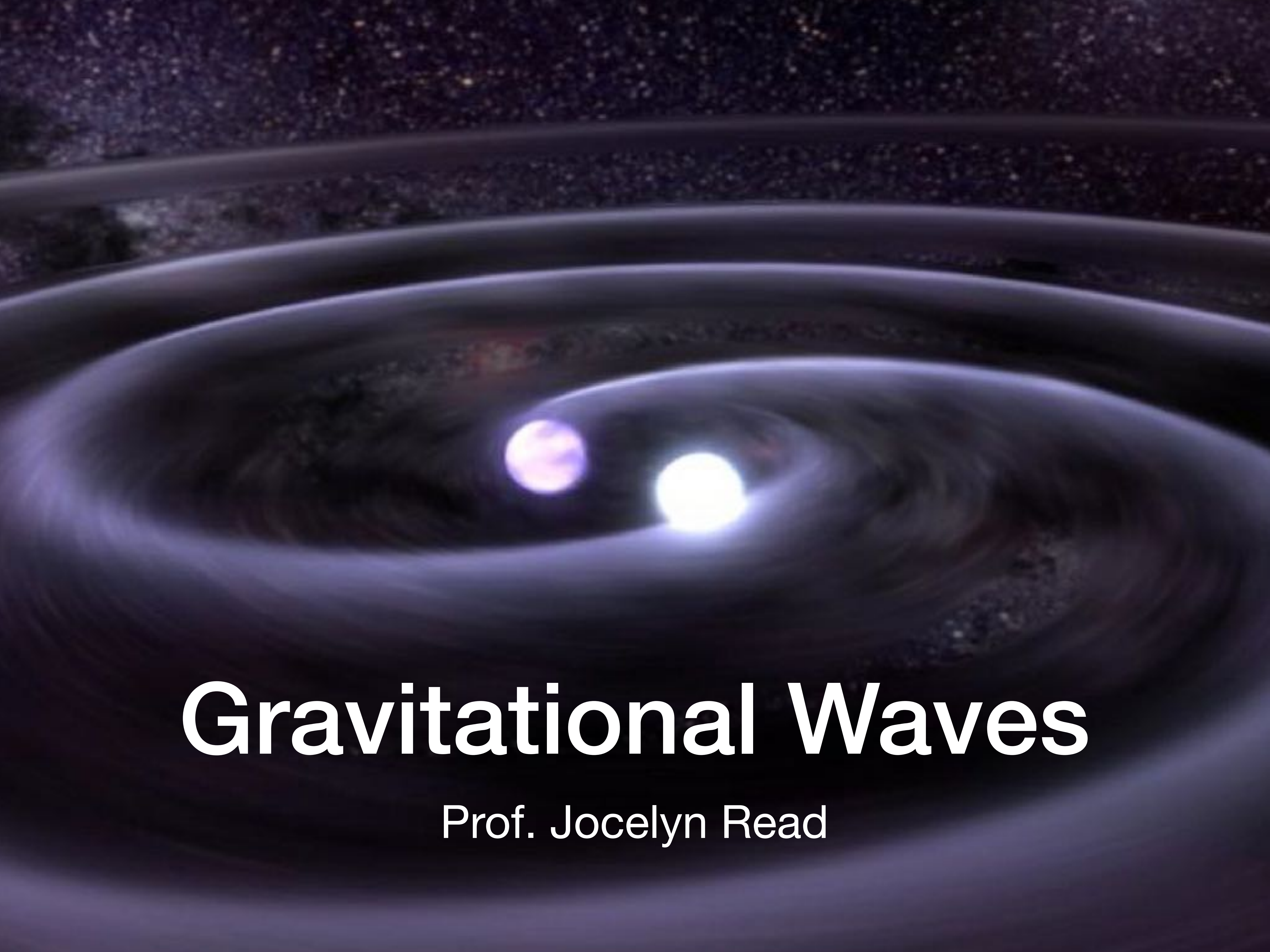
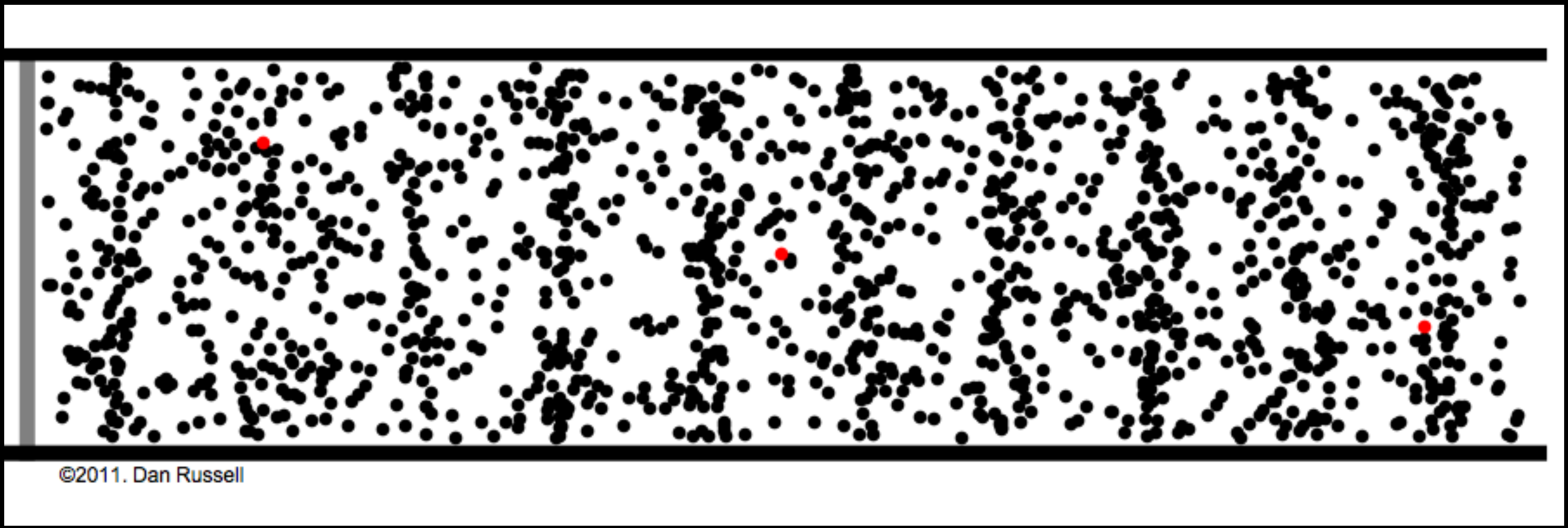
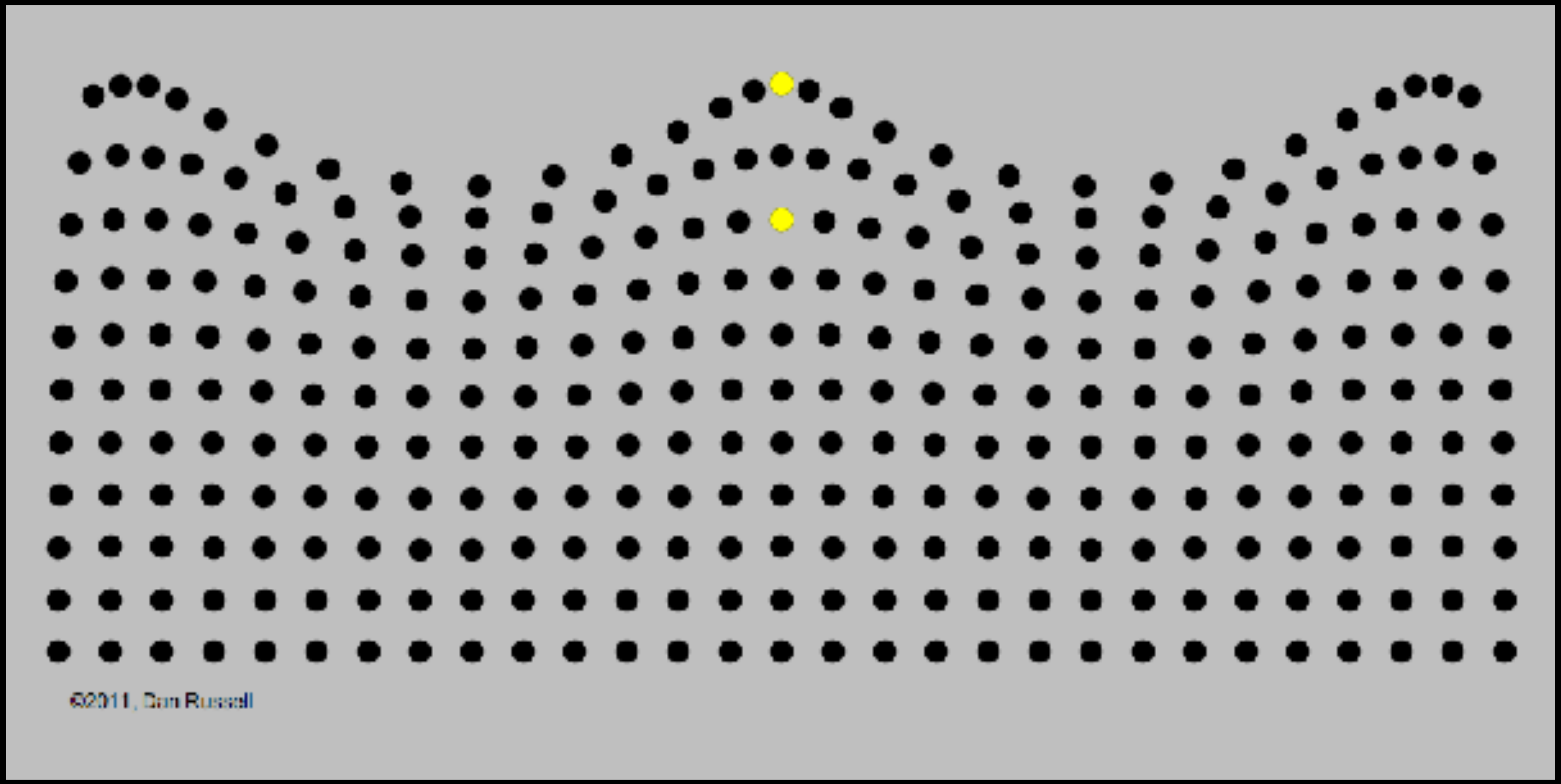


Gravitational Waves

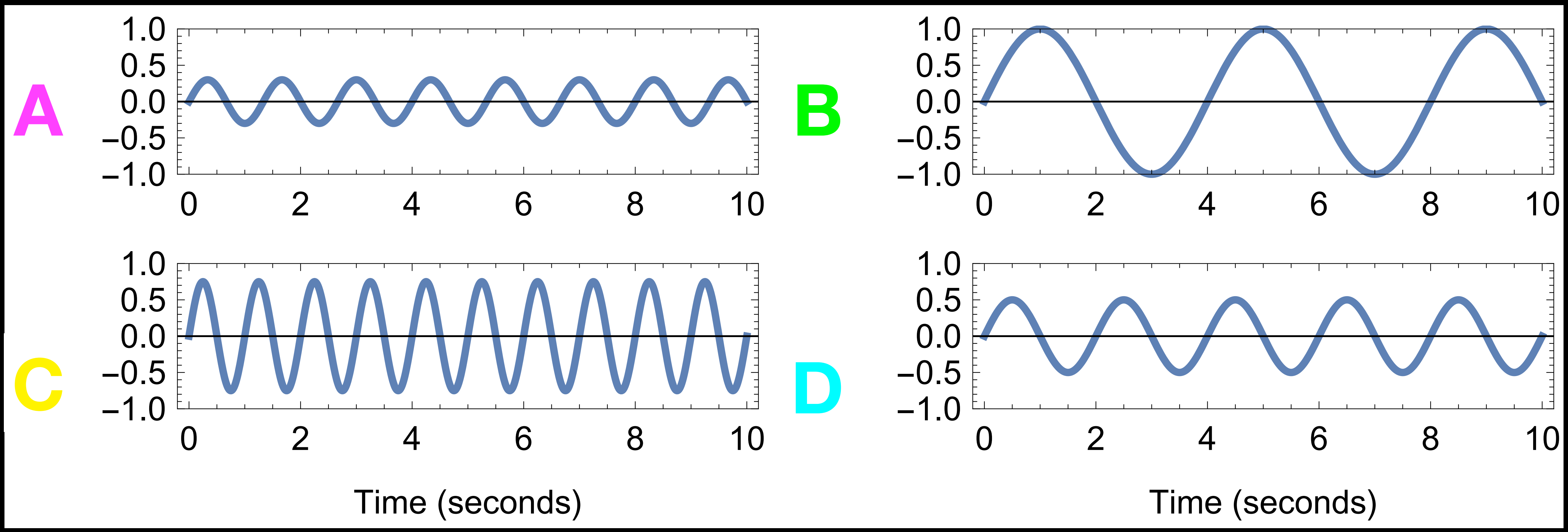
Prof. Jocelyn Read

Waves



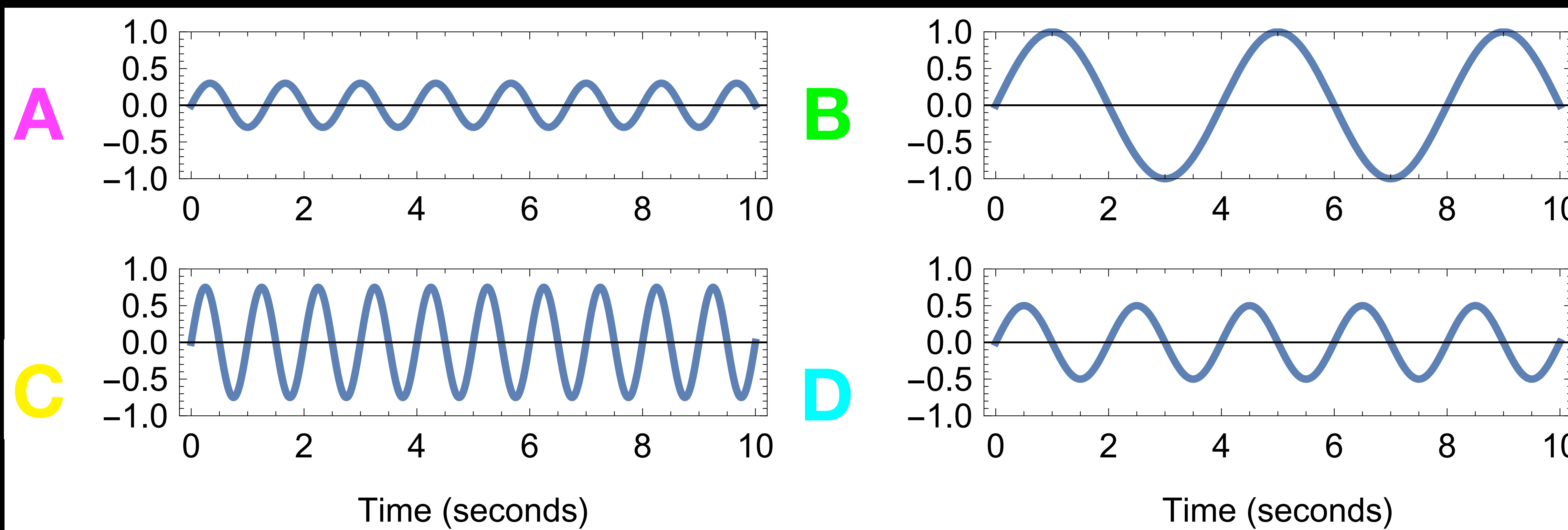


- Consider the following four waves, plotted over time:



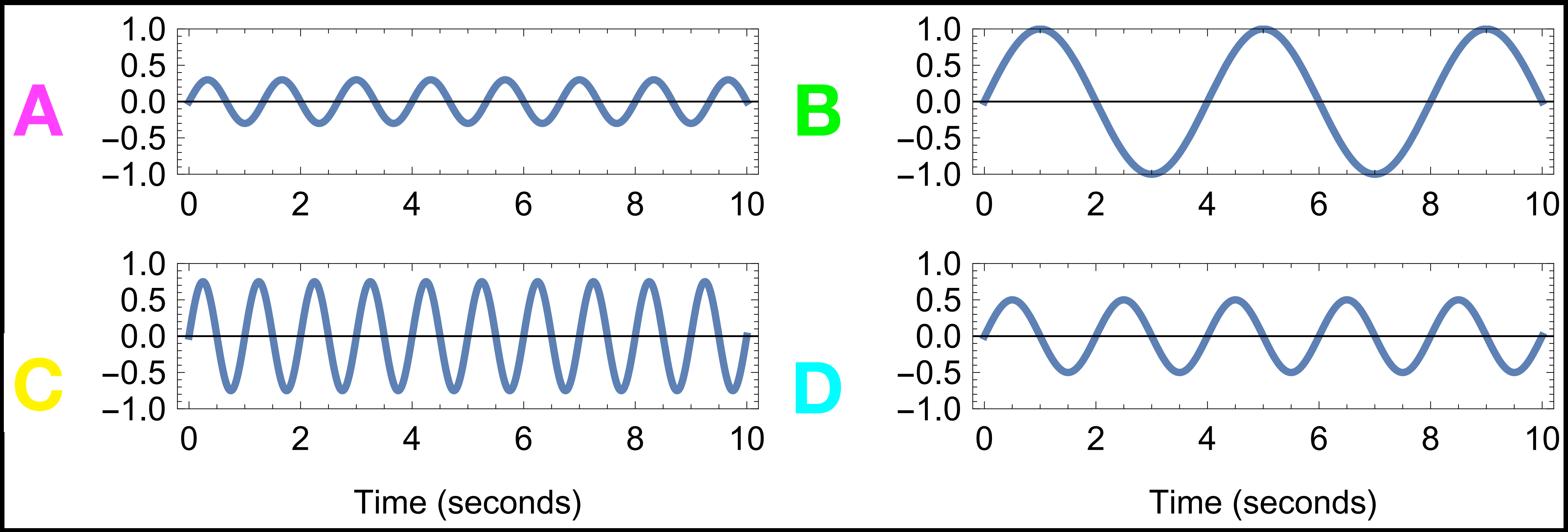
- Which has the largest amplitude?

- Consider the following four waves, plotted over time:



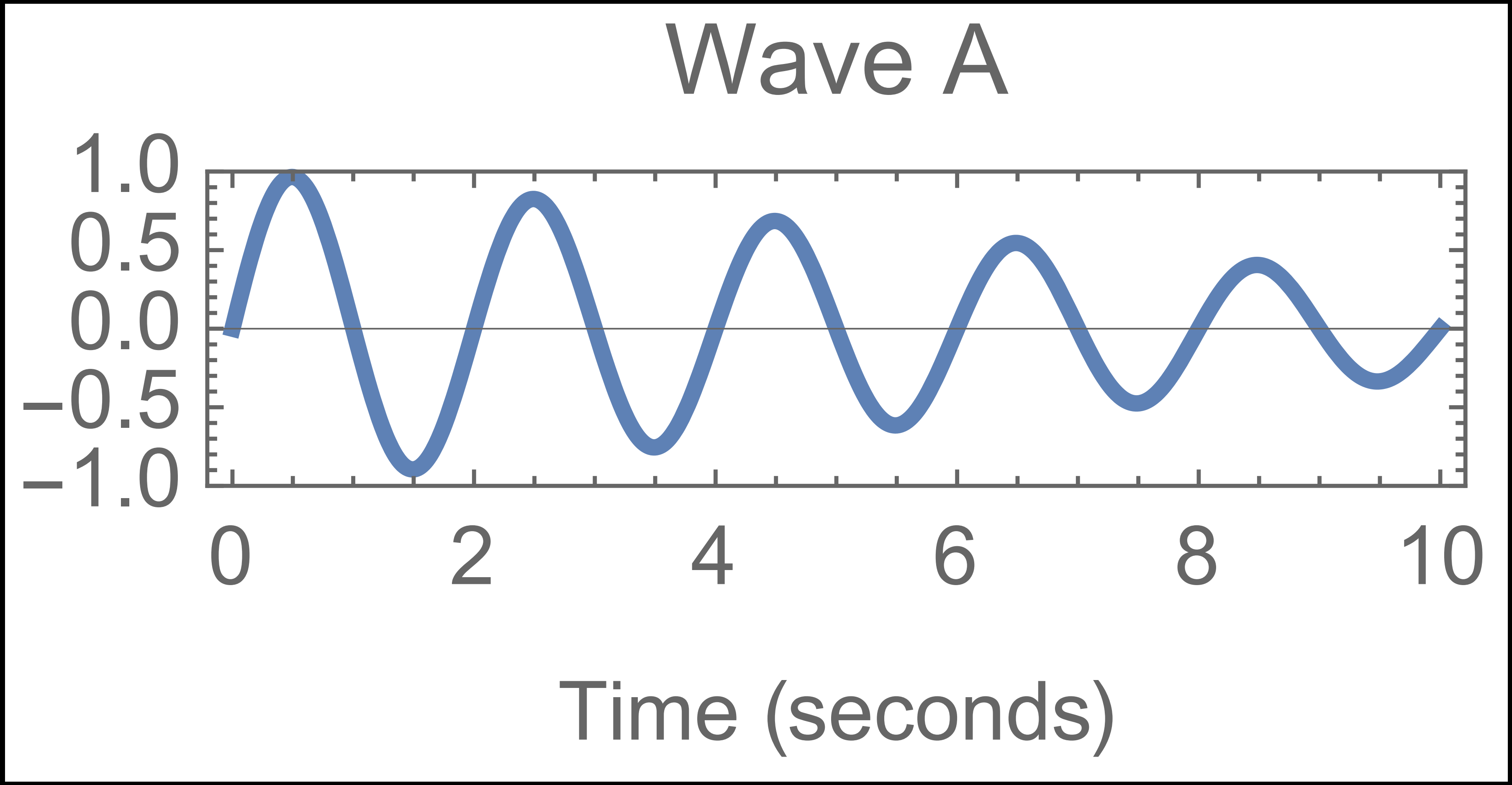
- Which has the shortest period *(time taken for one wave cycle)*?

- Consider the following four waves, plotted over time:



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

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



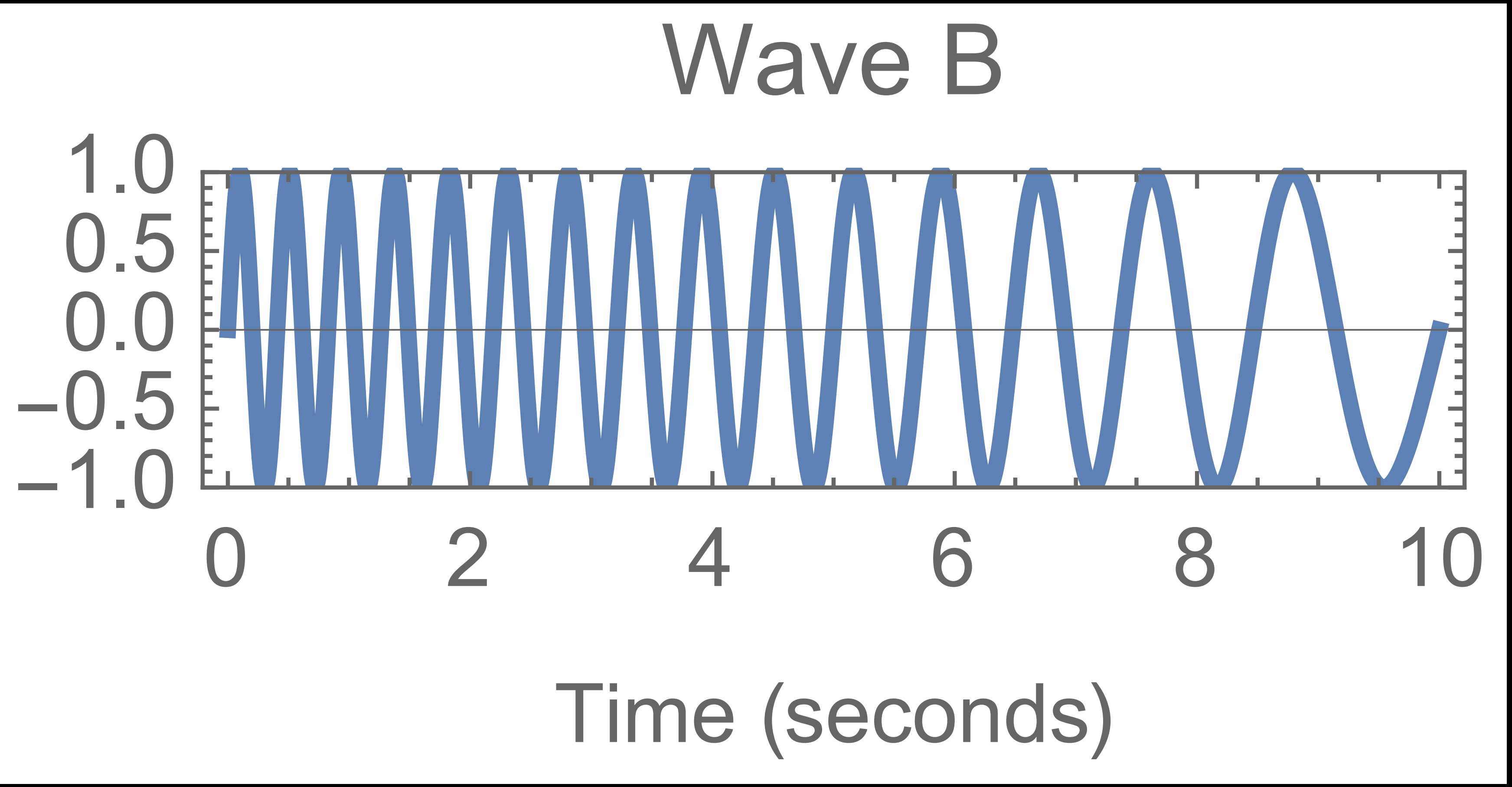
A. Amplitude is increasing

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

Gravity

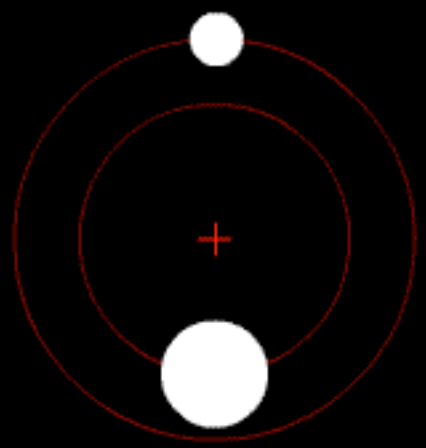
Earth and Its Moon
as seen from NASA's Mars Reconnaissance Orbiter, Nov. 20, 2016

Gravity + Relativity: General Relativity

Newton:

Falling and orbiting are explained by the same gravitational force

All masses attract each other



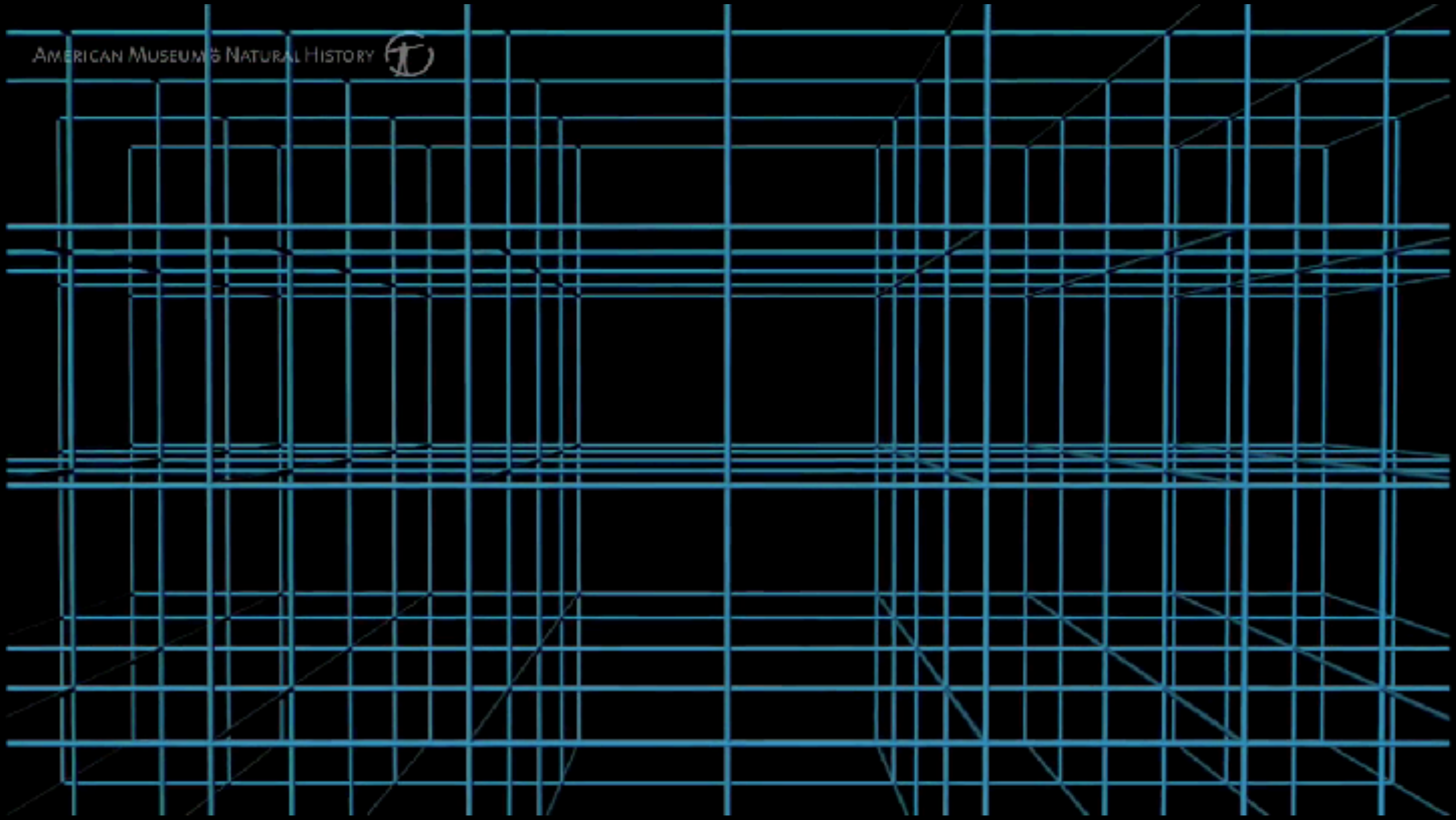
Relativity:

Space and time are not distinct

Nothing travels faster than light

“Matter tells space-time how to curve and space-time tells matter how to move.”

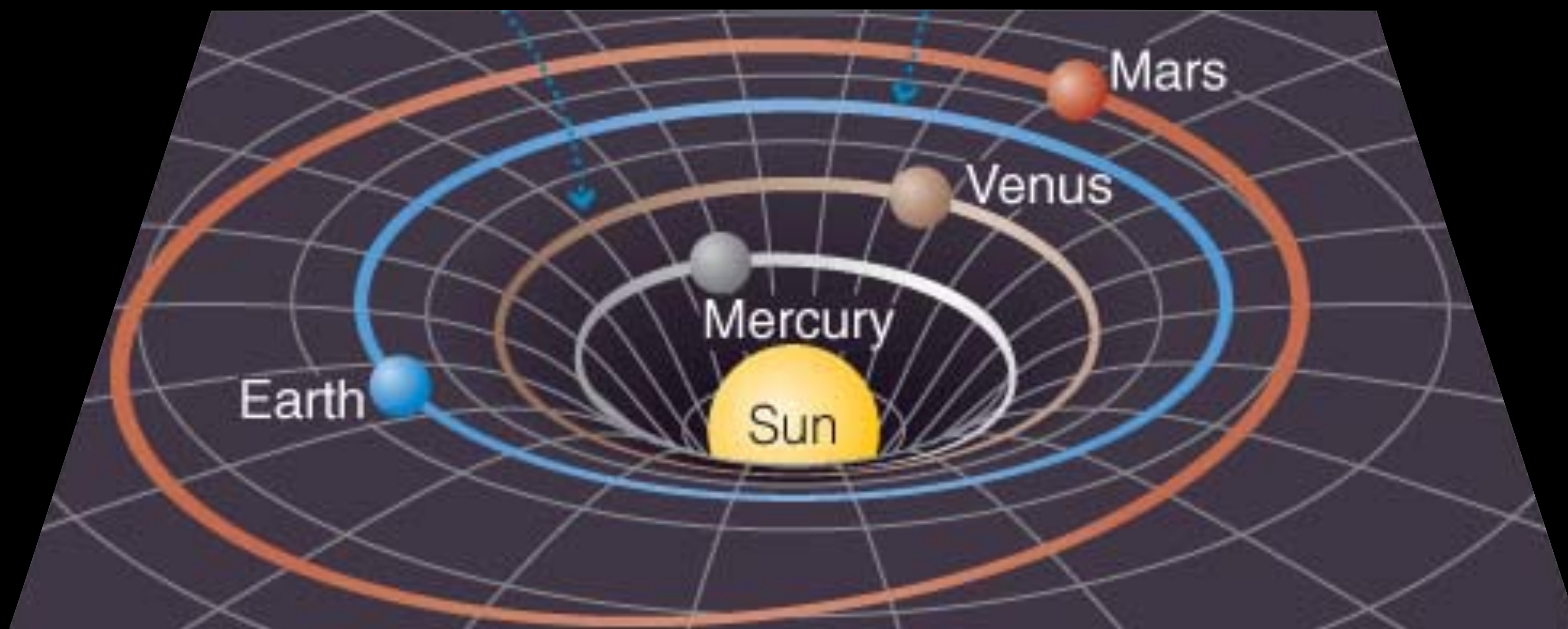
- John A. Wheeler



American Museum of Natural History
“Gravity: Making Waves”

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

- John A. Wheeler



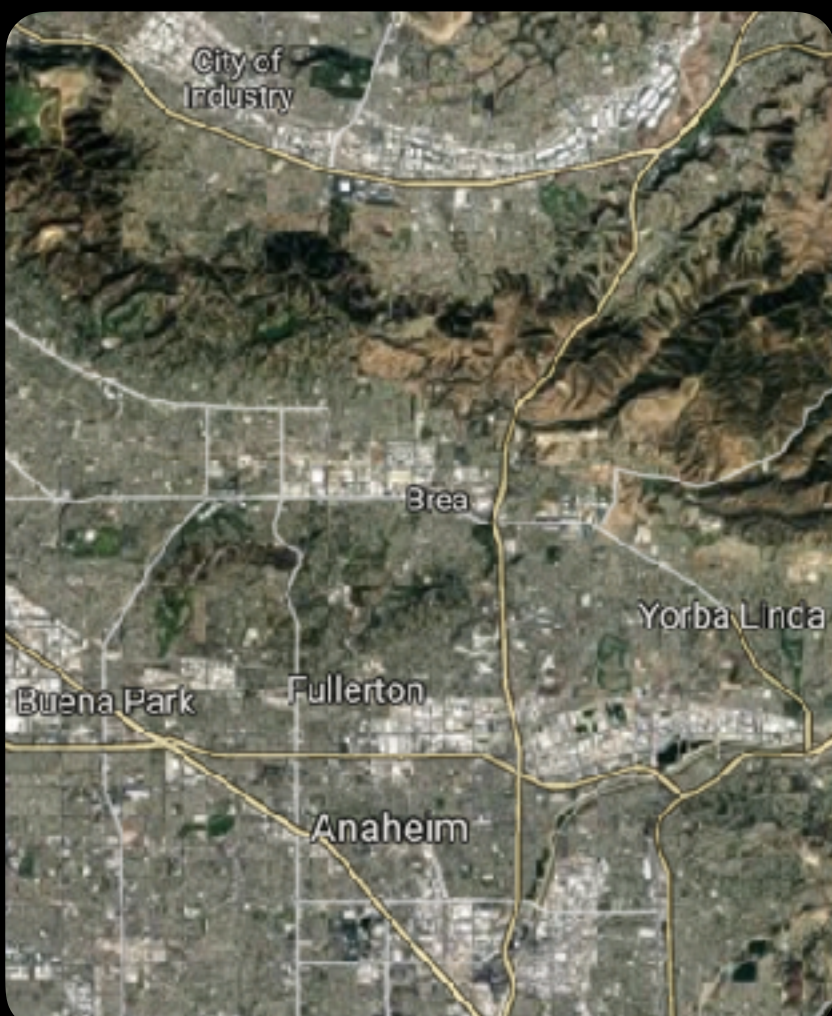
Addison Wesley

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

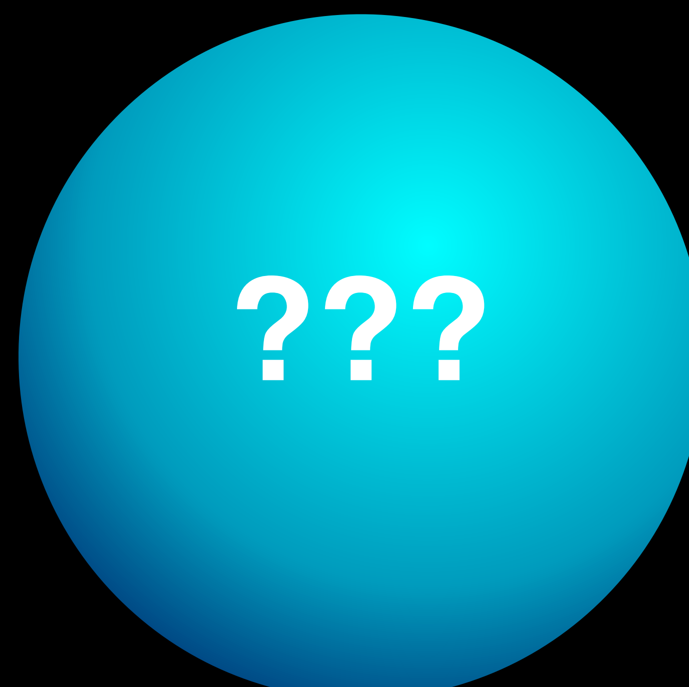
If you make an object smaller in size, but keep the mass the same, the gravitational effects get stronger

Compact objects

Fullerton area

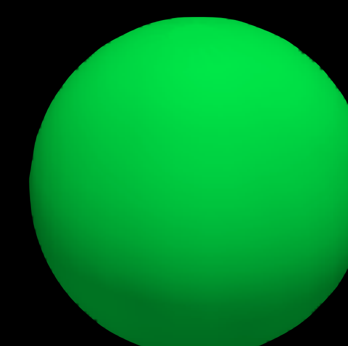


Neutron star



Mass = 1.5 ☀️
Radius = 9-15 km

Black hole (low-mass)

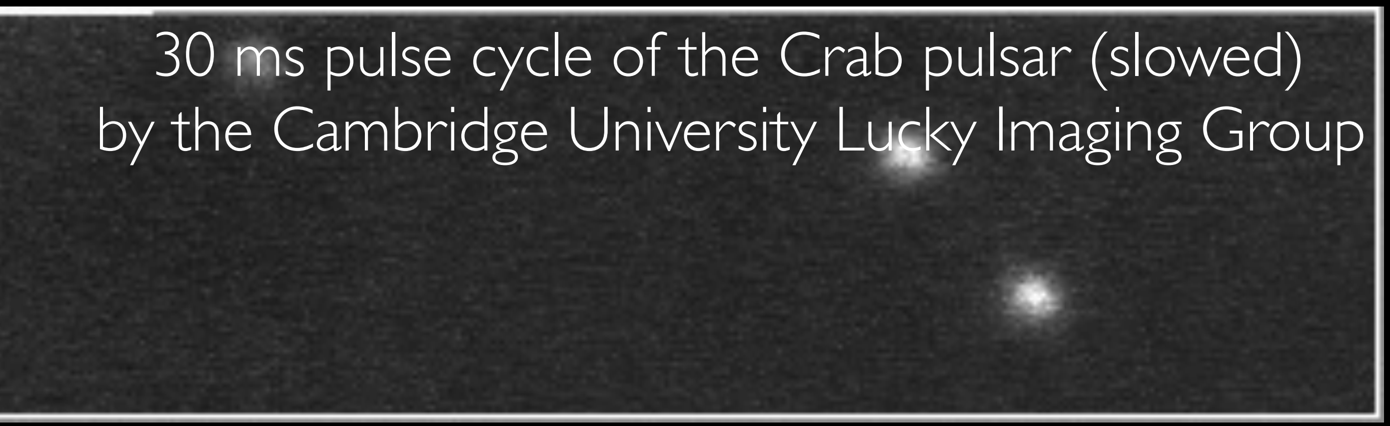


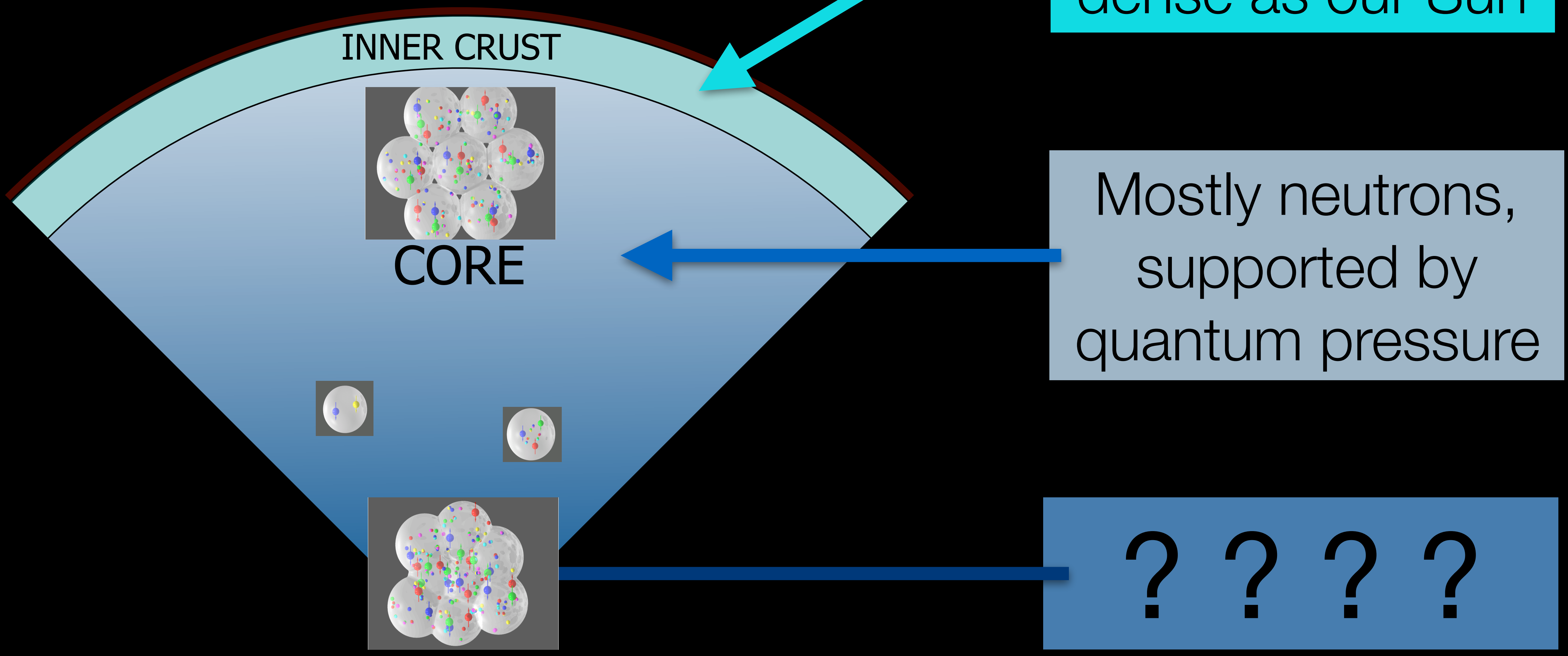
Mass = 1.5 ☀️
Radius = 4.5km

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

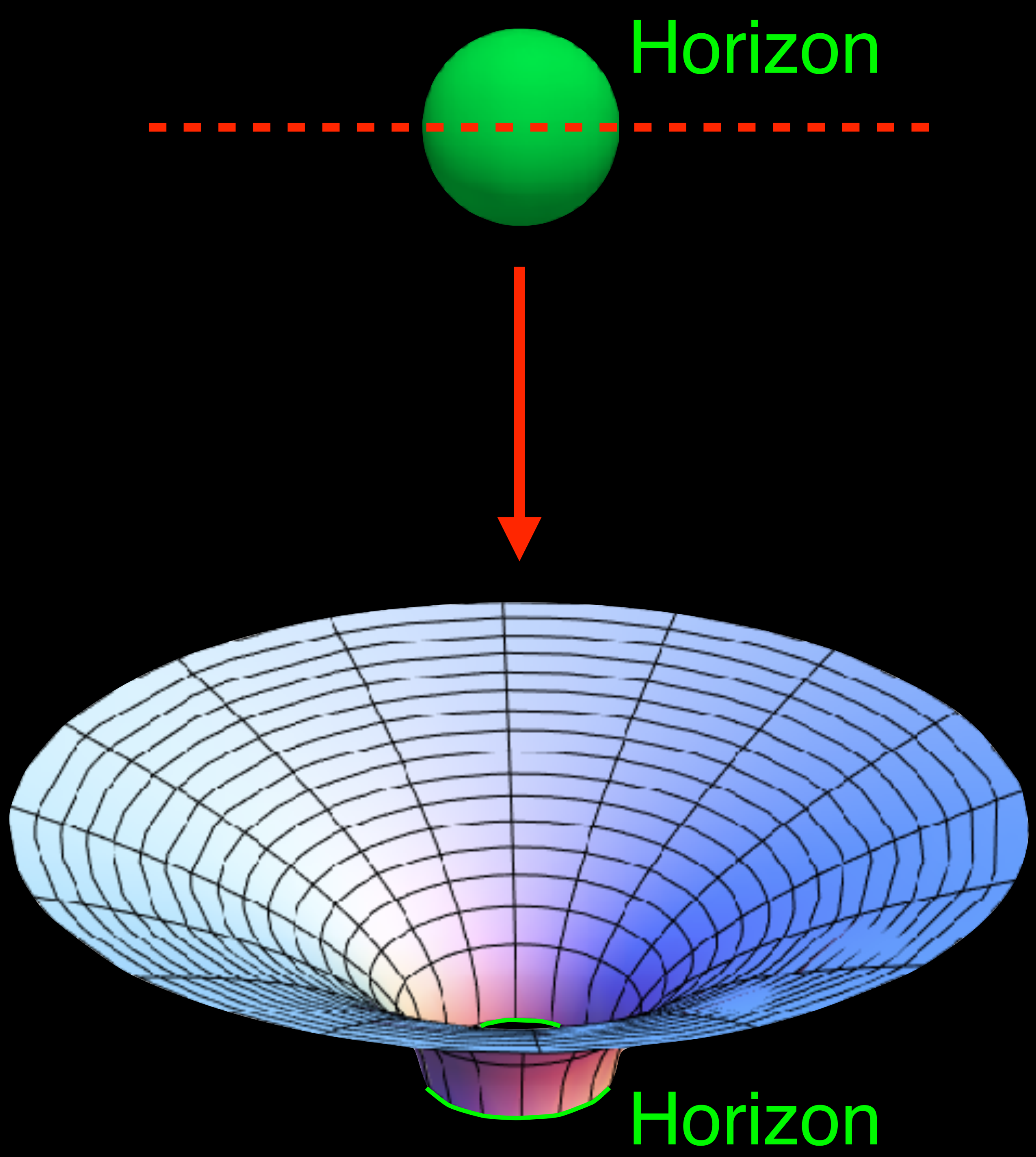
Neutron stars: matter's last stand against gravity





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



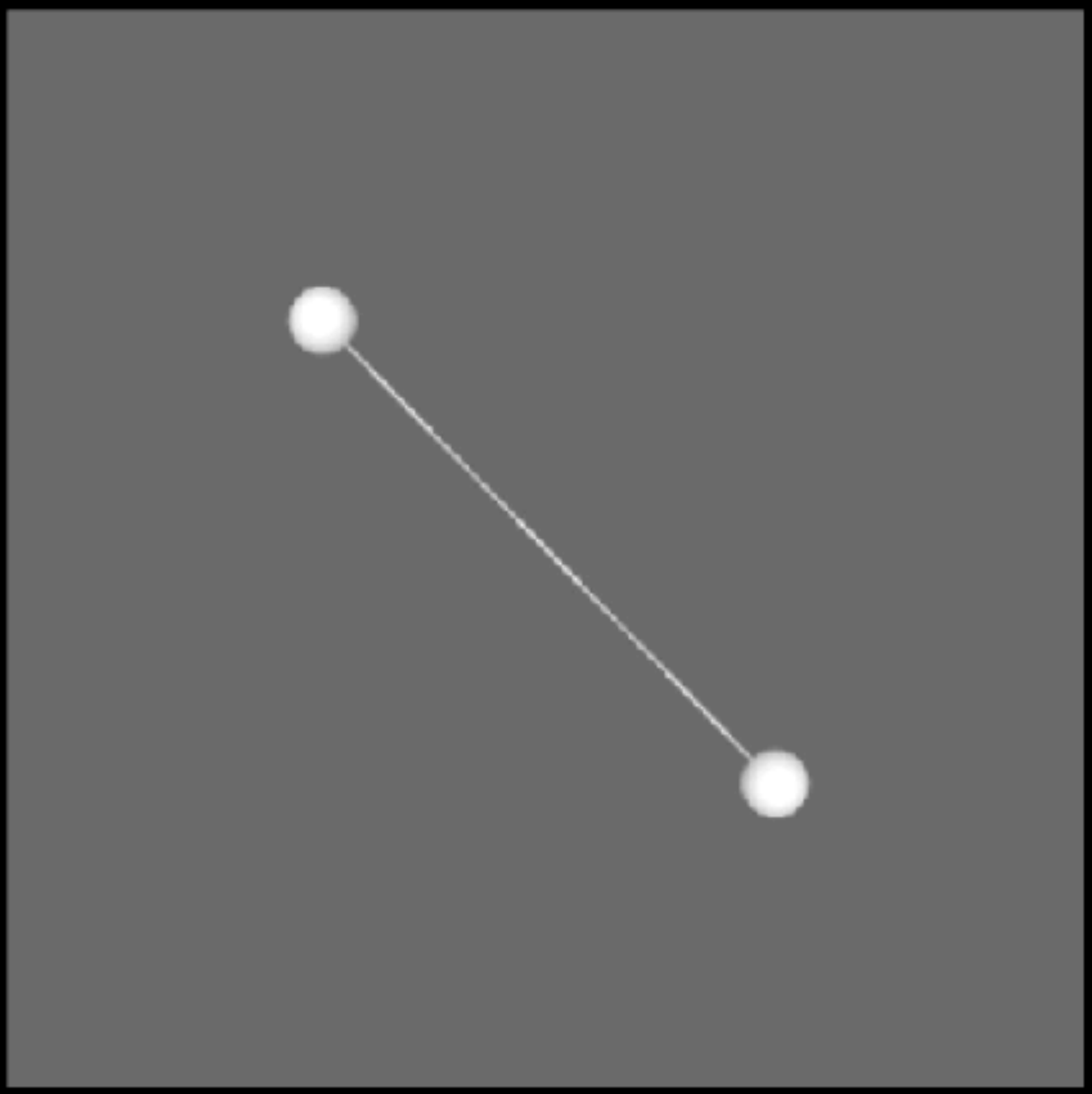
Images from Wikipedia

Mass in Motion

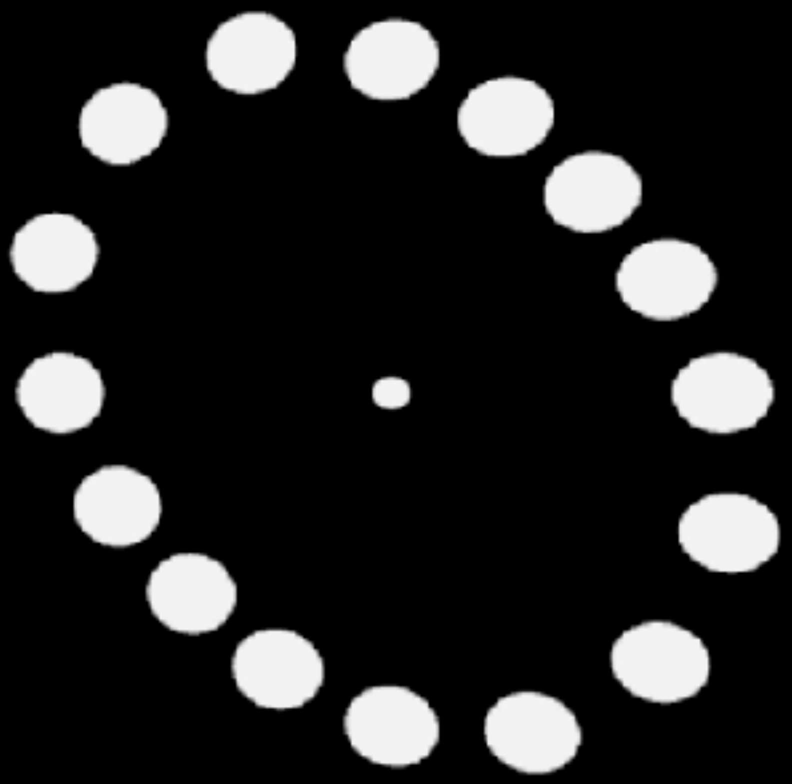
- Newtonian Gravity: "Action at a distance"
  - Instantly feel the new position of a moving object
- General Relativity:
  - Changes in curved spacetime ripple out at the speed of light

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

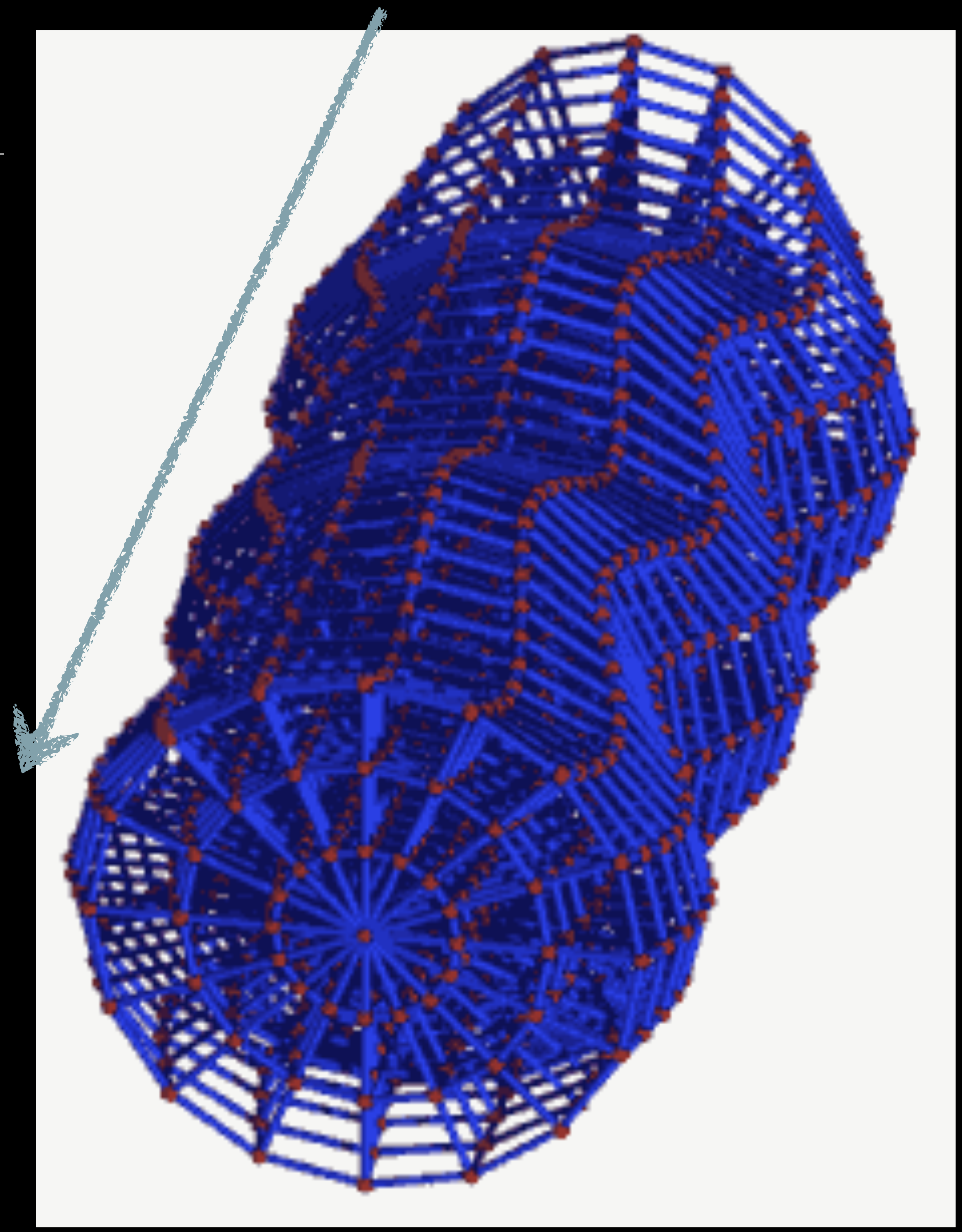
Which of the following would **not** emit gravitational waves?

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

Hint: would gravitational pull change?

Gravitational wave

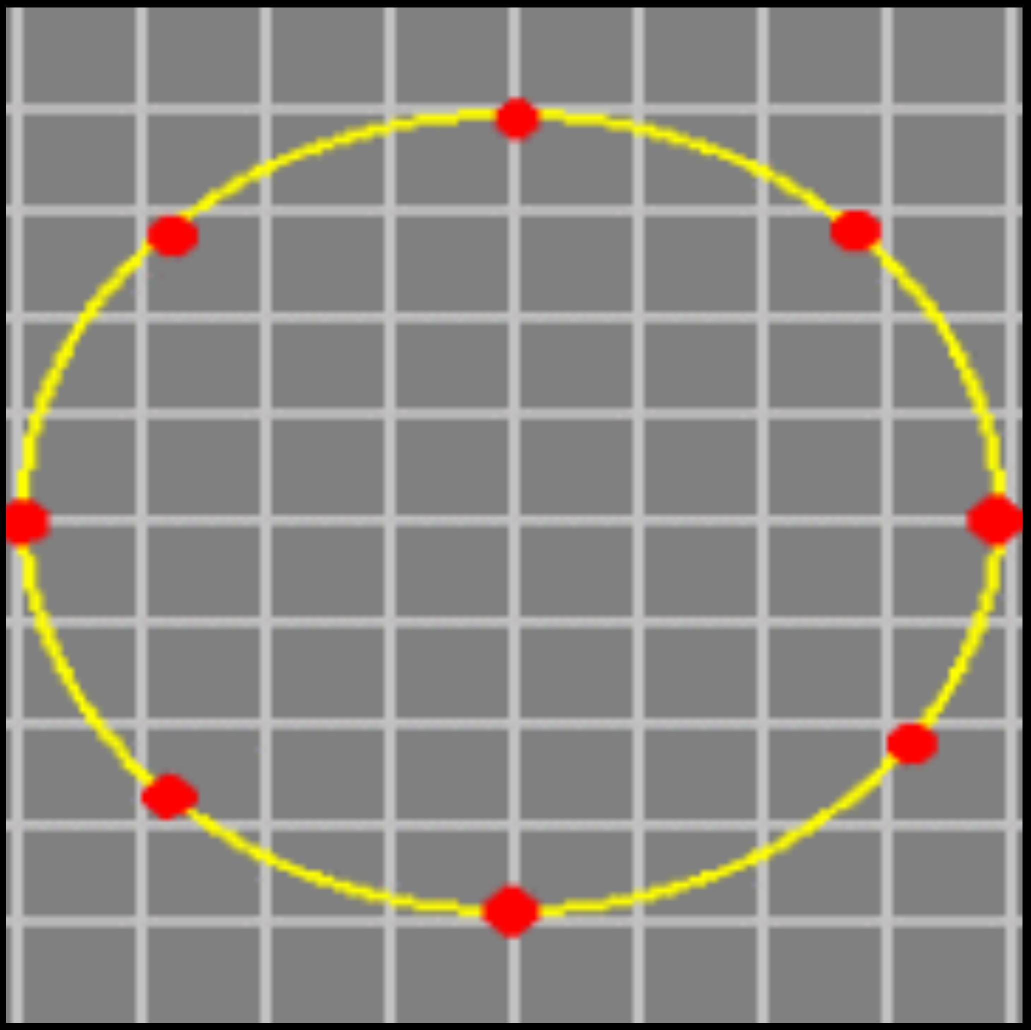
- Stretching and squeezing space
- Traveling at the speed of light

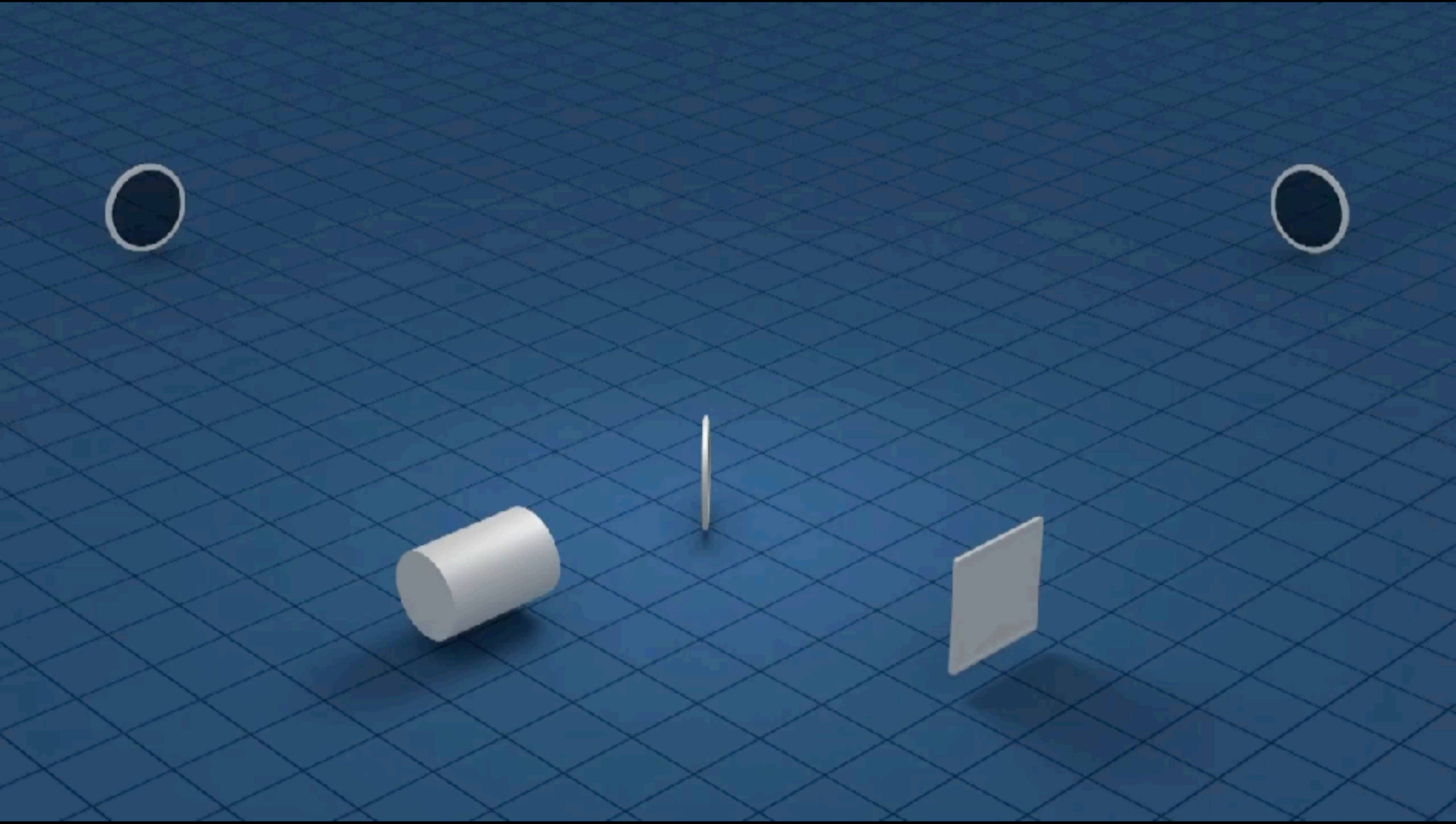


Animation from http://www.einstein-online.info/spotlights/gravWav

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%



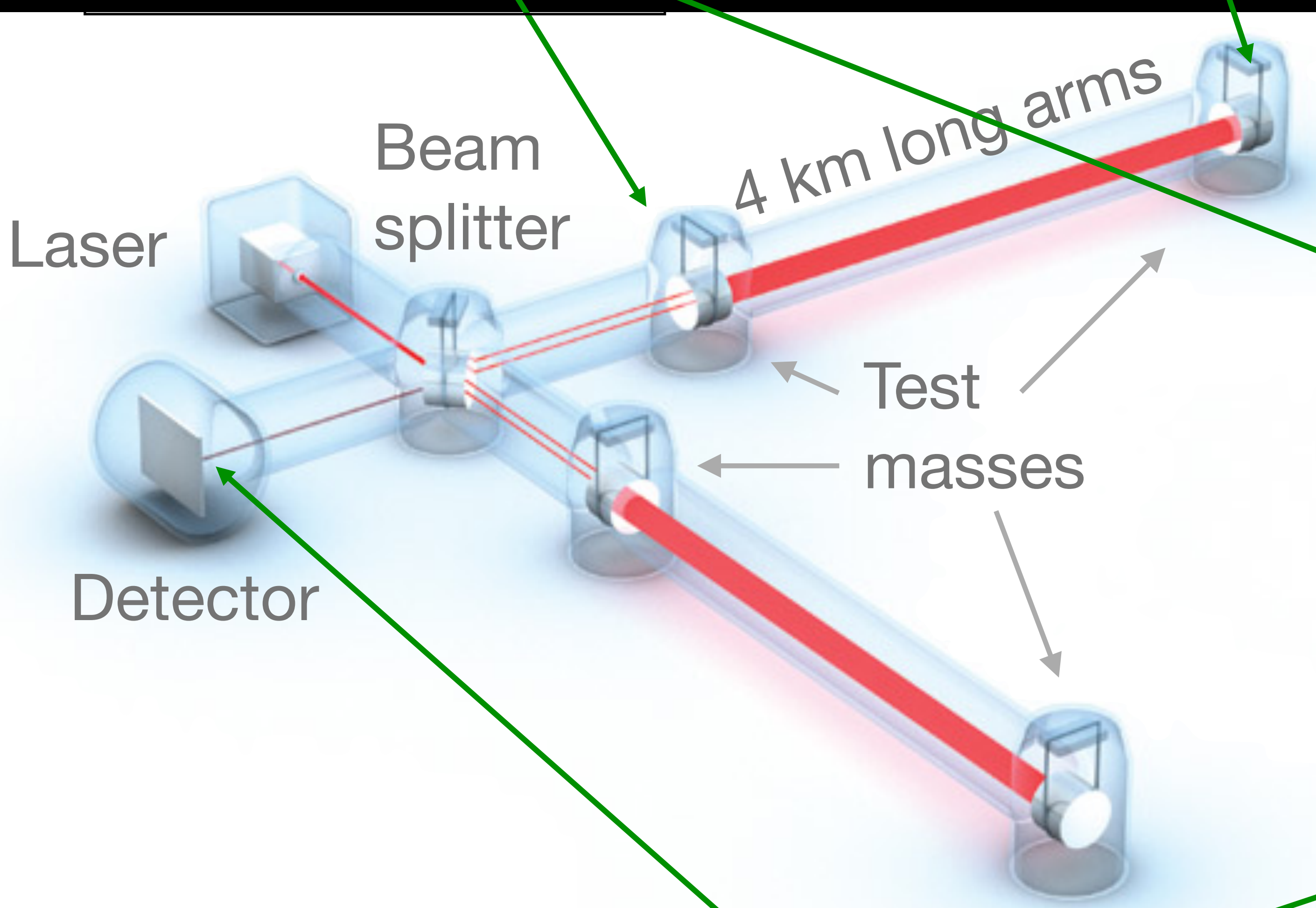


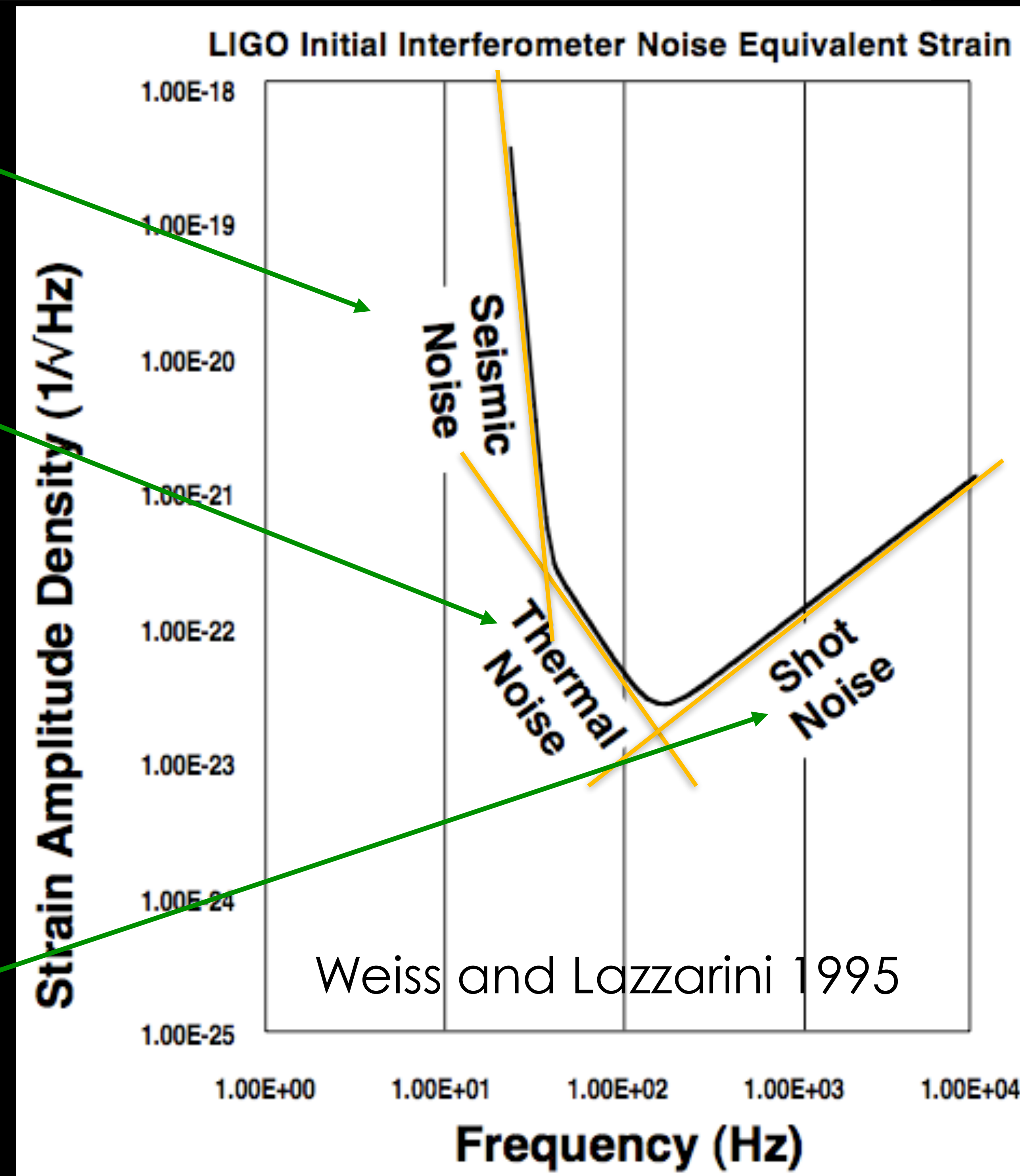
Animation: LIGO

Competing sources of mirror motion

Thermal K_BT motion of molecules shakes mirrors

Seismic motion of ground shakes mirrors





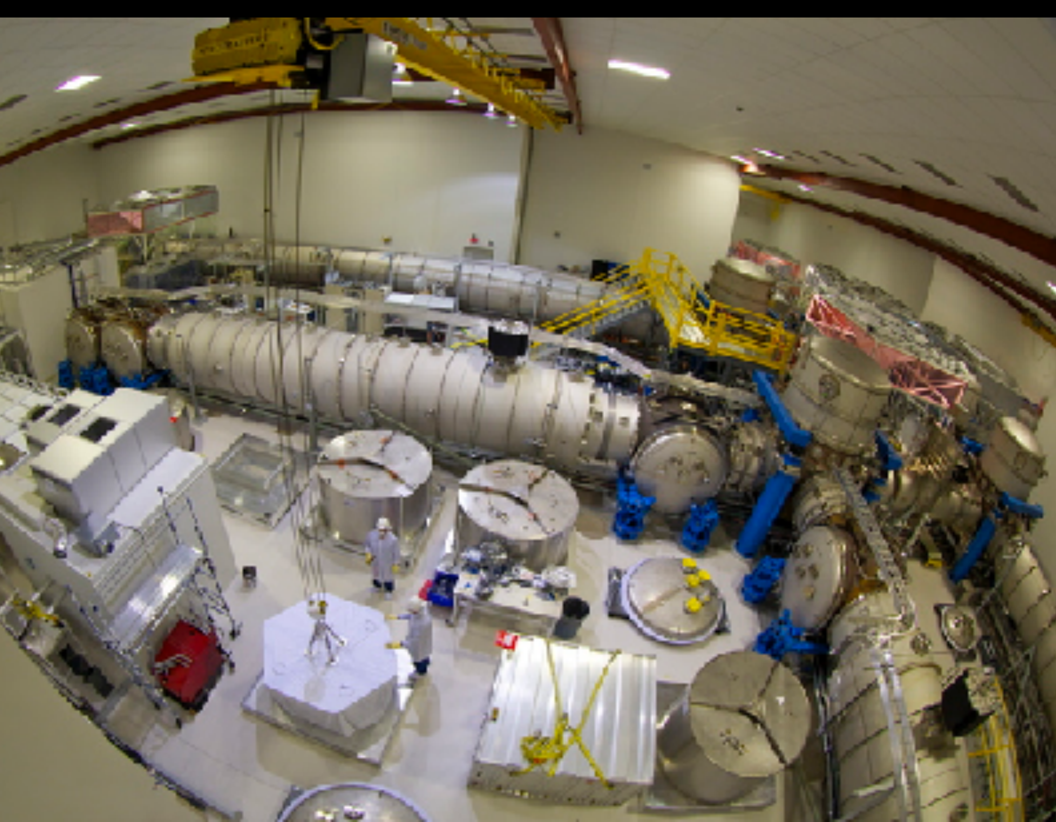
Photons arrive in a statistical pitter patter

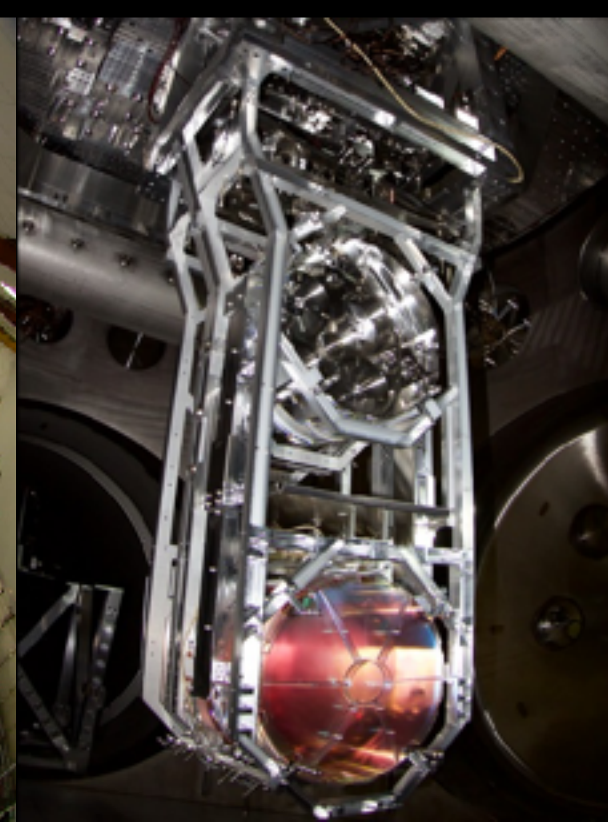
Slide courtesy Josh Smith, CSUF

LIGO Hanford, Washington
2015+

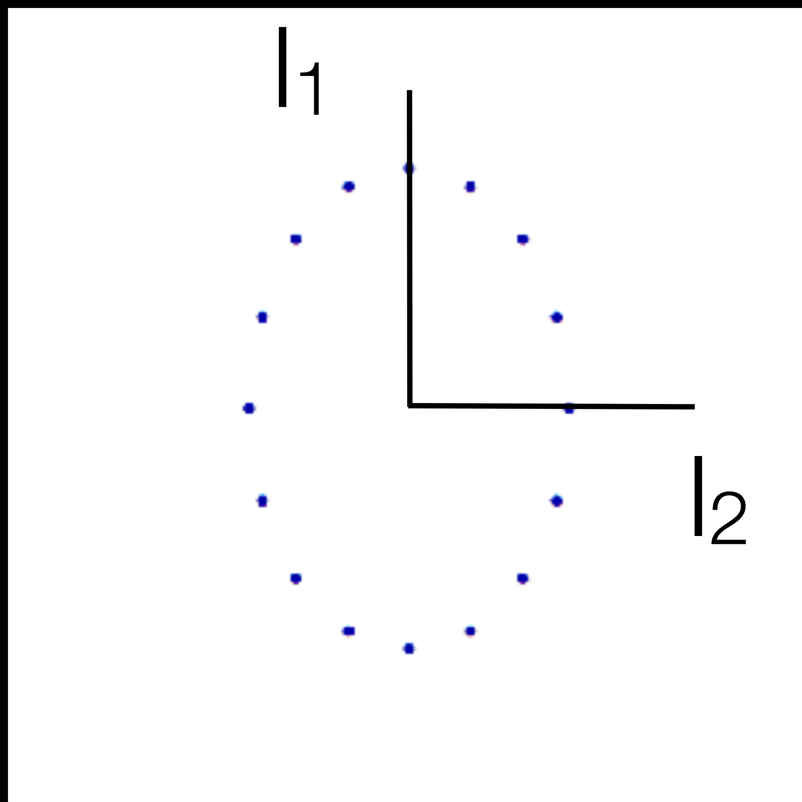
LIGO Livingston, Louisiana
2015+

Virgo, Italy
2017+





Plotting gravitational waves

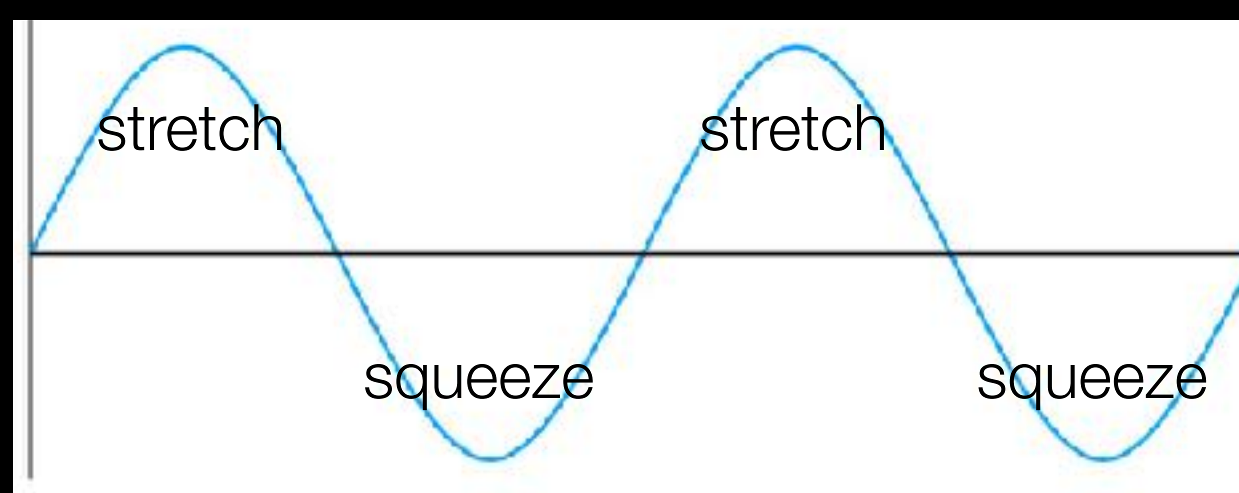


Gravitational-wave *strain*

$h_+ \sim (l_1 - l_2)/l_{av}$

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

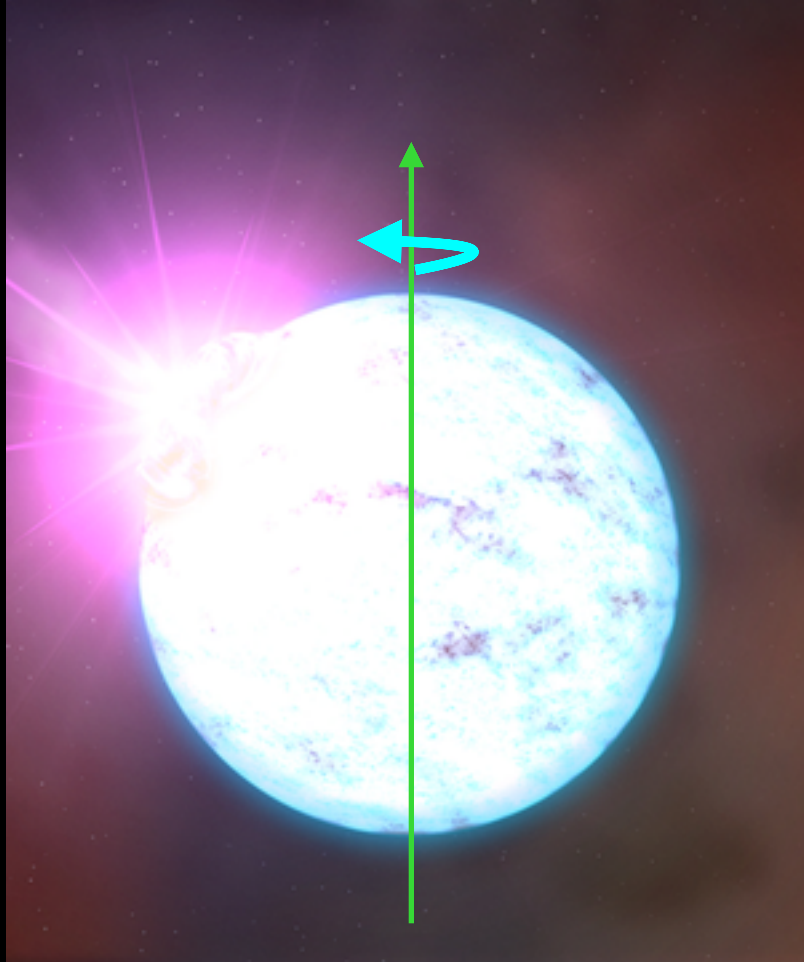
Strain



Time

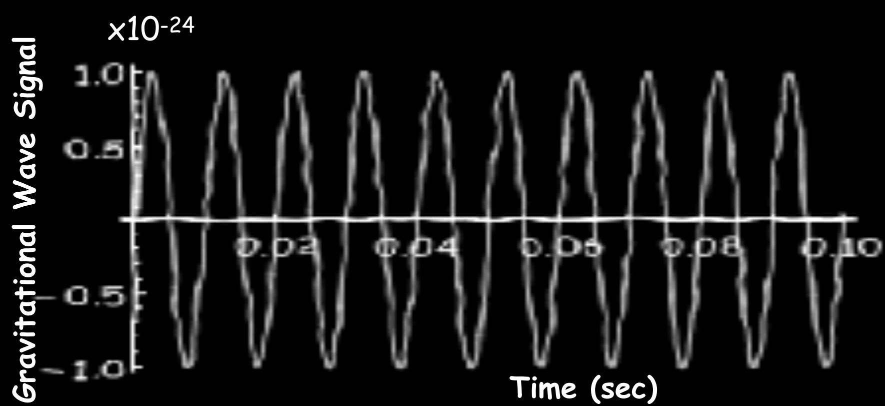
If a gravitational wave and an electromagnetic wave were both emitted at the same time from a cataclysmic event in a distant galaxy, which wave would get to earth first?

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

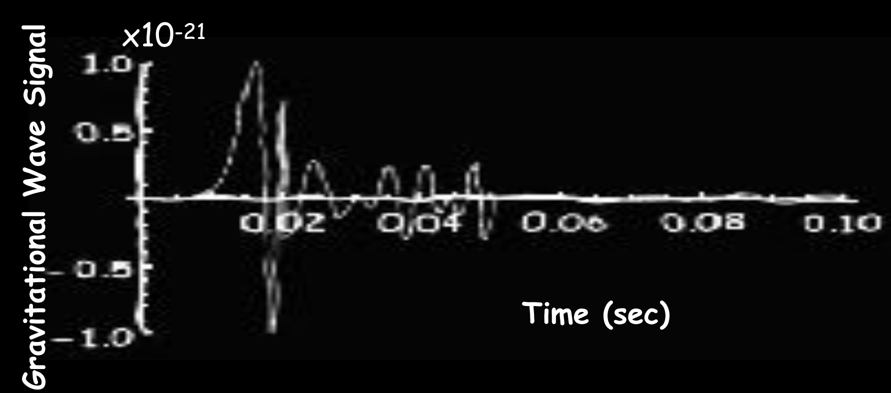


A neutron star is spinning at a steady rate. A heavy mountain on its surface is carried around by the star's spin. What GW pattern is produced?

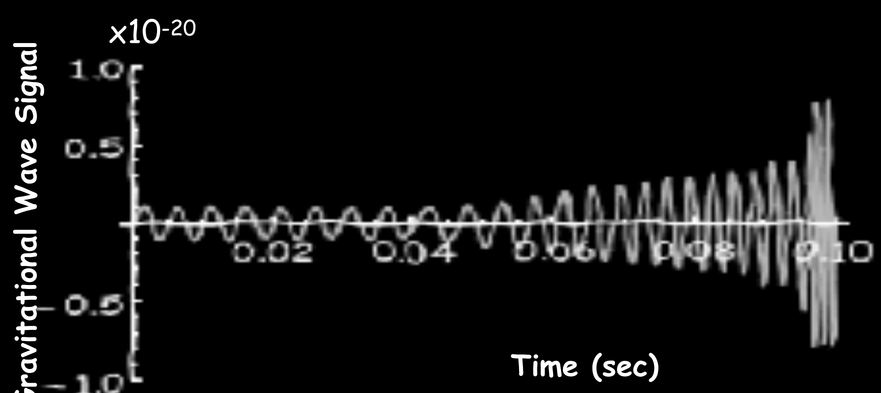
A.



B.

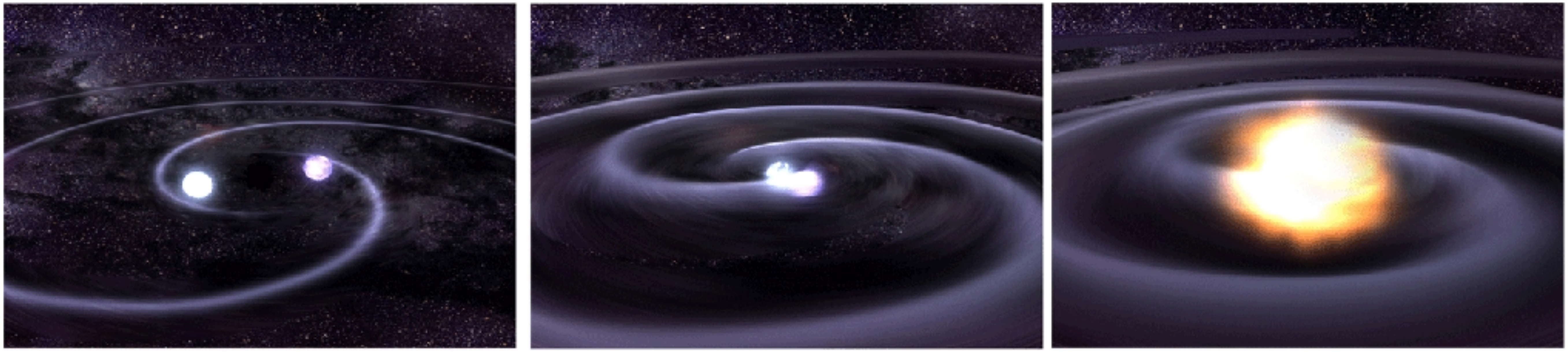


C.



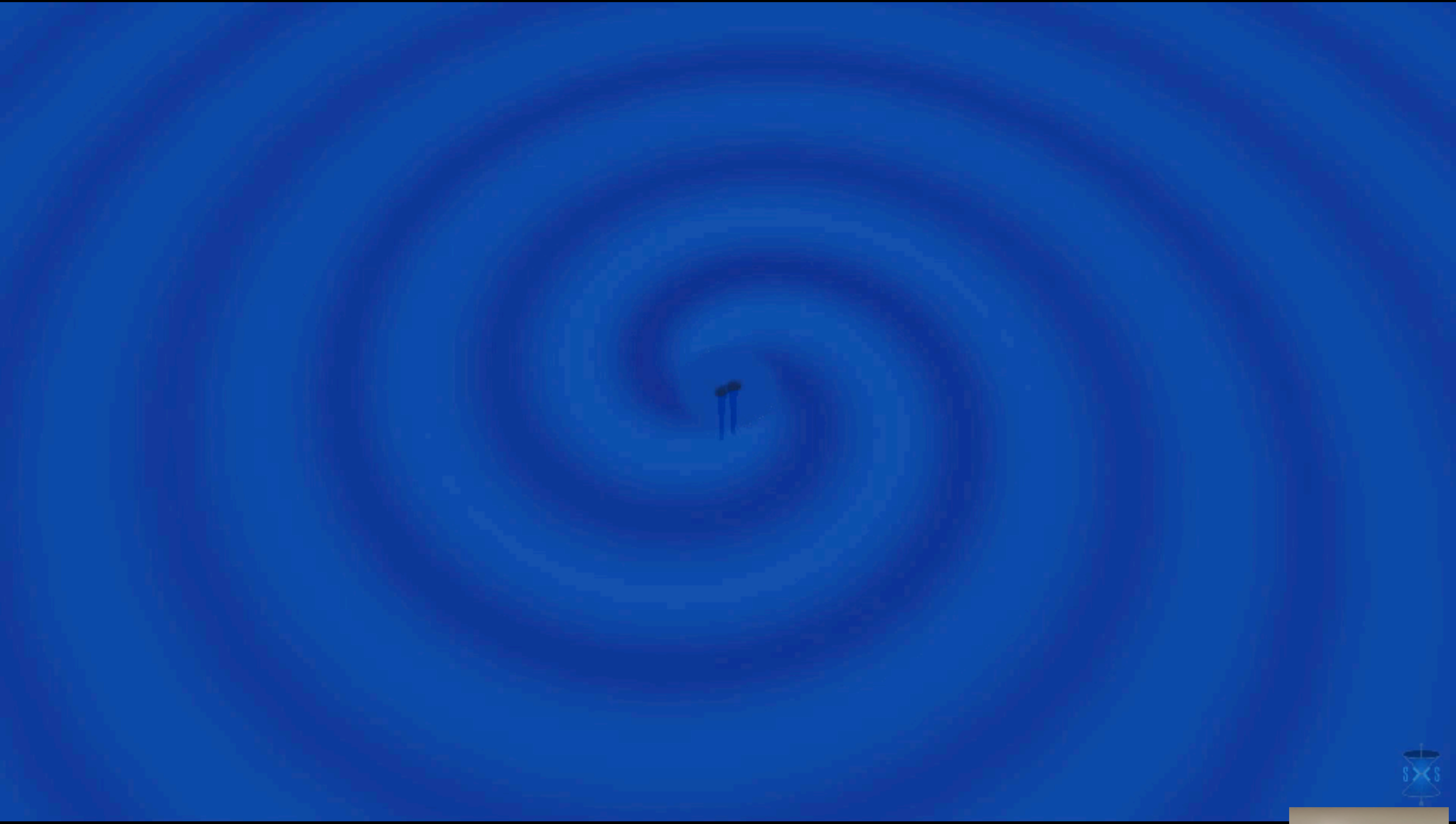
D. No GW produced

Merger / Coalescence

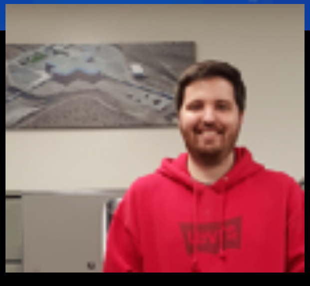


- Orbiting stars emit gravitational waves; waves carry away energy
- Orbits with lower energy are closer together
- Closer orbits produce stronger waves

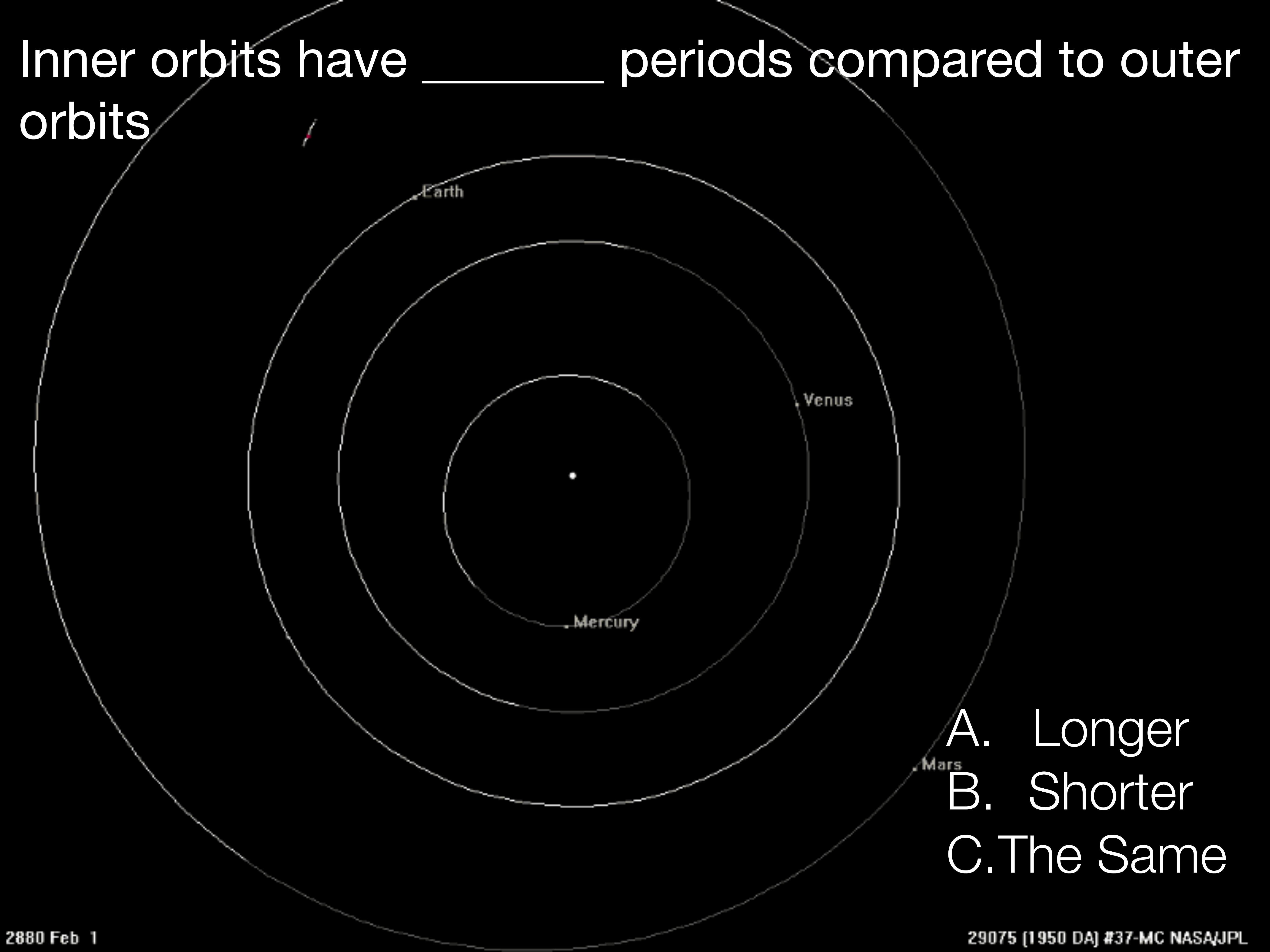
Gravitational Waves from merging black holes



Movie by CSUF student Nick Demos,
Simulating eXtreme Spacetimes collaboration

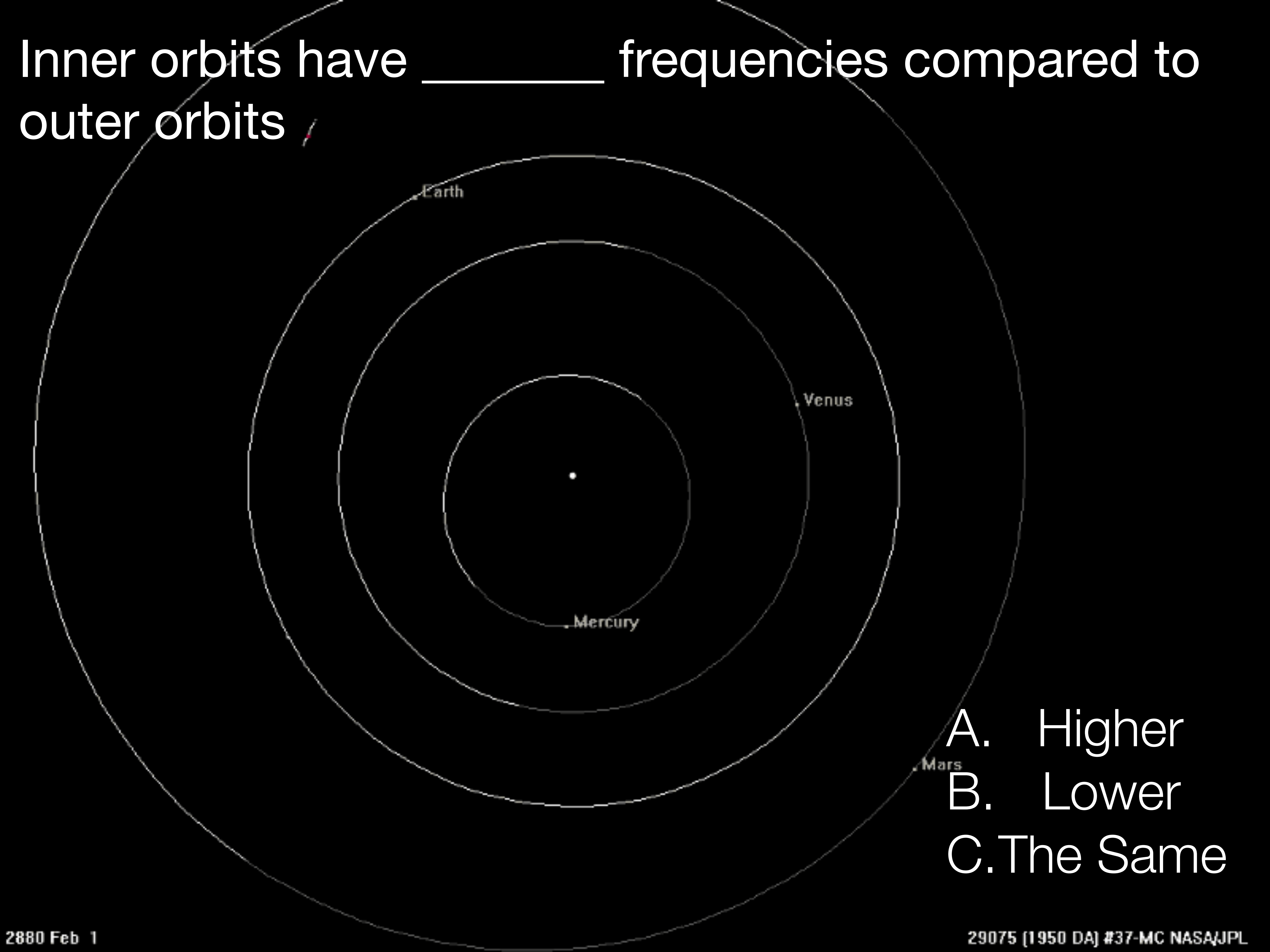


Inner orbits have ________ periods compared to outer orbits



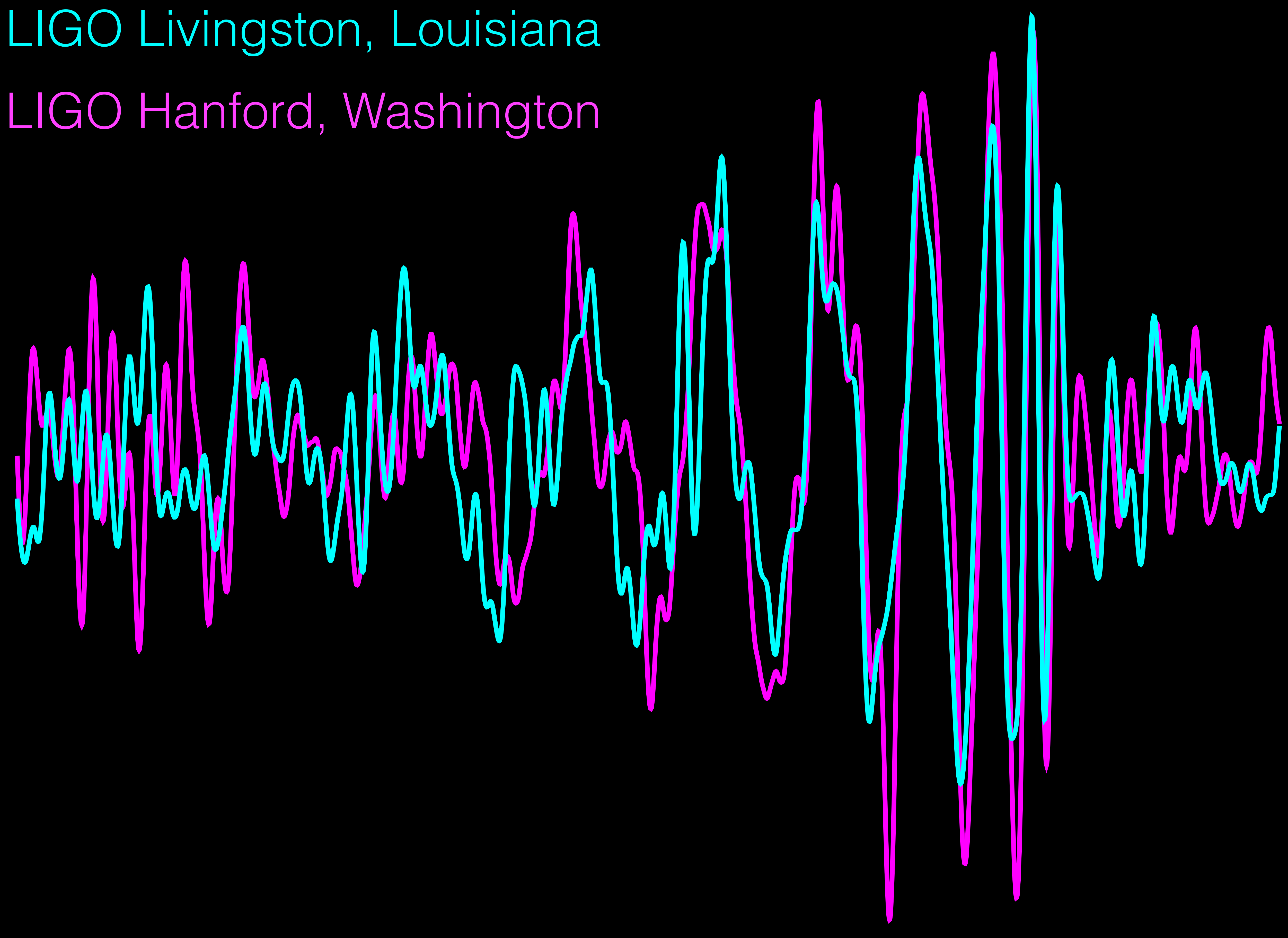
A. Longer
B. Shorter
C. The Same

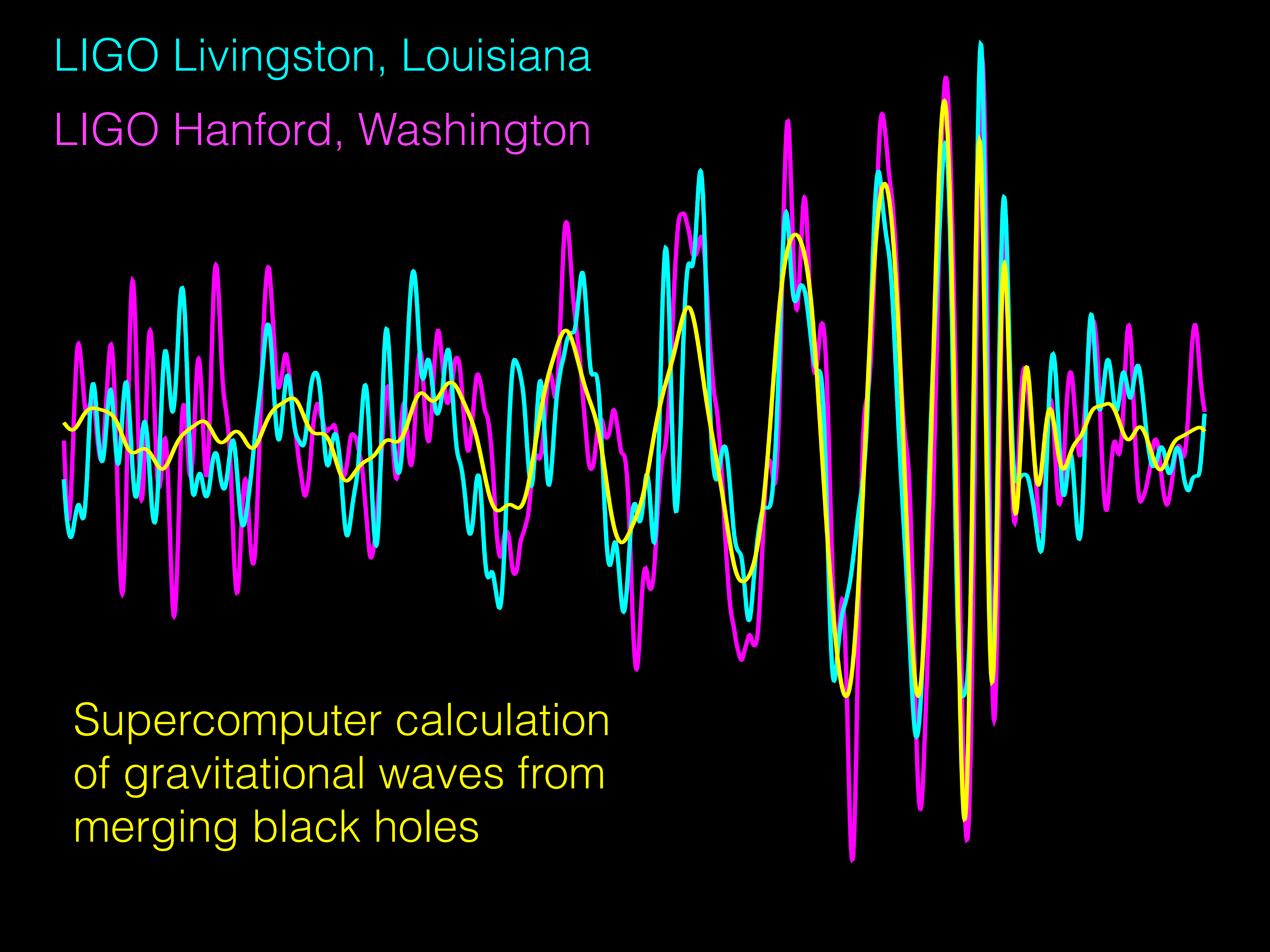
Inner orbits have _______ frequencies compared to outer orbits



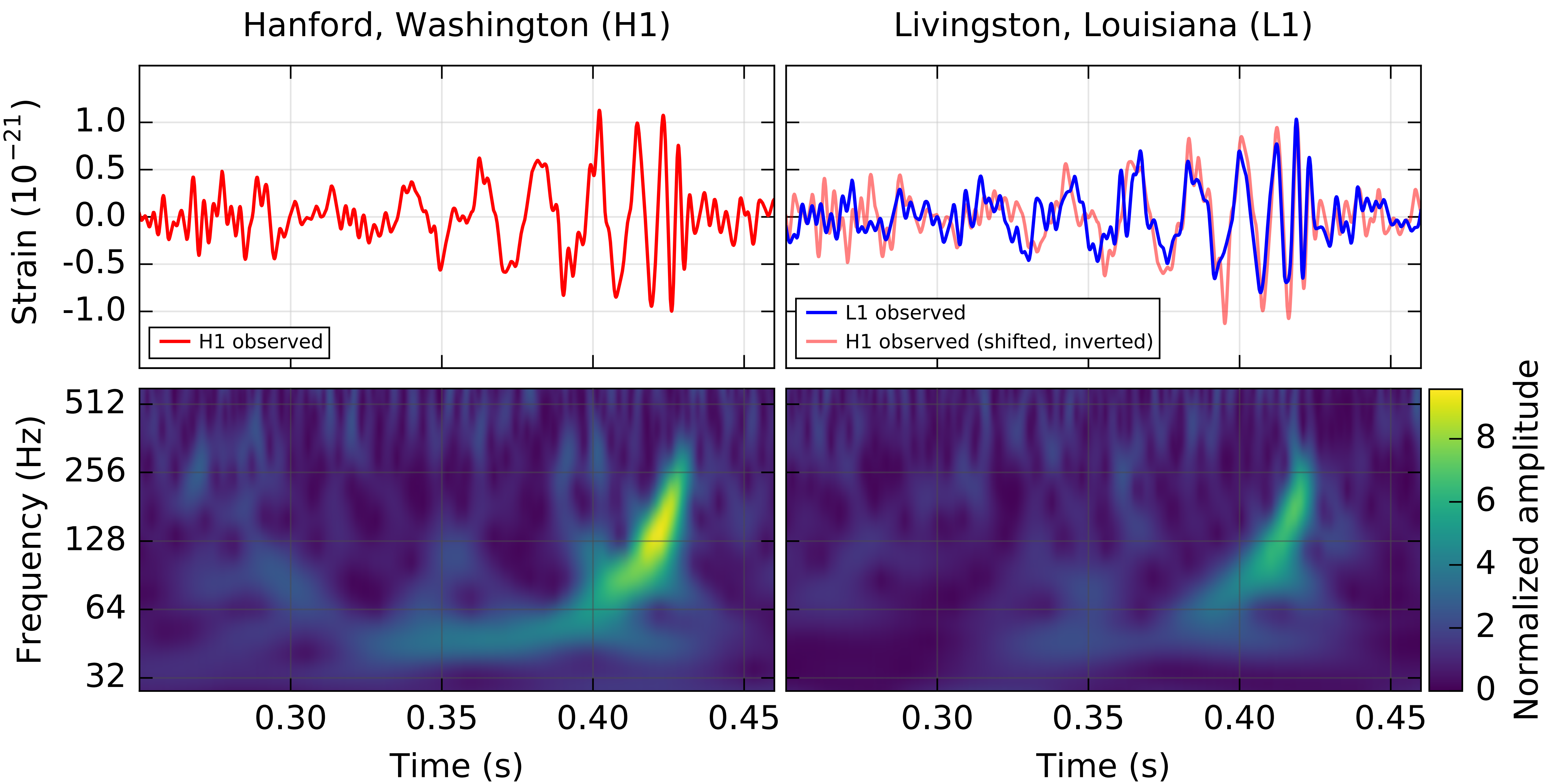
A. Higher
B. Lower
C. The Same

- 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

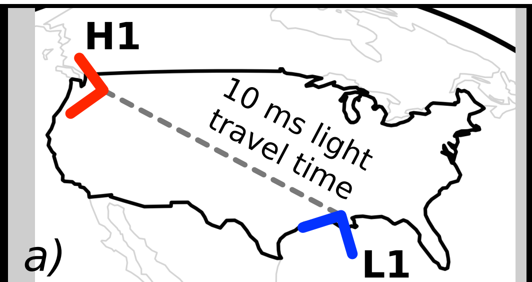

LIGO Livingston, Louisiana
LIGO Hanford, Washington
Supercomputer calculation
of gravitational waves from
merging black holes

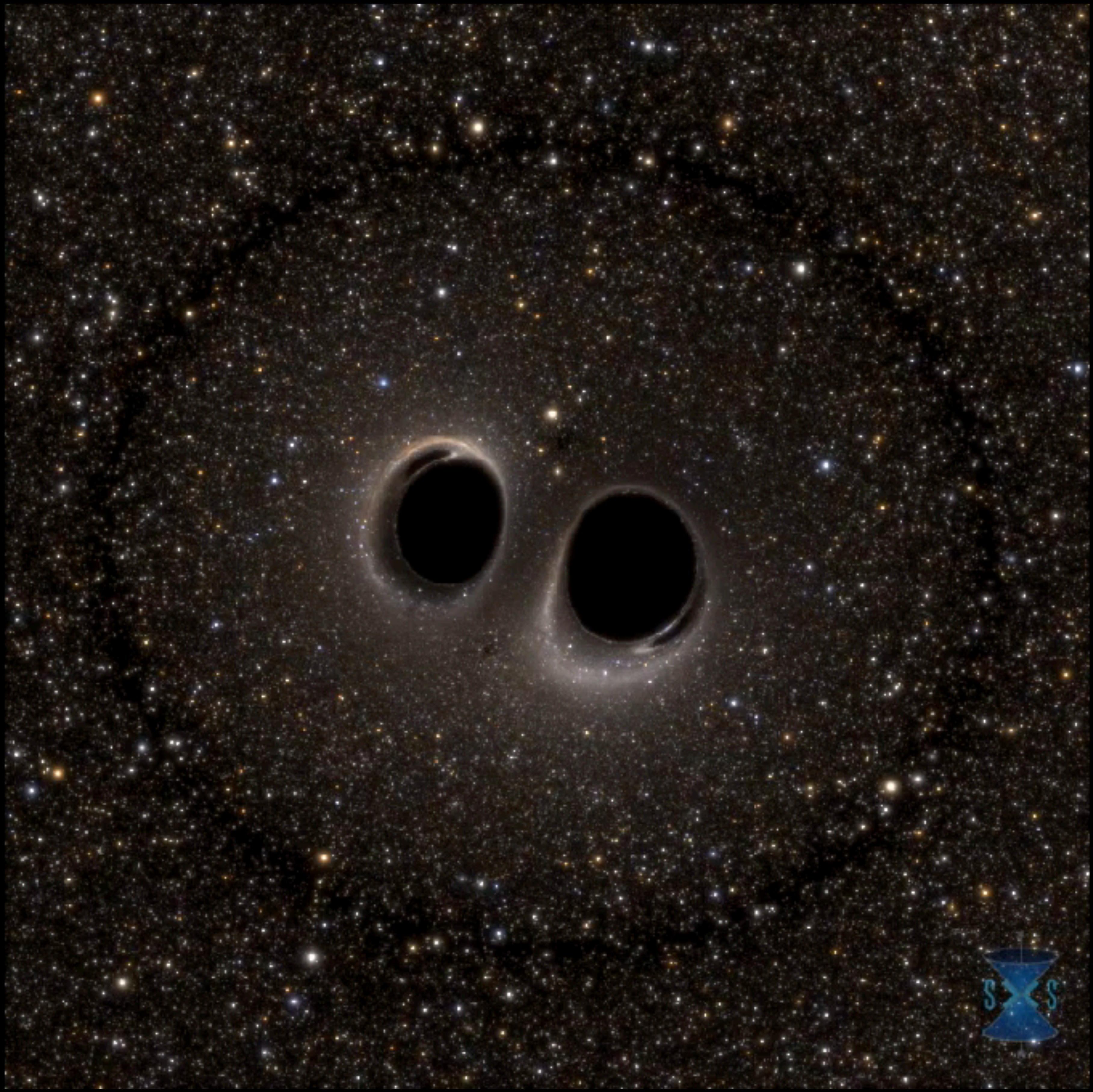
Observation of Gravitational Waves from a Binary Black Hole Merger



September 14, 2015 at 09:50:45 GMT

PRL 116, 061102 (2016)





Movie by CSUF student Haroon Khan,
SXS collaboration

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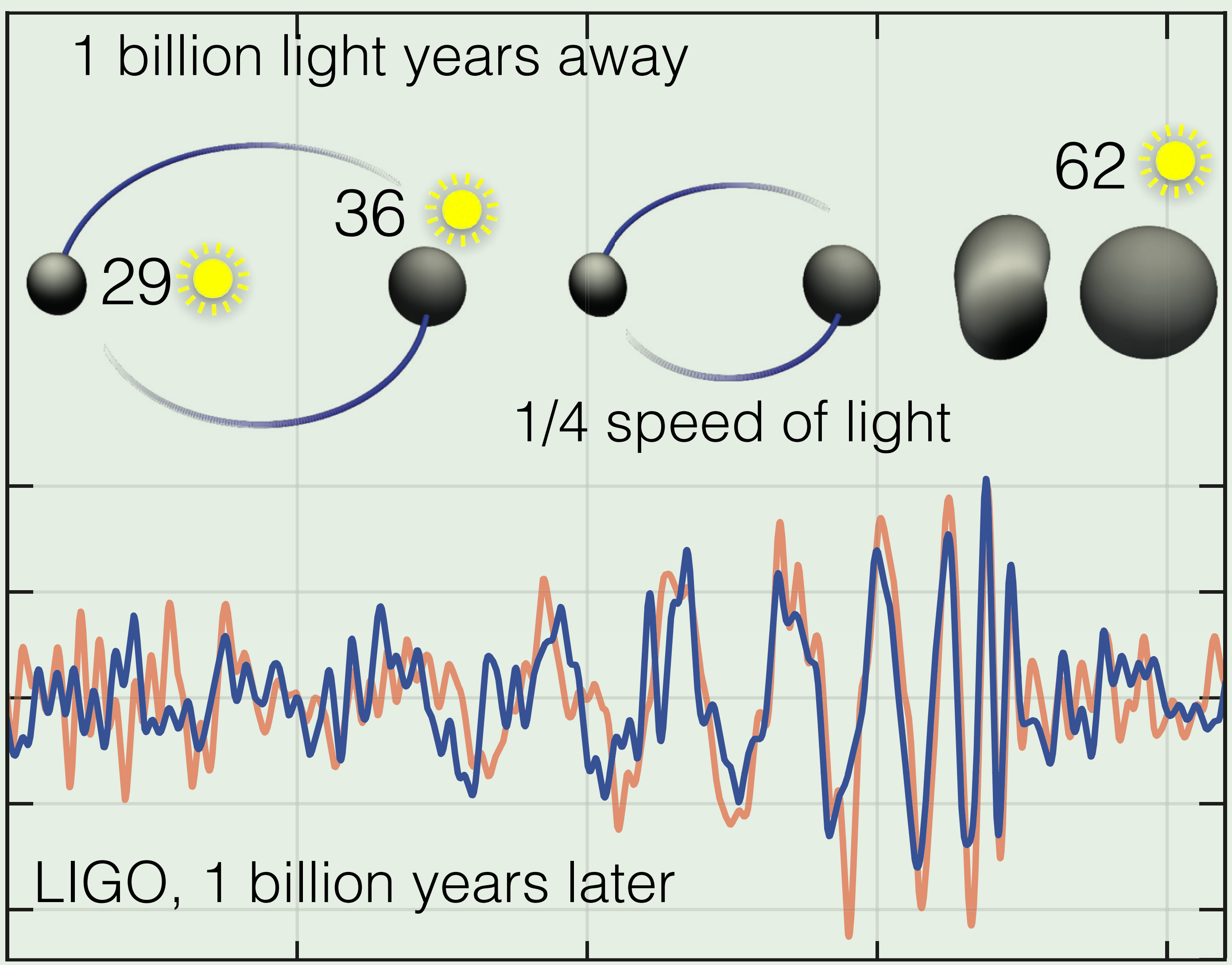
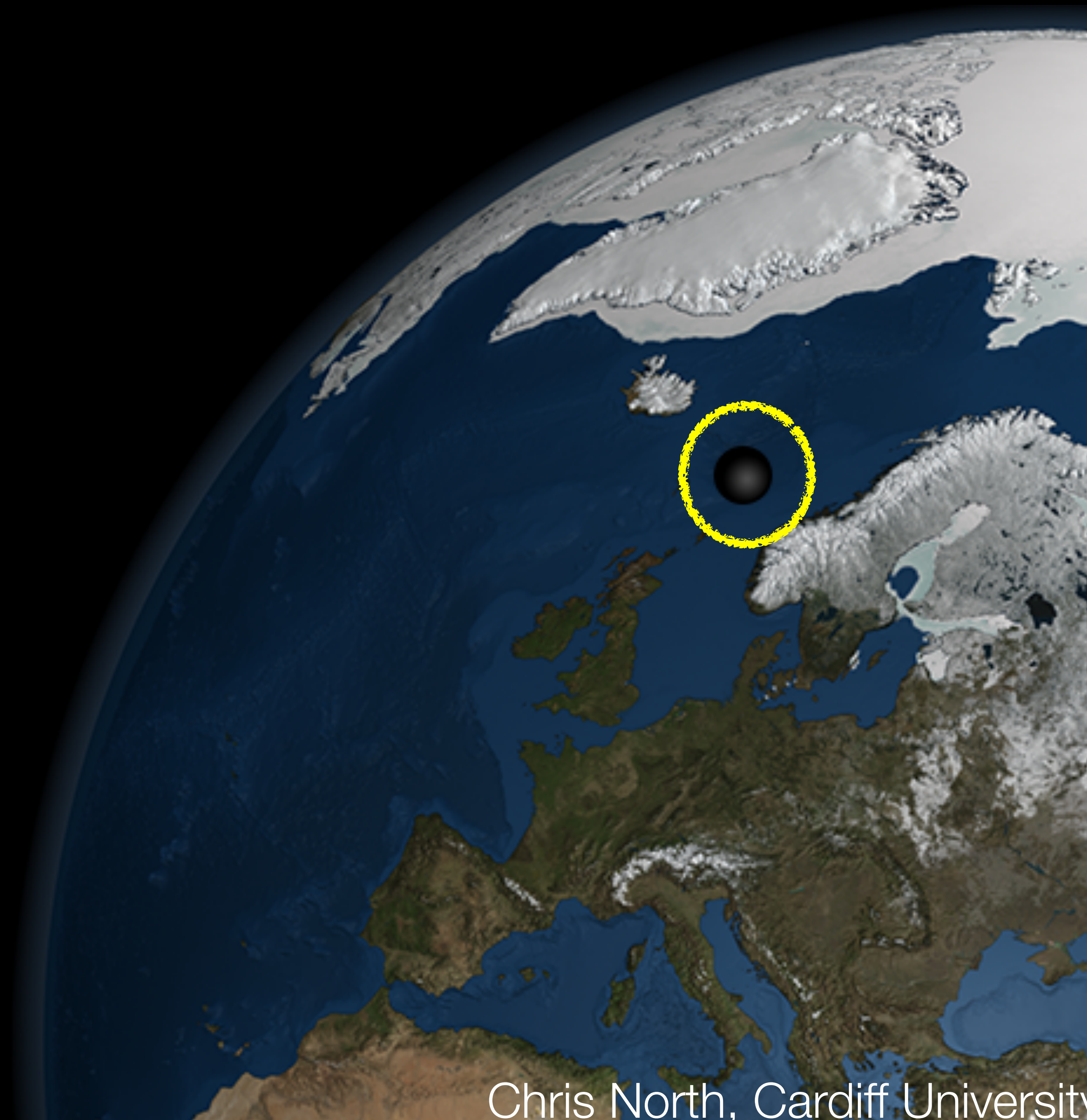


Properties of the binary black hole merger GW150914: Result of merger

Final black hole:
62±4 solar
masses
spinning at
about 100 Hz

Estimated
luminosity (in GW)
~10^{56} erg/s



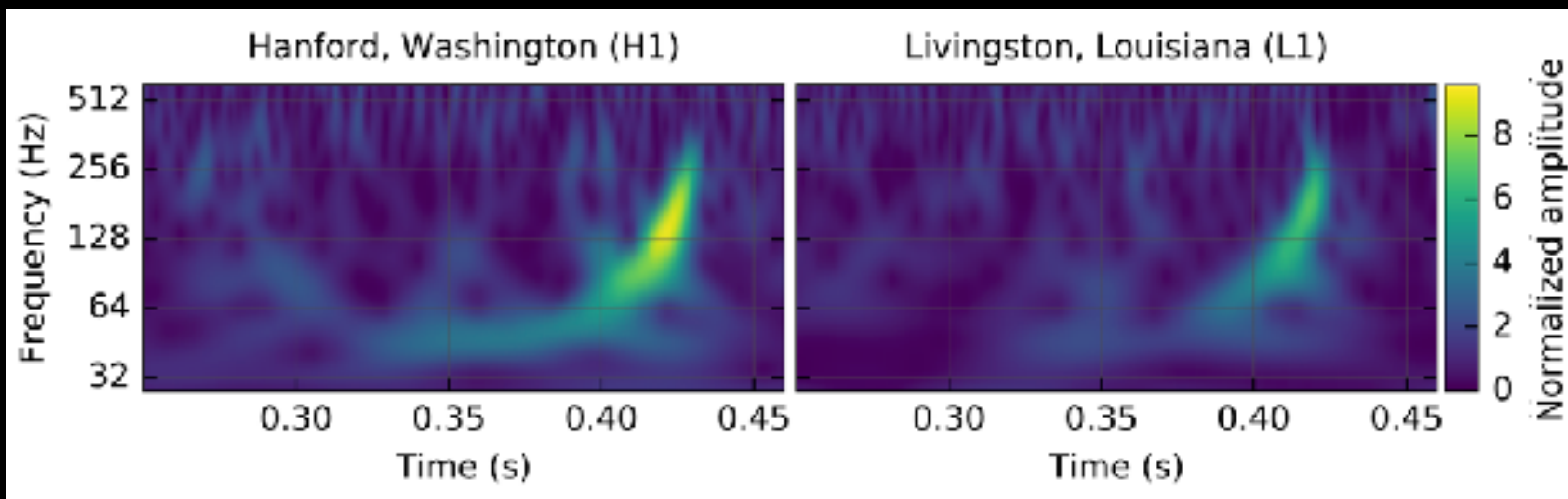
What did this mean?

- First direct detection of gravitational waves
  - Opened the field of gravitational-wave astronomy
- Direct observation of stellar mass black holes (3!)
- First observation of two black holes merging to form one final black hole
- No deviations from General Relativity seen in this strong-field, high-velocity regime

BBH detections

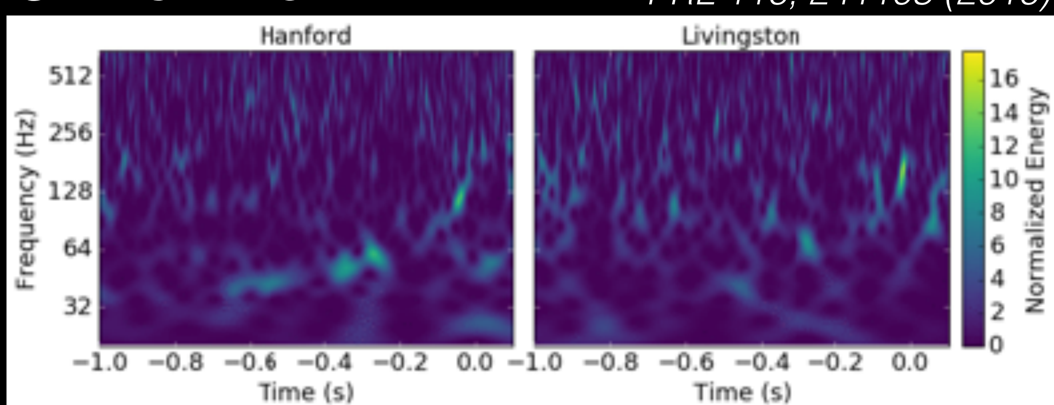
GW150914

PRL 116, 061102 (2016)



GW151226

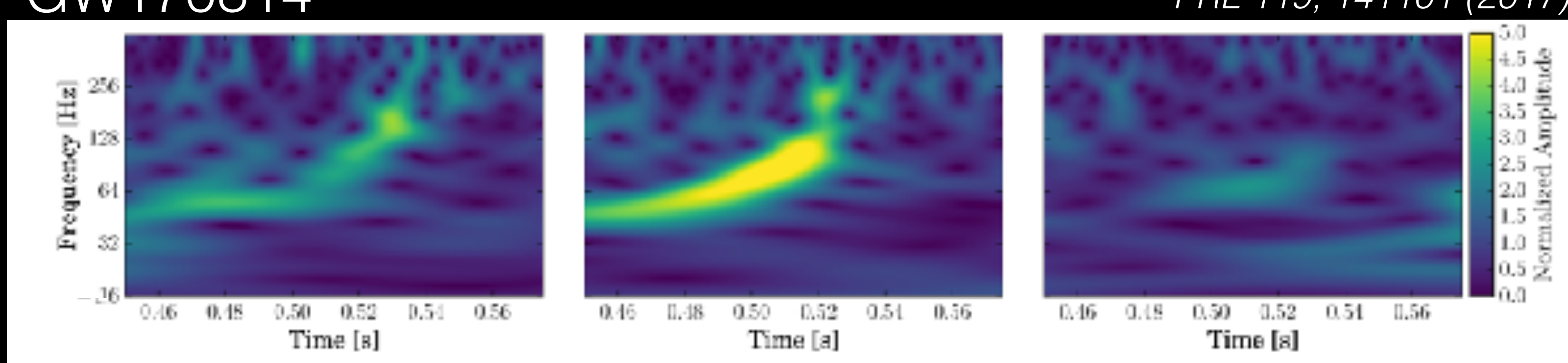
PRL 116, 241103 (2016)



< 2 s of data shown for each

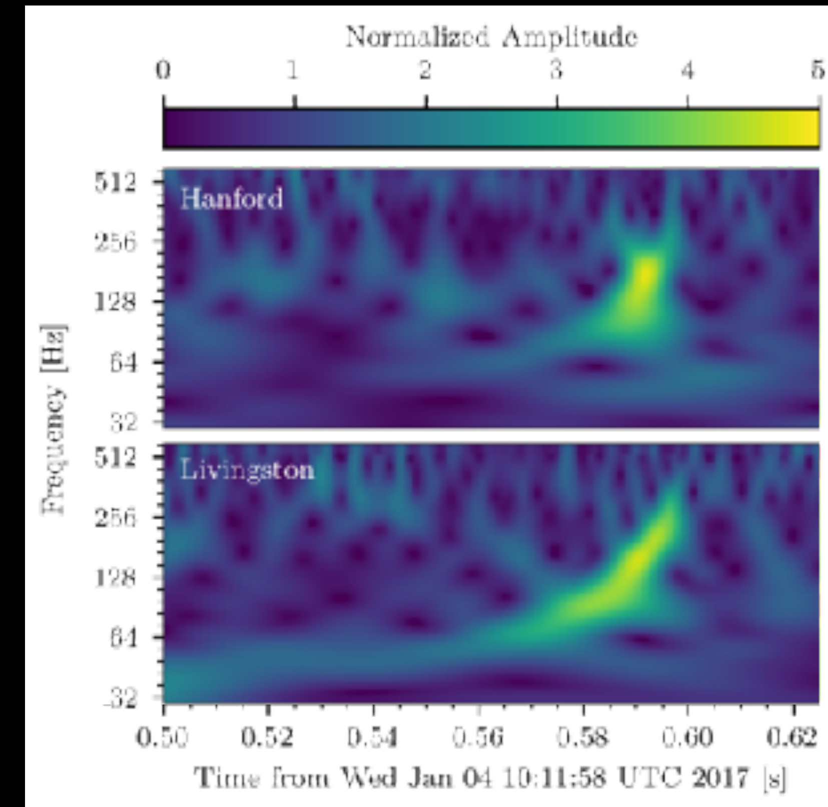
GW170814

PRL 119, 141101 (2017)

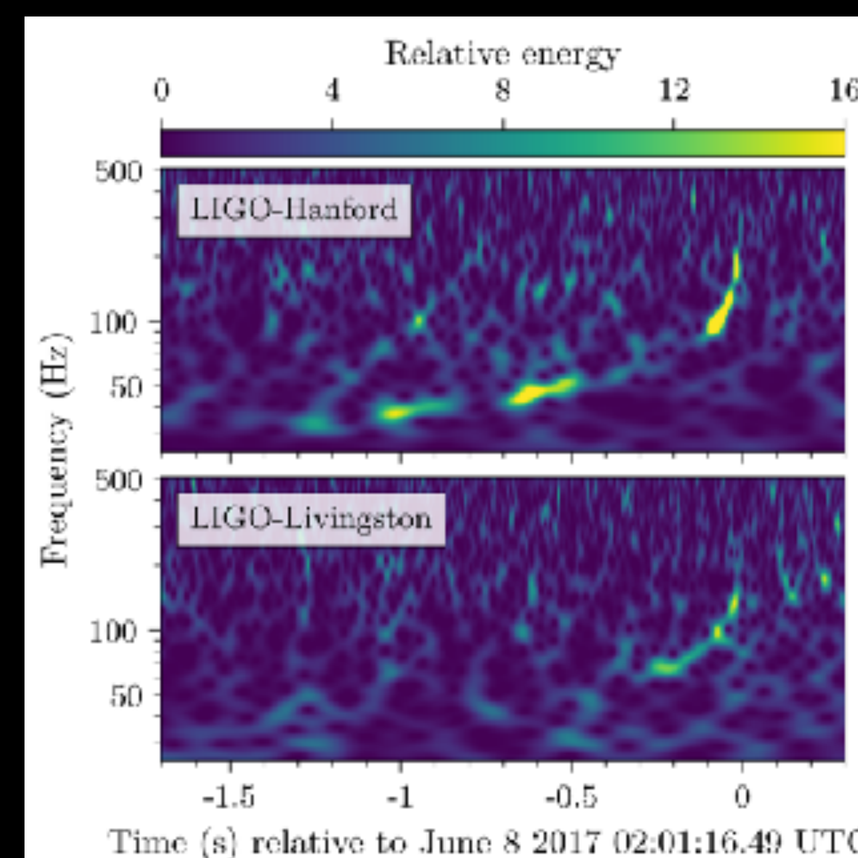


PRL 118, 221101 (2017)

GW170104



GW170608



Simulations of BBH sources

Time
to merger: 0.454 s

GW150914
M=36,29Msun
D=440Mpc

GW151226
M=14,7Msun
D=440Mpc

M=31,19Msun
D=880Mpc
GW170104

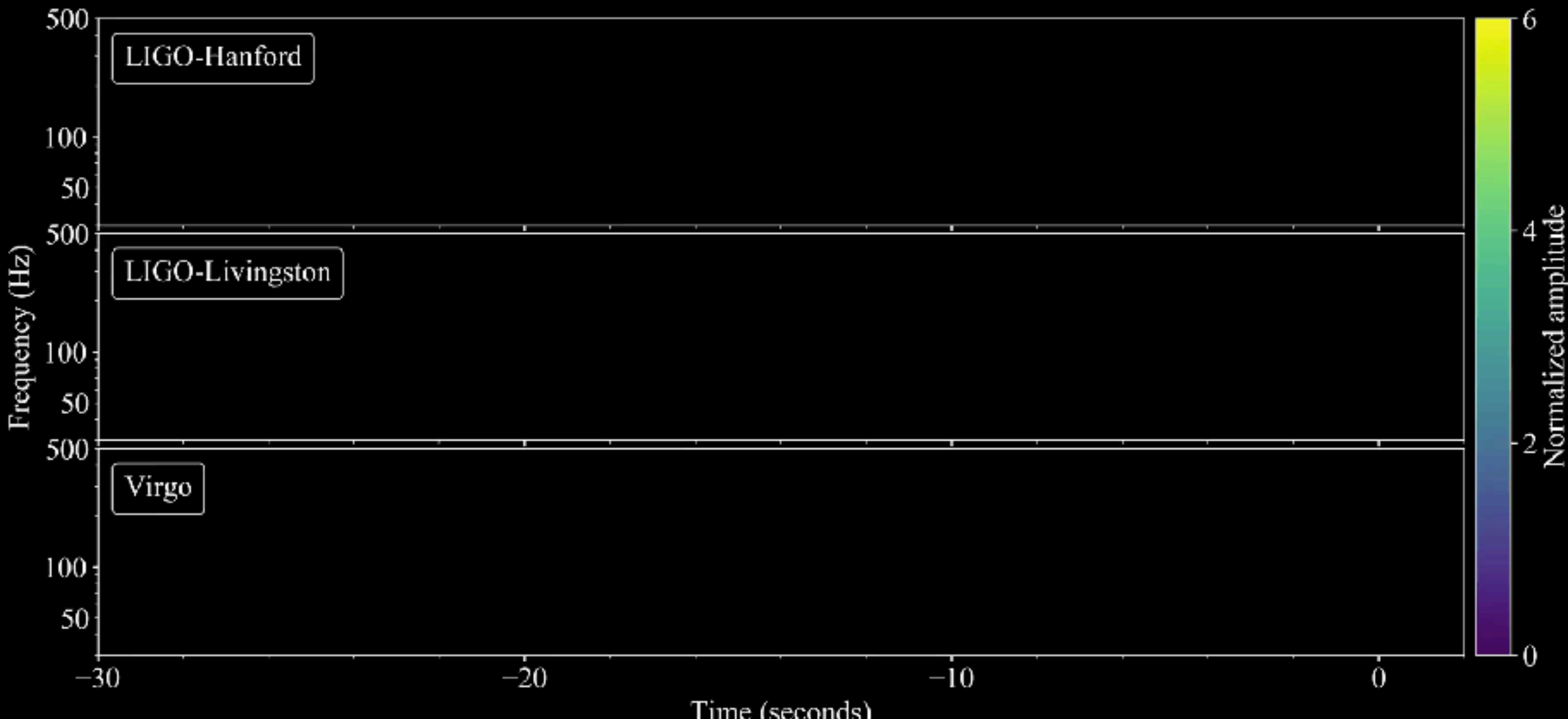
M=12,7Msun
D=340Mpc
GW170608

M=31,25Msun
D=540Mpc
GW170814

Teresa Ramirez/CSUF/SXS

August 17, 2017 5:41:04AM PDT

Gravitational waves from a neutron-star merger



LIGO/Virgo data visualization and sound: Lovelace, Brown, Macleod, McIver, Nitz

August 17, 2017   5:41:04AM PDT

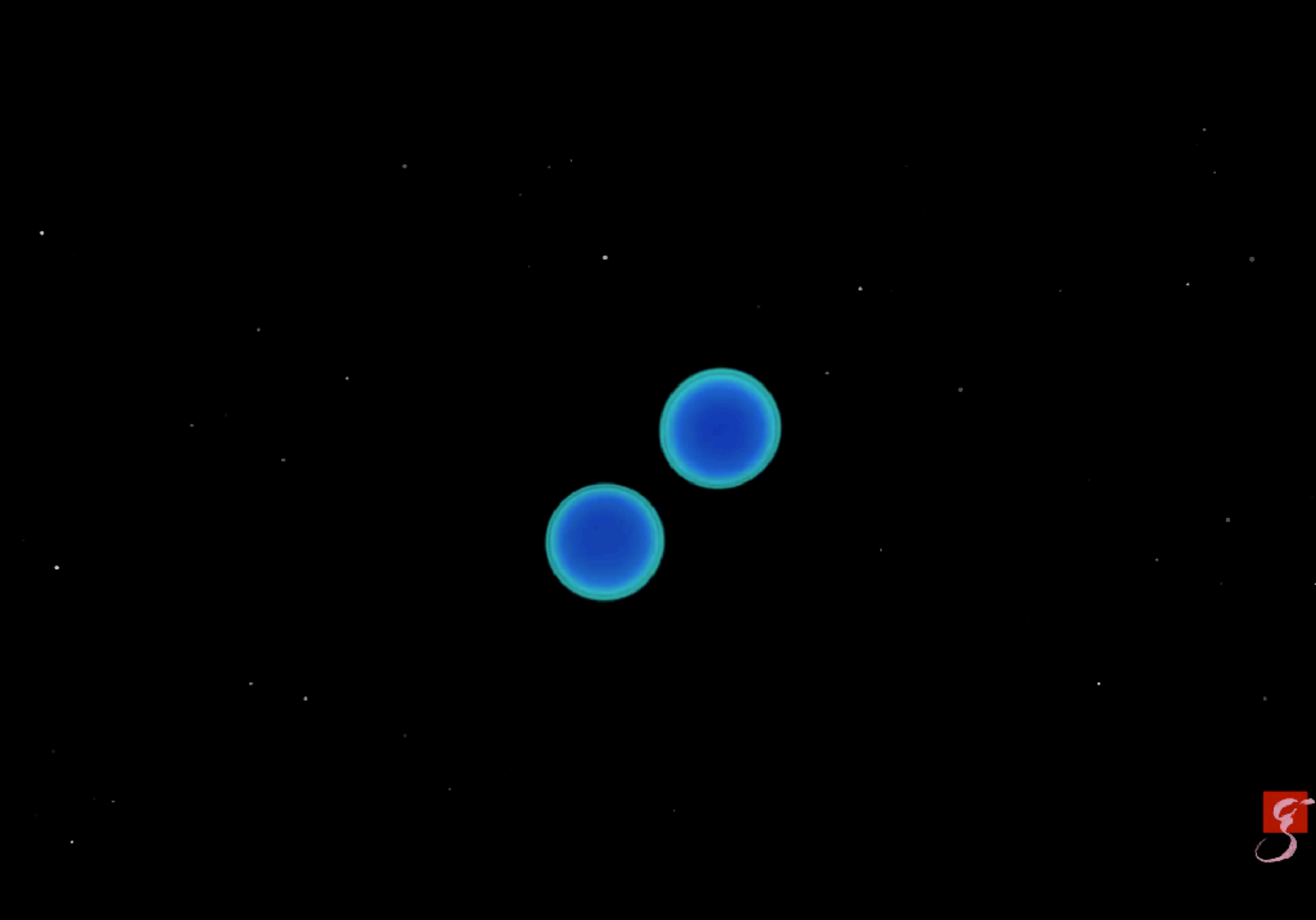
Gravitational waves from a neutron-star merger

The LIGO Scientific Collaboration and the Virgo Collaboration

Visualization created for the LIGO Scientific Collaboration and the Virgo Collaboration by
Geoffrey Lovelace, Duncan Brown, Duncan Macleod,
Jessica McIver, and Alex Nitz

Physical Review Letters ***119****, 161101 (2017)*
doi:10.1103/PhysRevLett.119.161101

LIGO/Virgo data visualization and sound: Lovelace, Brown, Macleod, McIver, Nitz



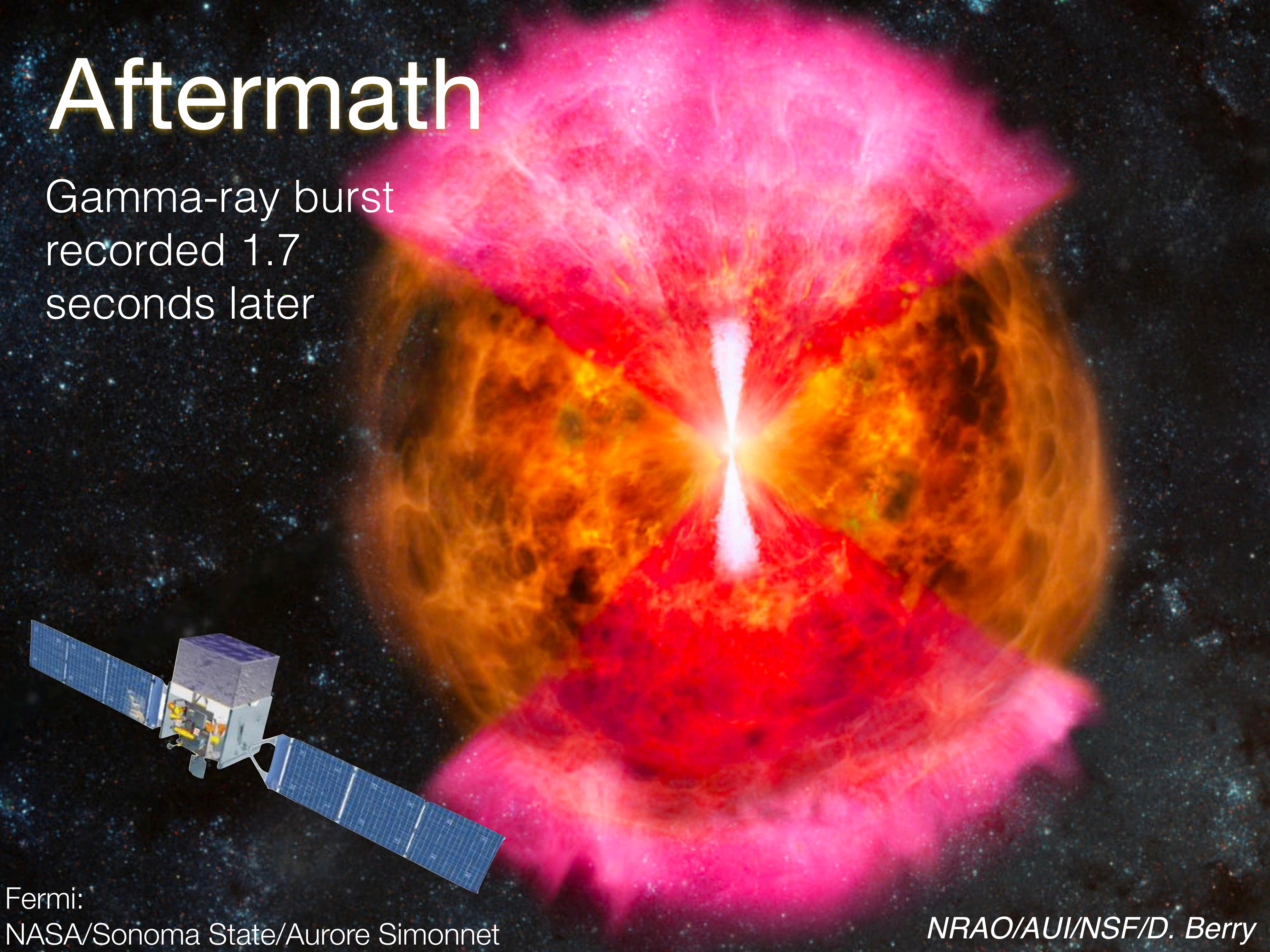
Neutron-star merger simulation: T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (AEI)

BAM collaboration

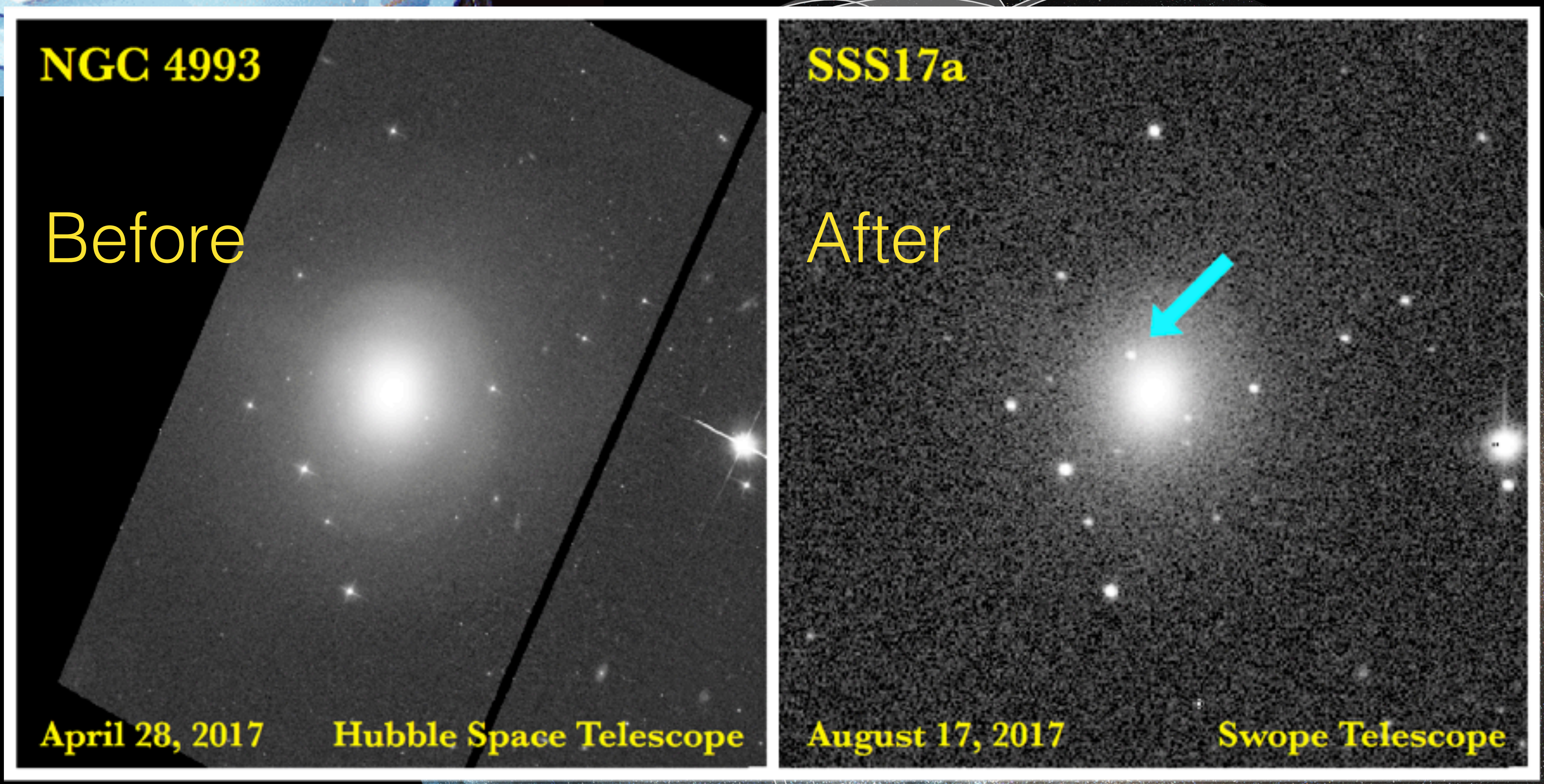
Computational Relativity

Florida Atlantic University
Friedrich Schiller University Jena
Istituto Nazionale di Fisica Nucleare
Max Planck Institute for Gravitational Physics
Università di Parma
Universidade Federal do ABC

We gratefully acknowledge support by:
DFG, ERC, FAPESP, INFN, Max Planck Society, MIUR, NSF
GSC, ISCRA, LRZ, NIC, PRACE, XSEDE


Aftermath
Gamma-ray burst recorded 1.7 seconds later
Fermi:
NASA/Sonoma State/Aurore Simonnet
NRAO/AUI/NSF/D. Berry

A Flash of Light



LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

ESO/N.R. Tanvir, A.J. Levan, VIN-ROUGE collaboration

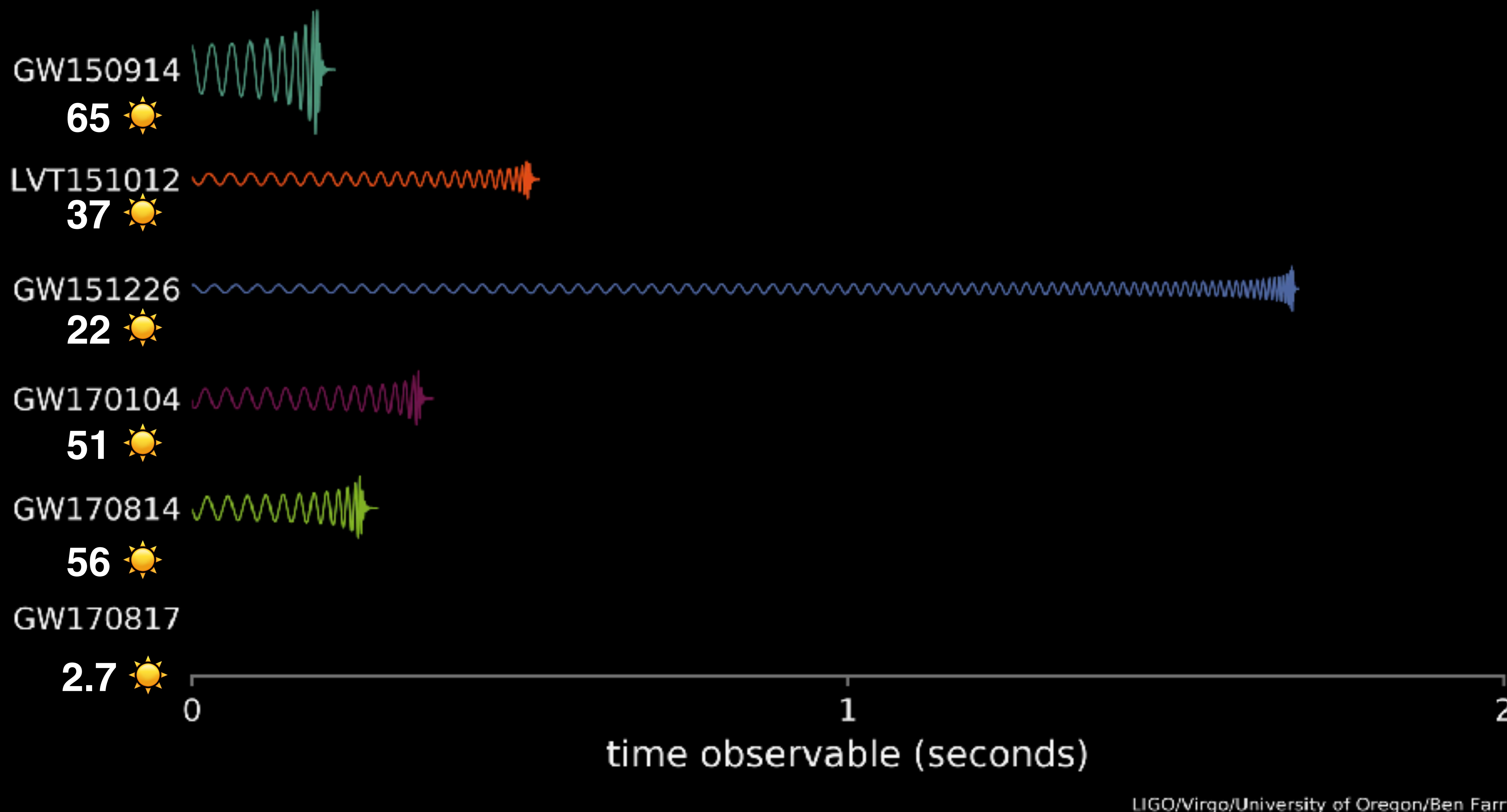
The Golden Binary

- First joint gravitational-wave and light-wave observation
  - NGC 4993, 130 million light years away
- Mystery solved: neutron star mergers make gamma ray bursts
- Neutron star mergers produce heavy elements in our universe
- Measure that light and gravity travel at the same speed
- A new way to measure the Universe’s expansion
- New limits on properties of matter in its densest state

Where did the elements come from?

A family of compact binary mergers

Starting at the same *frequency*



Sources of gravitational waves

Early Universe:

Inflation, Phase Transitions

Supermassive binary black hole mergers

Compact objects captured by supermassive black holes

Merging compact object binaries

LIGO/ Virgo Sources

10^{-16} (today)

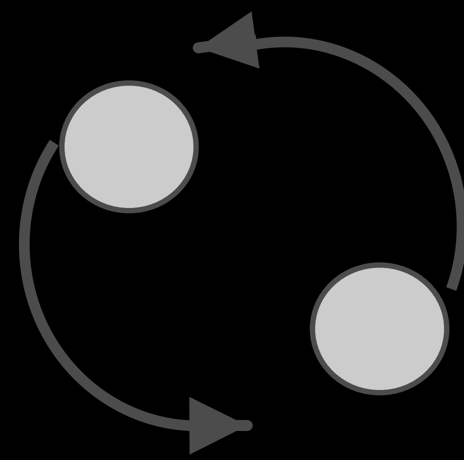
10^{-8} (~cycle/year)

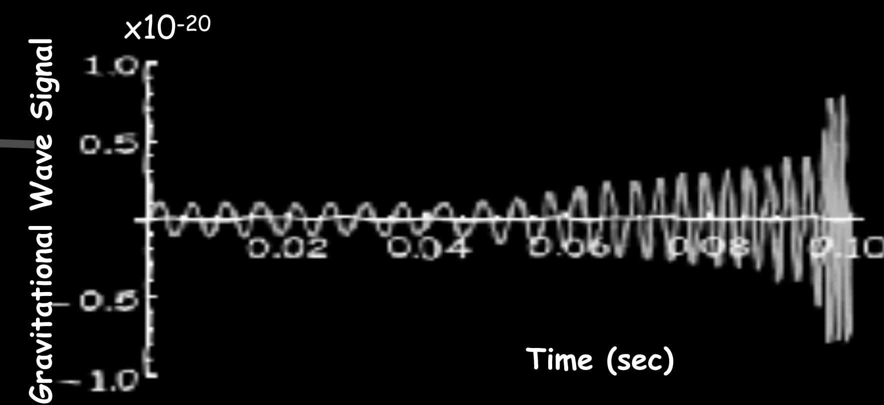
10^{-4} (~cycle/hour)

10^{2} (audio)

GW frequency (Hz)

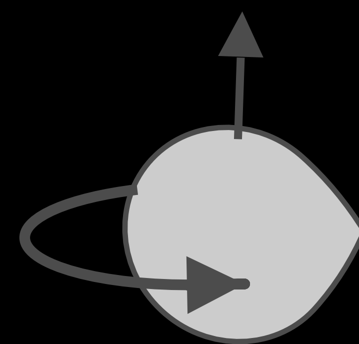
Colliding neutron stars & black holes

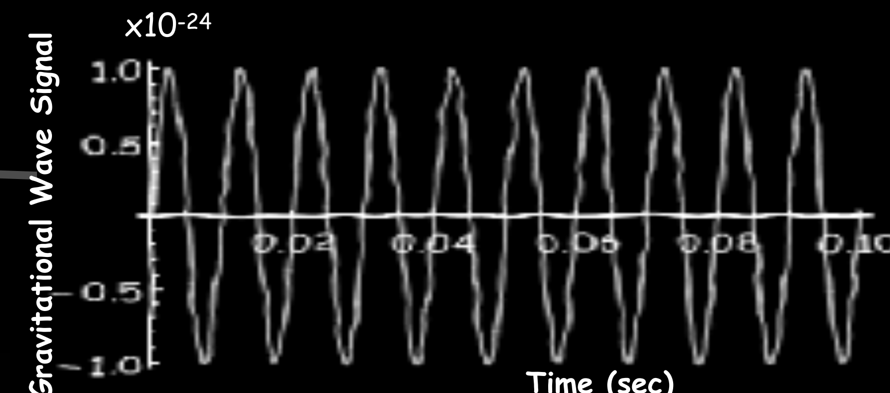




Chirp

Spinning neutron star with a bump



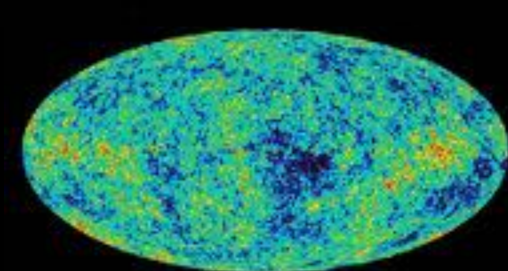


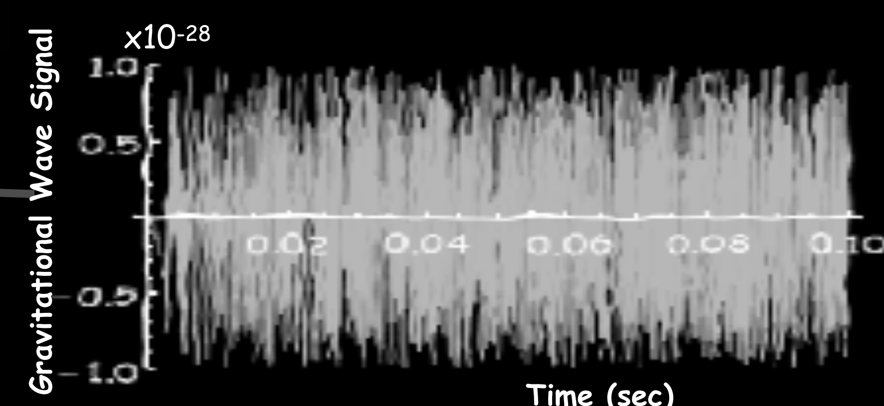
Sine wave

Asymmetrical Supernova

Burst

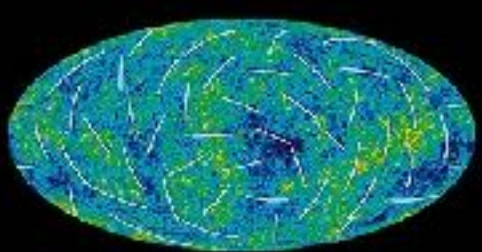
Early Universe gravitational wave background

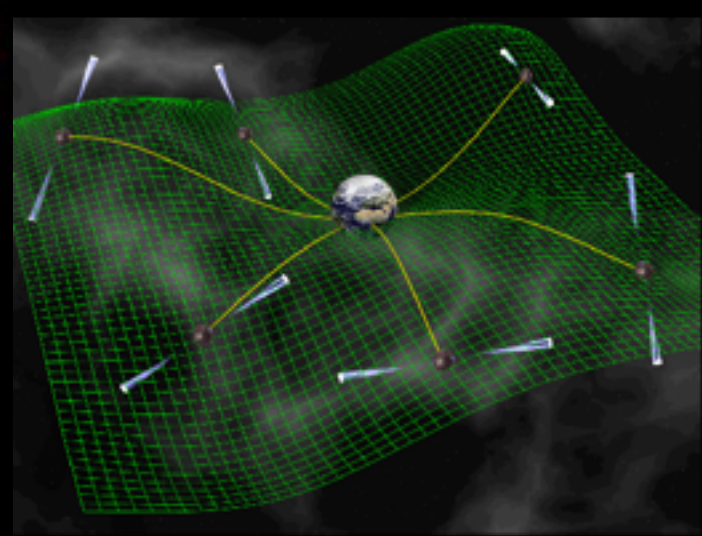


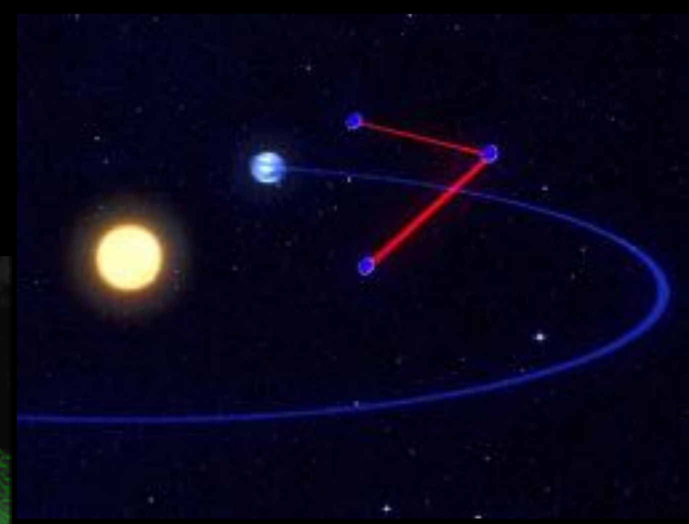


Random noise

Measuring gravitational waves near Earth







Cosmic Microwave Background

Pulsar timing

Space-based interferometer

Ground-based interferometers

10^{-16} (today)

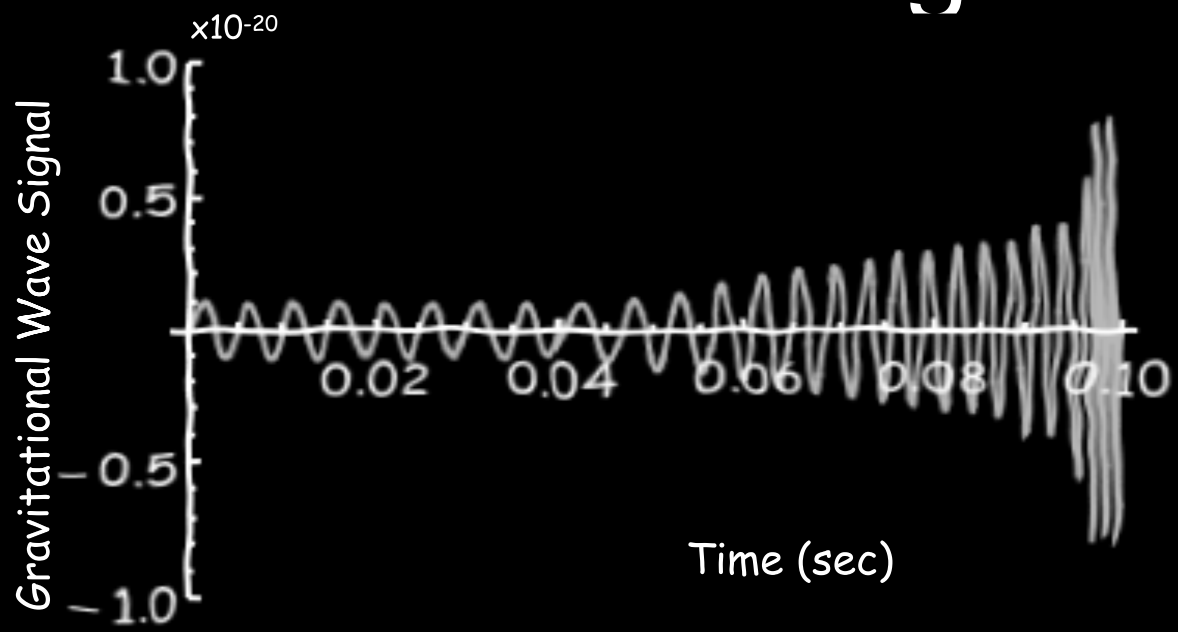
10^{-8} (~cycle/year)

10^{-4} (~cycle/hour)

10^{2} (audio)

GW frequency (Hz)

LIGO measures the following waveform:



What is the most likely source?

A. A nearby red giant going supernova
B. The hot early universe
C. A non-spherical pulsar
D. A neutron star and a black hole spiraling into each other
E. None of the above

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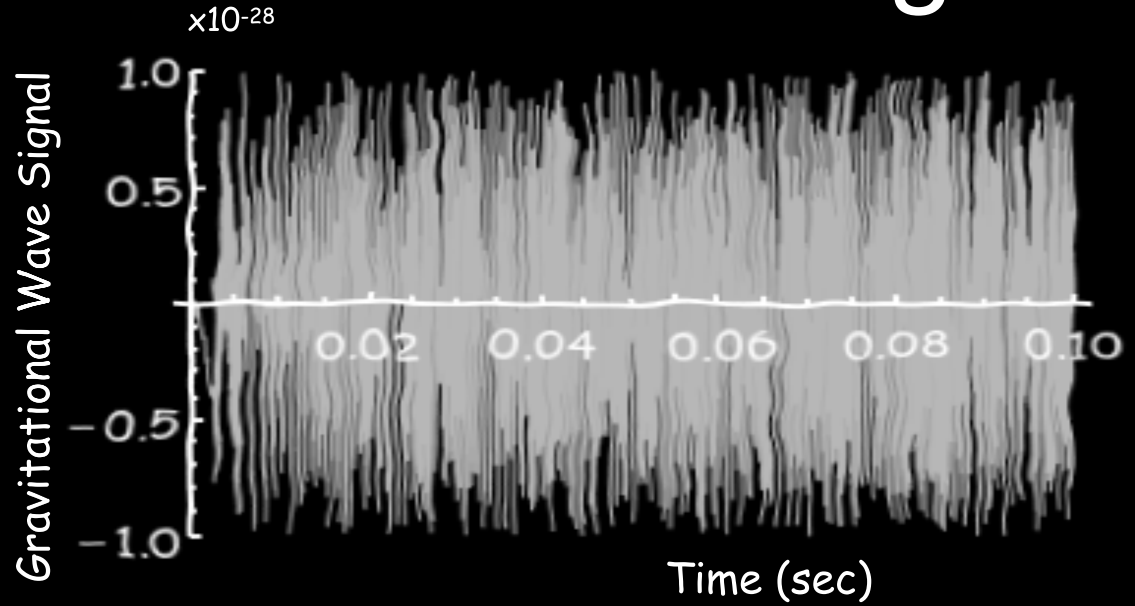

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