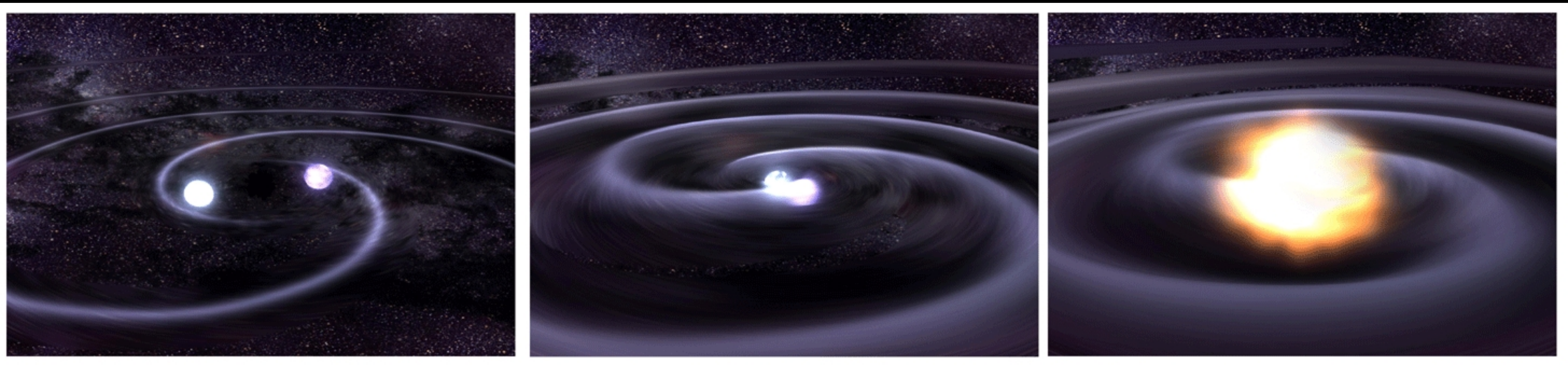
B.

C.



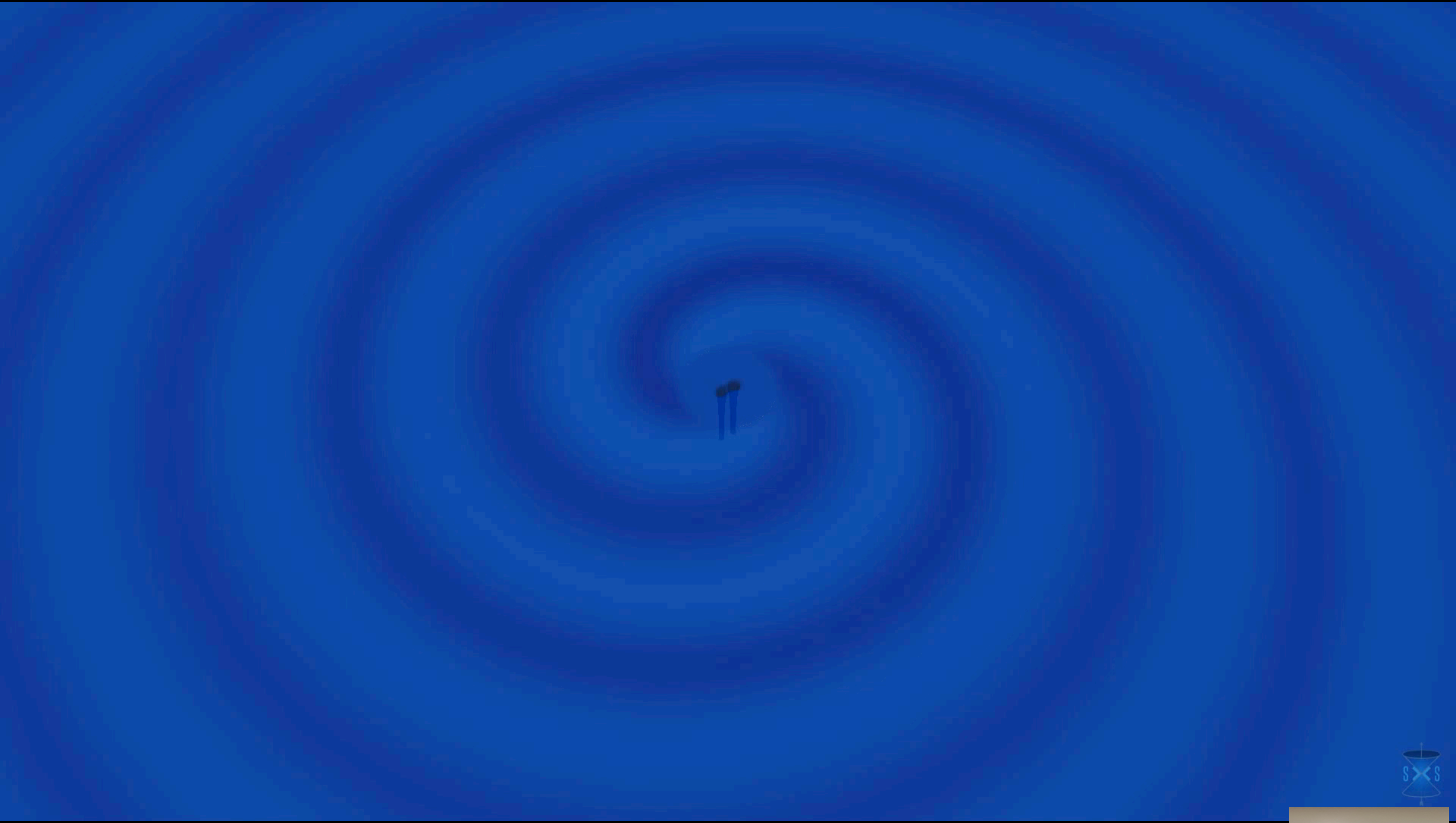
D. No GW produced

Merger / Coalescence



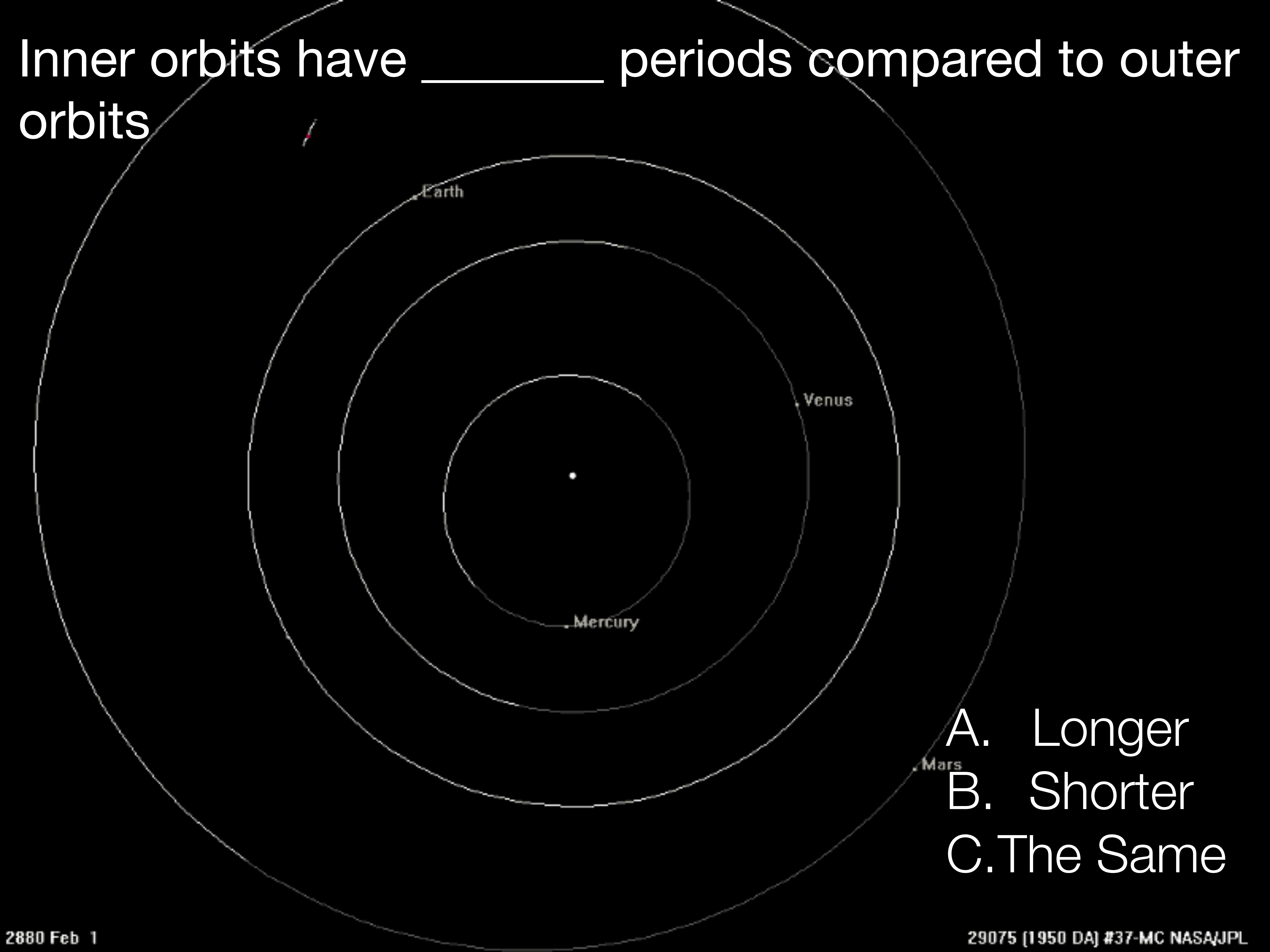
- Orbiting stars emit gravitational waves; waves carry away energy
- Orbits with lower energy are closer together
- Closer orbits produce stronger waves

Gravitational Waves from merging black holes



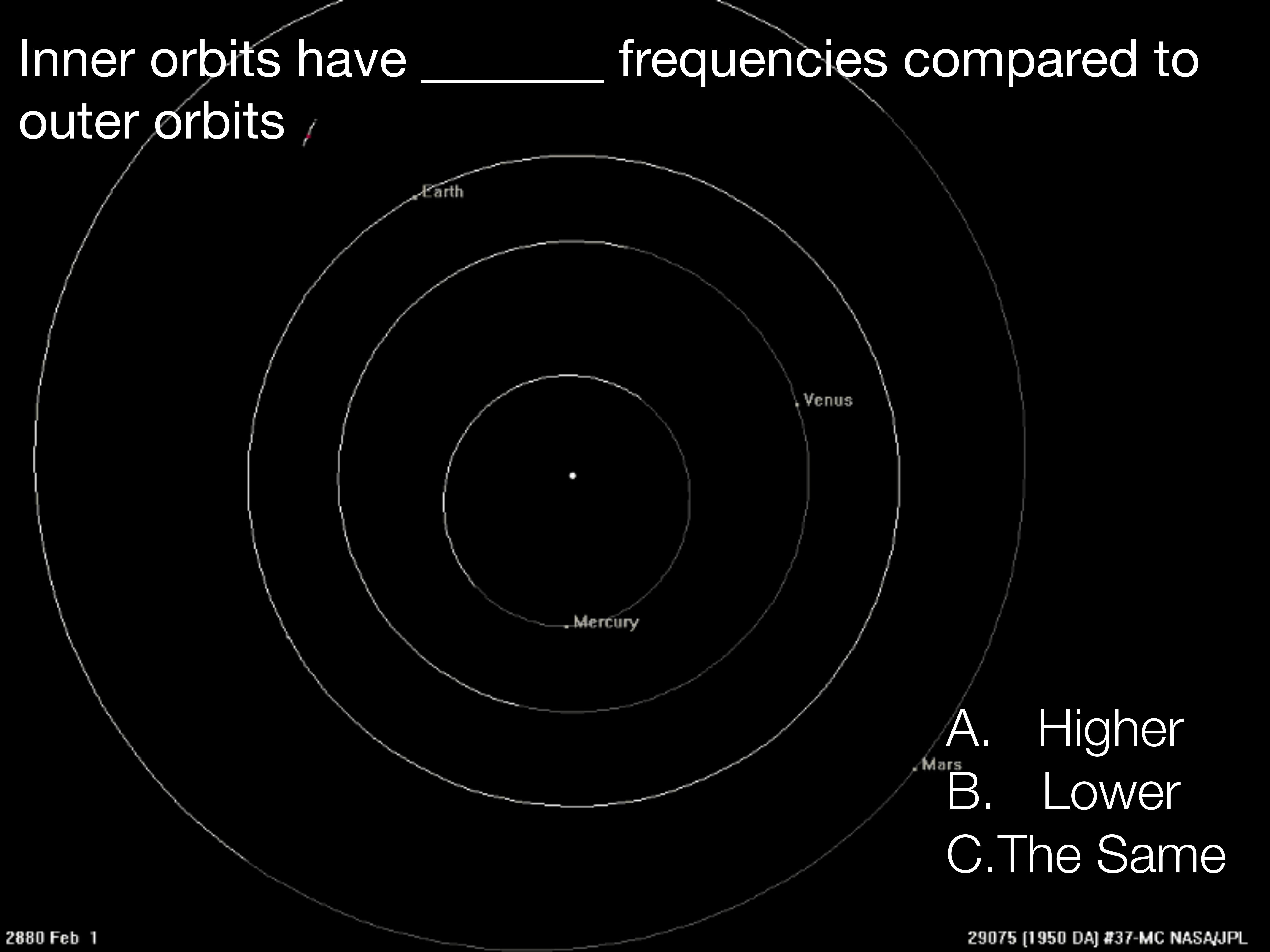
Movie by CSUF student Nick Demos,
Simulating eXtreme Spacetimes collaboration

Inner orbits have _______ periods compared to outer orbits



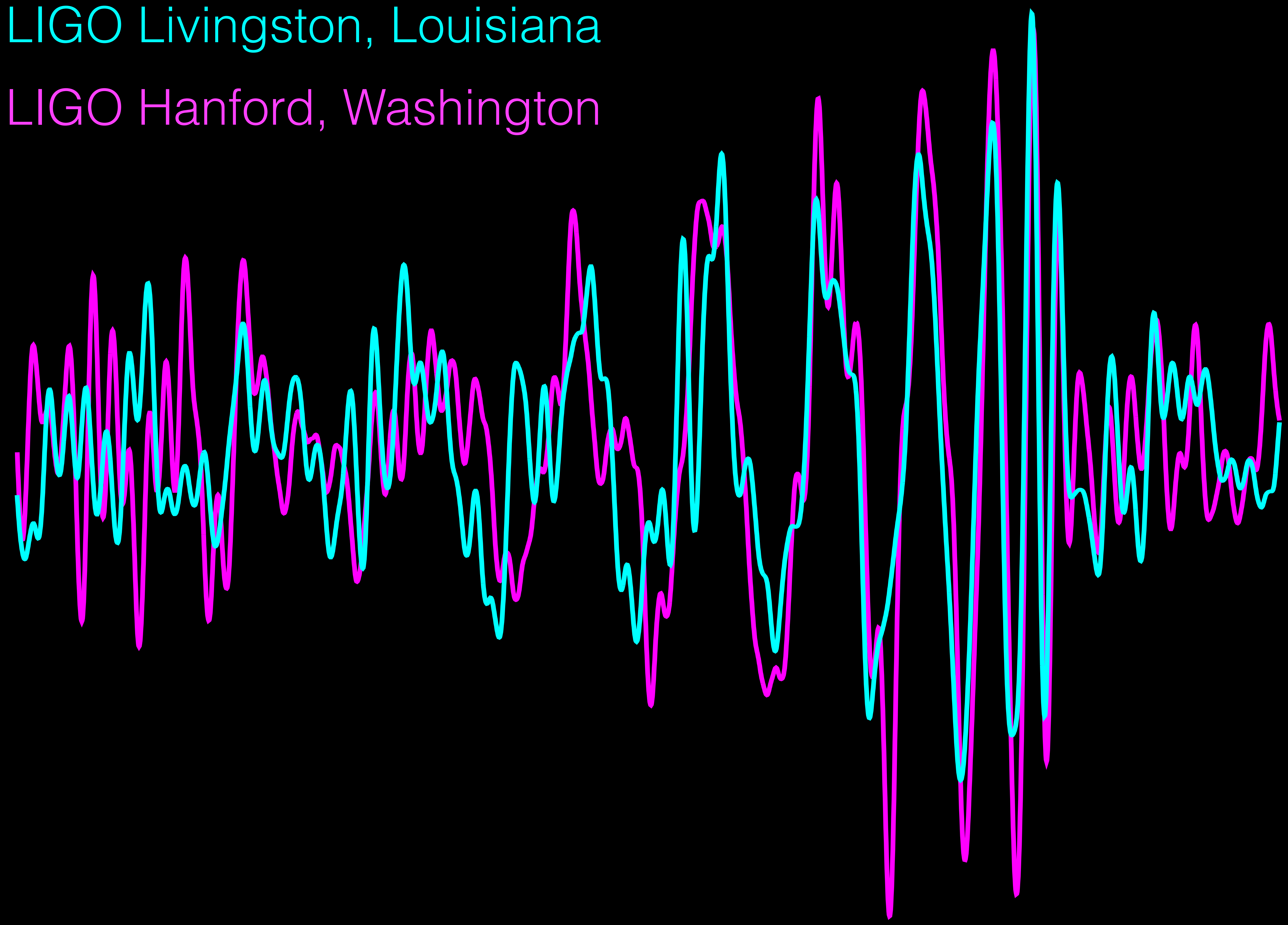
A. Longer
B. Shorter
C. The Same

Inner orbits have _______ frequencies compared to outer orbits

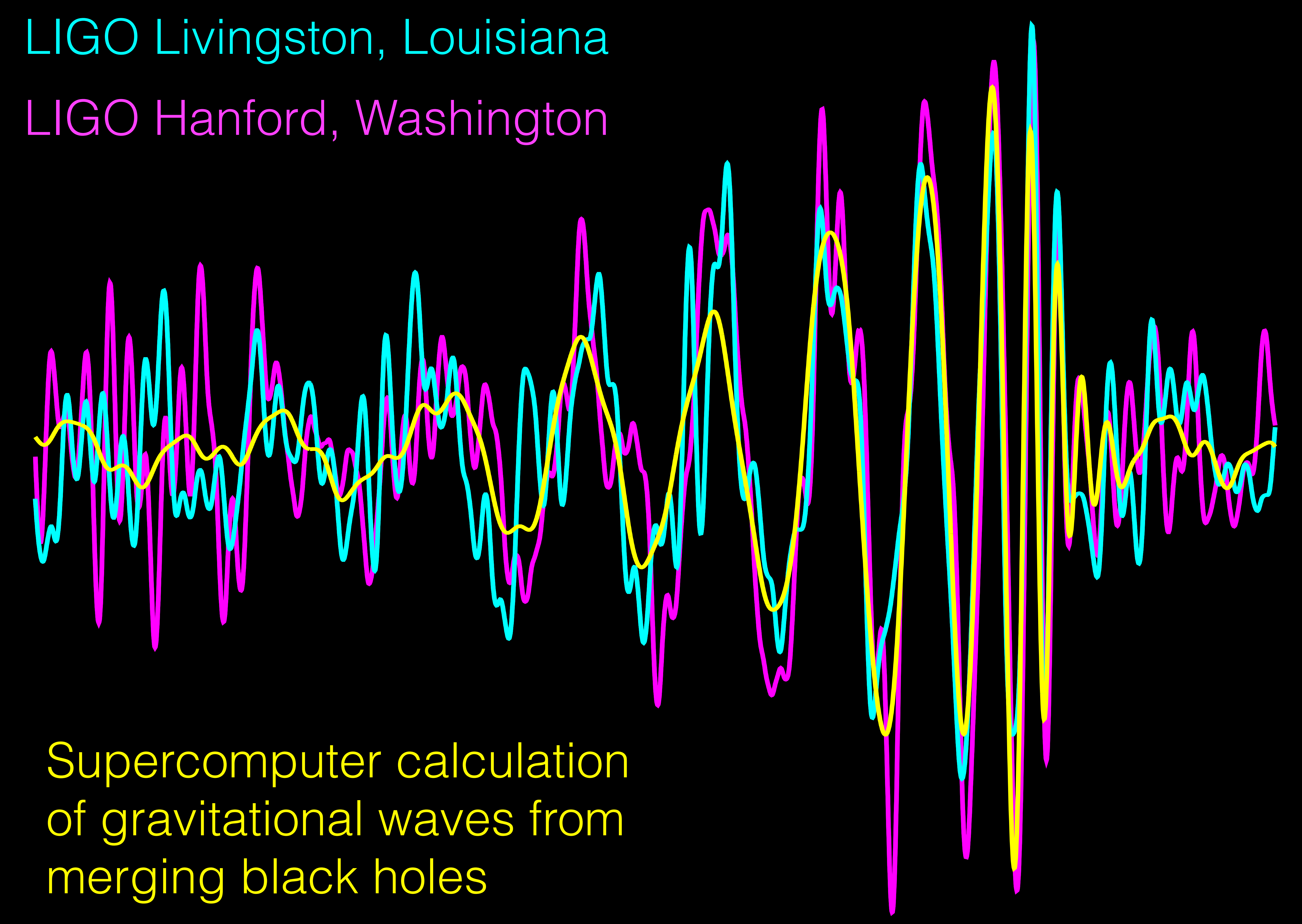


A. Higher
B. Lower
C. The Same

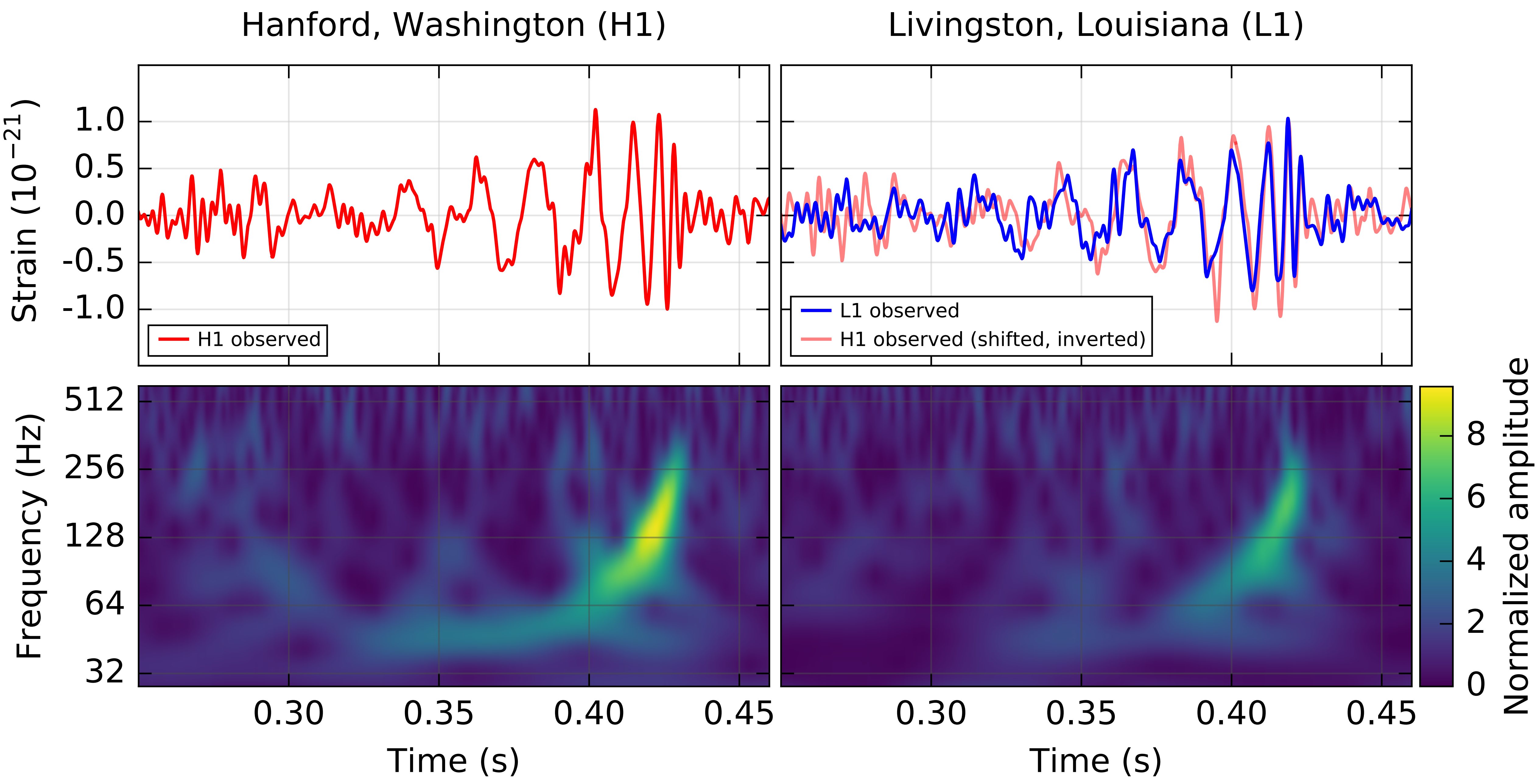
- As a binary black hole system emits gravitational waves, the separation of the two black holes will_______________ and the frequency of the binary orbit will ________________.
- As the black holes “inspiral”— fall together while orbiting— the gravitational-wave amplitude will _______________.
- *Sketch what you think the gravitational wave from merging black holes would look like*



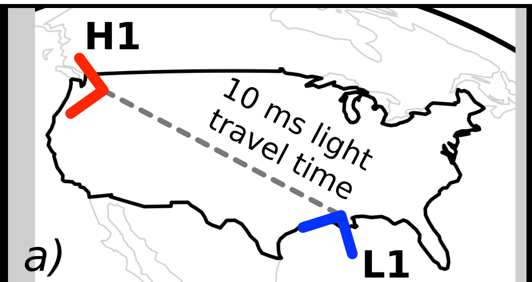
LIGO Livingston, Louisiana
LIGO Hanford, Washington


LIGO Livingston, Louisiana
LIGO Hanford, Washington
Supercomputer calculation of gravitational waves from merging black holes

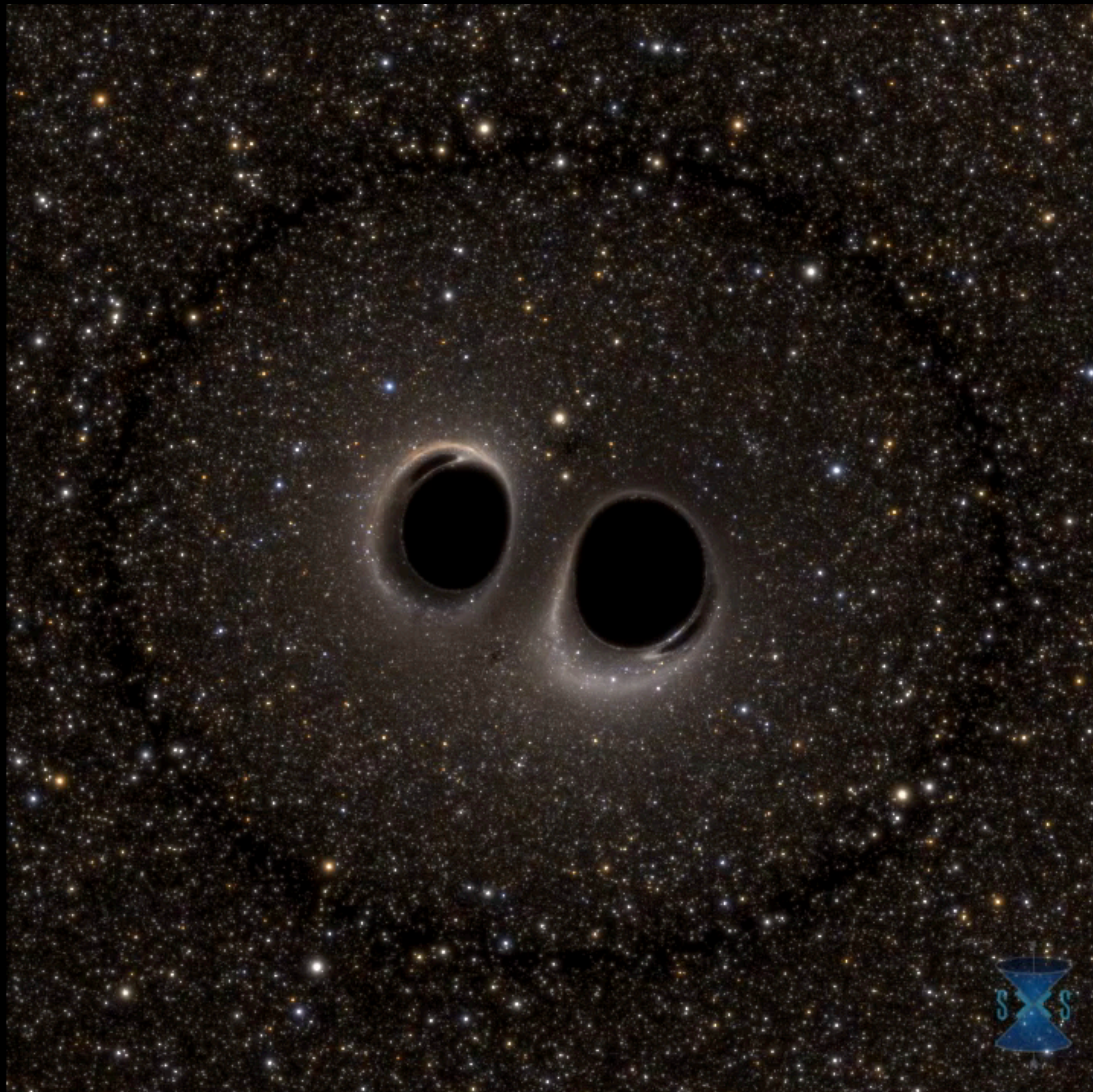
Observation of Gravitational Waves from a Binary Black Hole Merger



September 14, 2015 at 09:50:45 GMT



PRL 116, 061102 (2016)



Movie by CSUF student Haroon Khan,
SXS collaboration