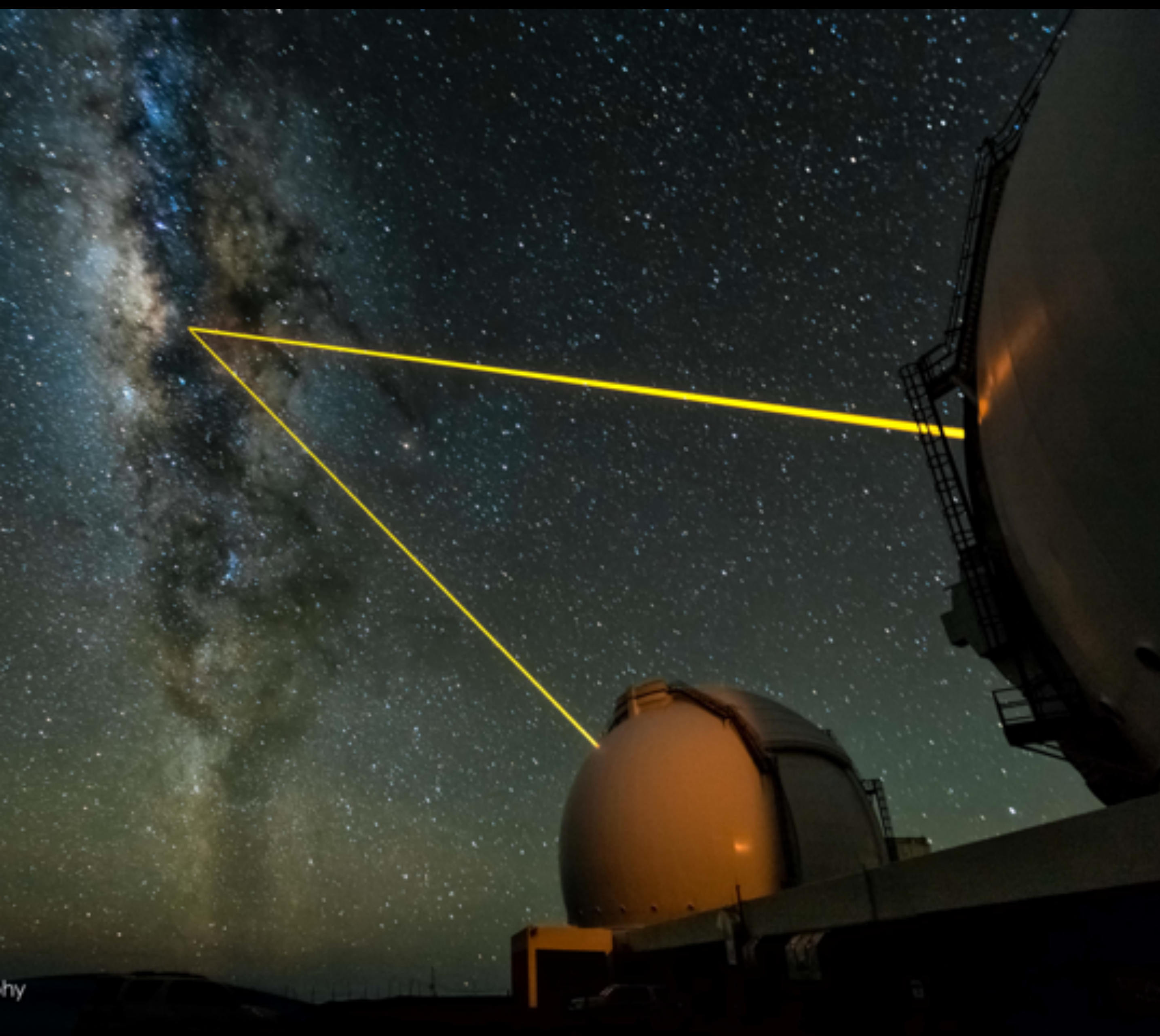
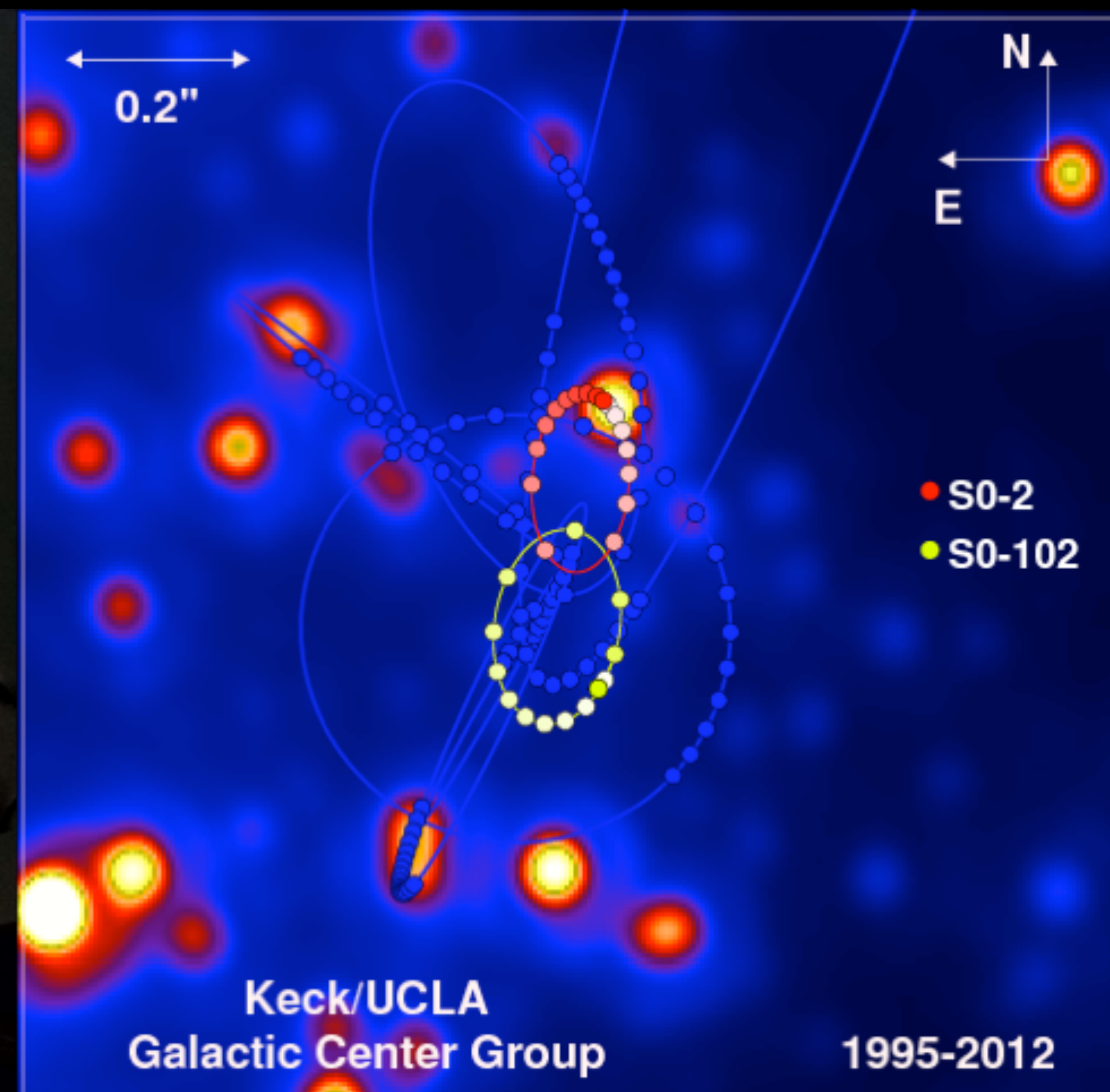
Welcome back to Introduction to Astronomy





Prof Joshua Smith and Ms. Gabriela Serna

Assignments

- Practice exam IV handed out next class
- Ranked study: Practice exam, past exams, past practice exams, lecture tutorials, clicker questions, homework, reading
- Final Exam:
  - Thursday, May 15, 2014 from 2:30pm-4:20pm (same room as class)

Class Evaluations

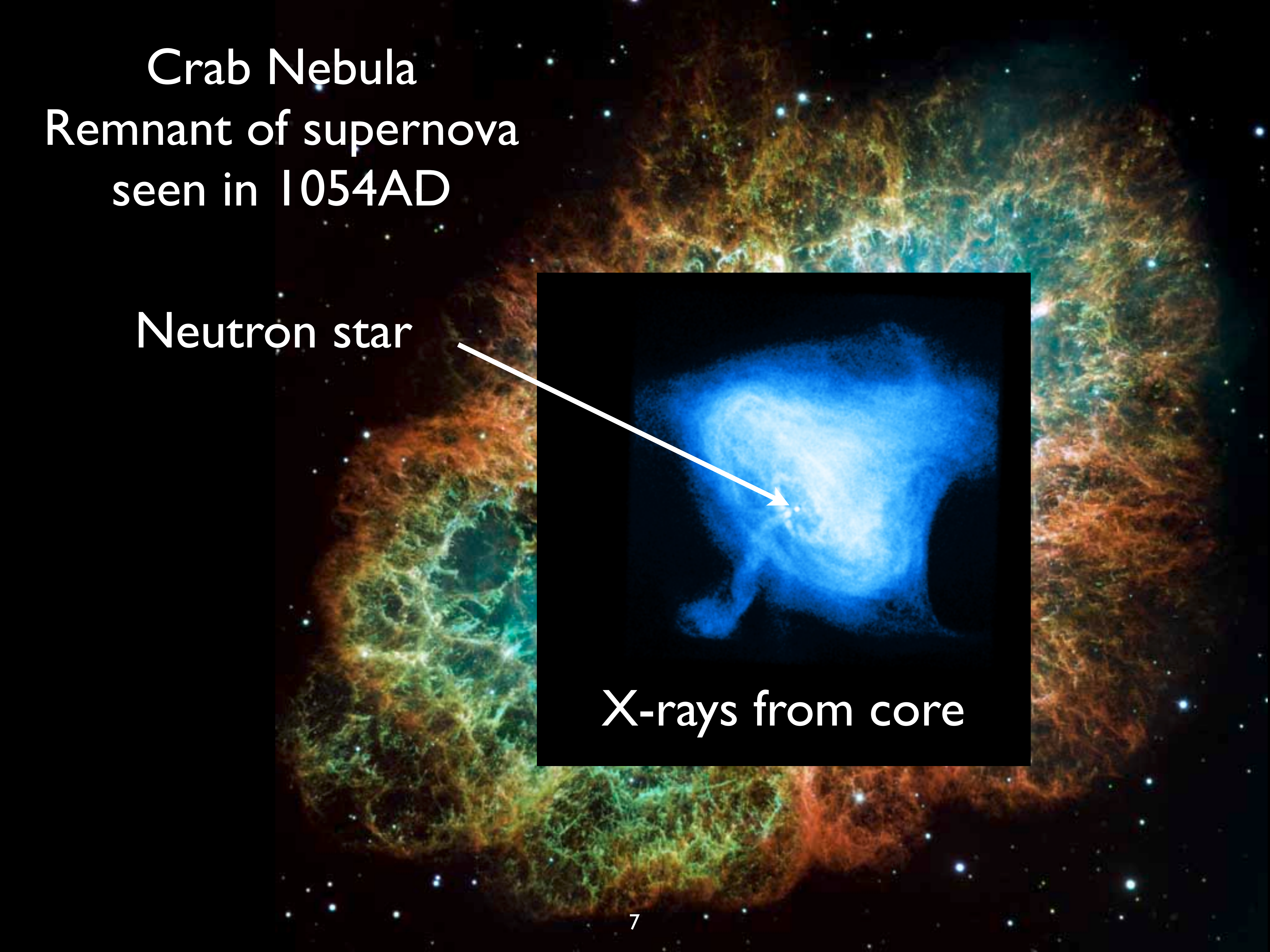
Neutron Stars, Black Holes, and Gravitational Waves

What's left after a core-collapse supernova?

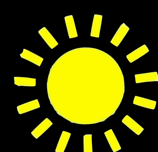
BBC

Cambridge University Lucky Imaging Group

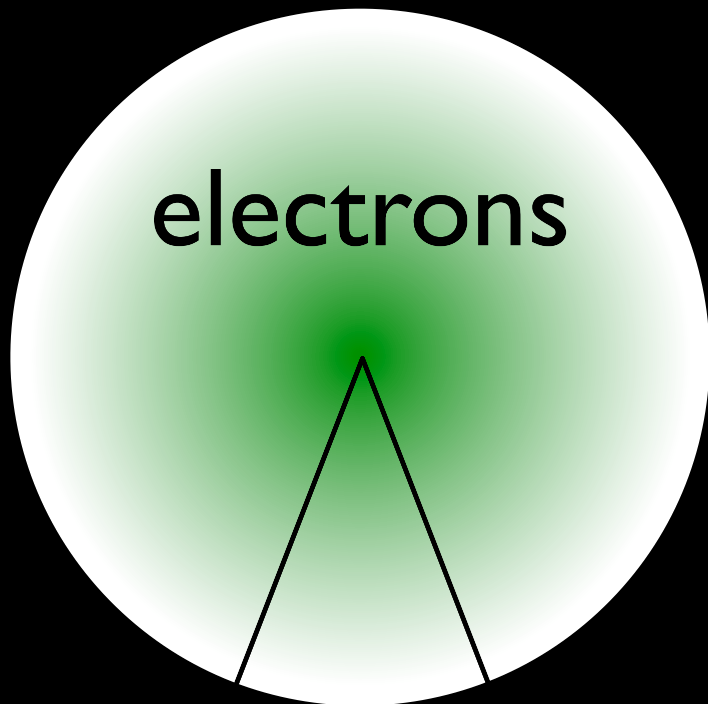
- 1967: Jocelyn Bell Burnell detects LGMs in the Crab Nebula!
- Flashes 30 times every second
- Then saw one from totally different part of sky
- Later discovered these are neutron stars

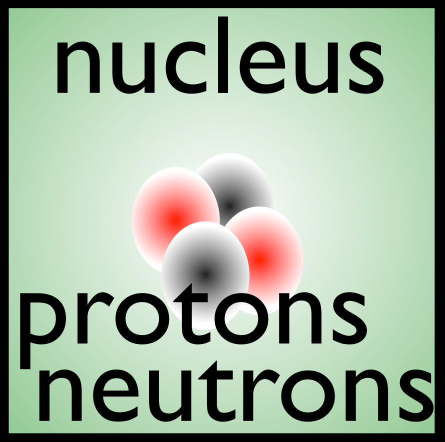

Crab Nebula
Remnant of supernova
seen in 1054AD
Neutron star
X-rays from core

Neutron Stars

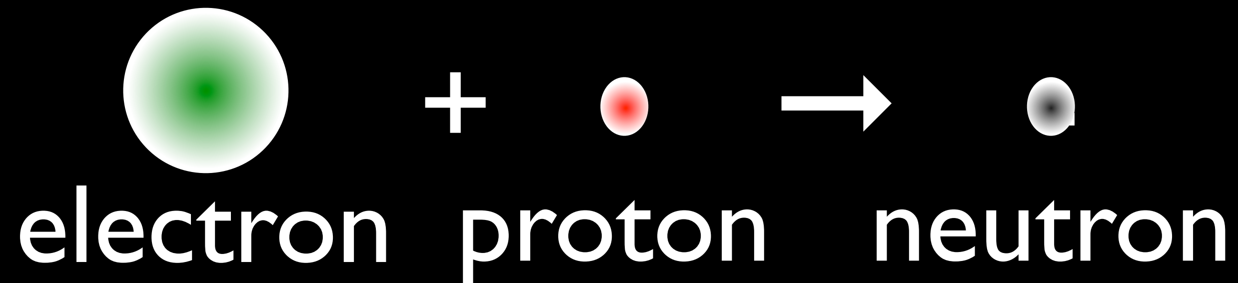
- Hot, dense "ash" of dead stars
- Mass:
  1 to 2 
- like a giant atomic nucleus

Neutron Stars: Matter's last stand against gravity

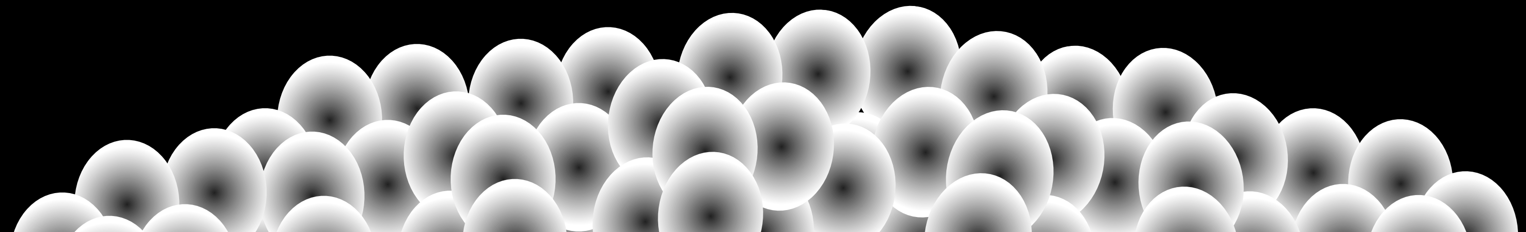




Charged particles combine into neutrons:



Quantum uncertainty principle and exclusion principle hold the star up against gravity!



Quantum pressure can only support up to 2 solar masses.

If the core of a massive star is larger than that it cannot be held up by quantum mechanics, and becomes a Black Hole!

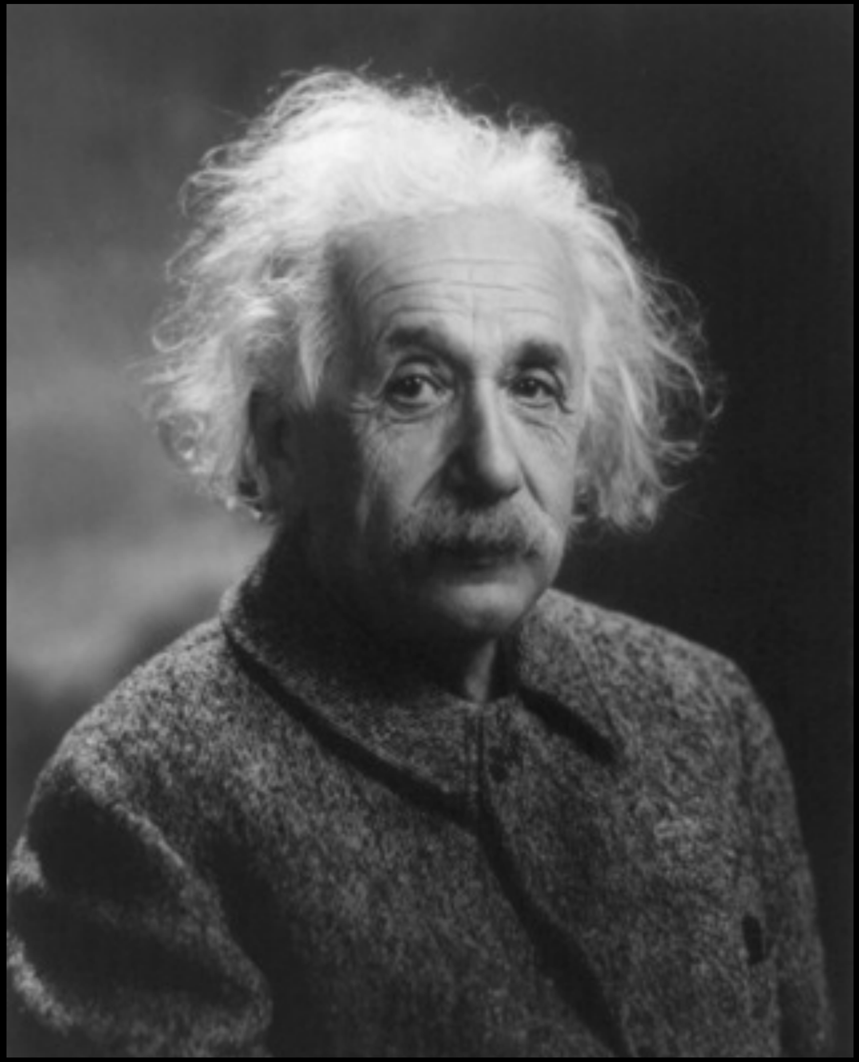
Black Holes

Albert Einstein, 1905

- Einstein discovers an essential law of the universe in his theory of special relativity:
  - No information can be transmitted faster than the speed of light
  - $c = 3.0 \times 10^8$ m/s
  - c = 186,000 miles per second

Albert Einstein, 1915

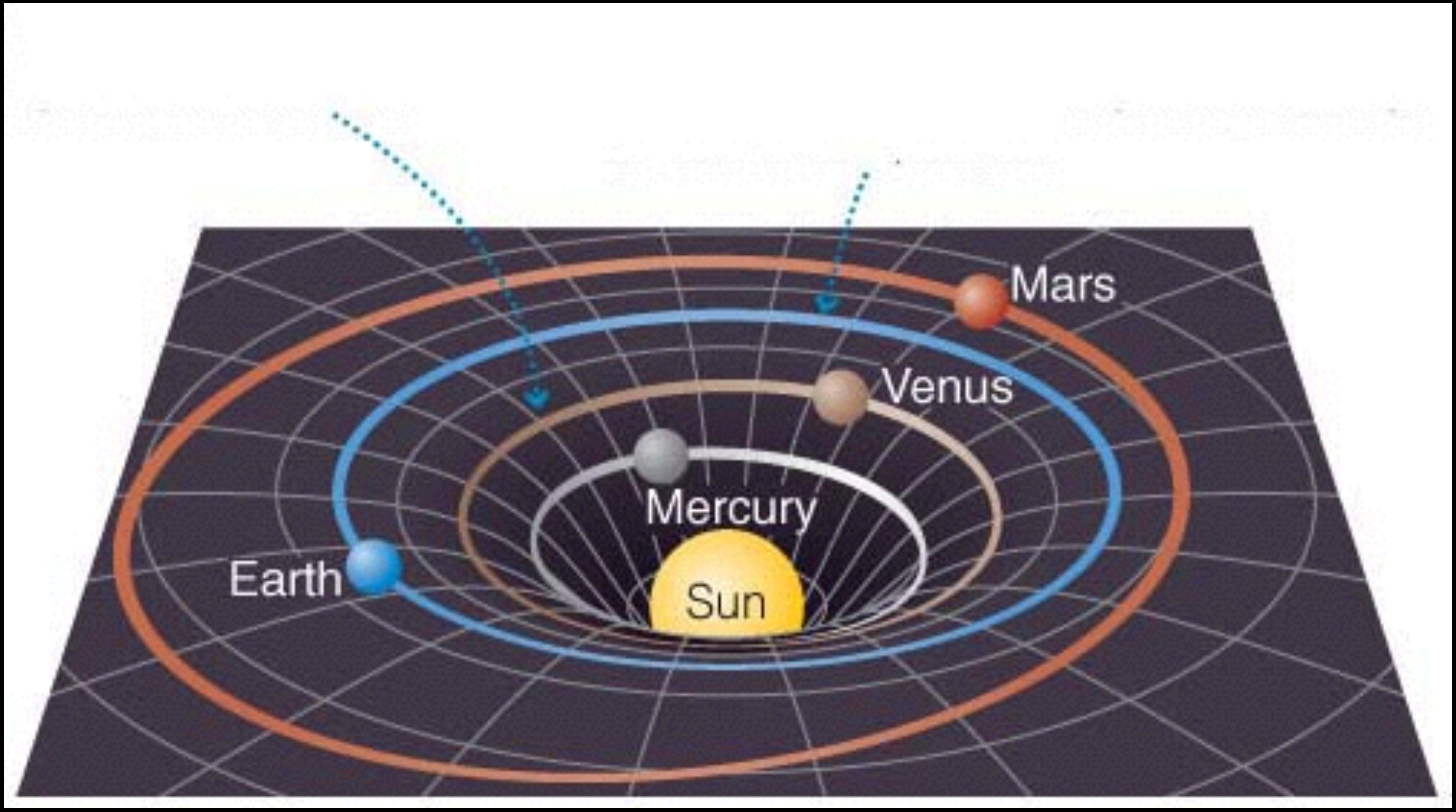
- The Theory of General Relativity is Einstein's theory of gravity
- It's more accurate than Newton's view of gravity as a force, $F=GMm/r^2$
  - especially for very strong gravity, and very high speeds
- Its key idea is that gravity is an effect of the curvature of space and time
- It also makes some strange predictions...

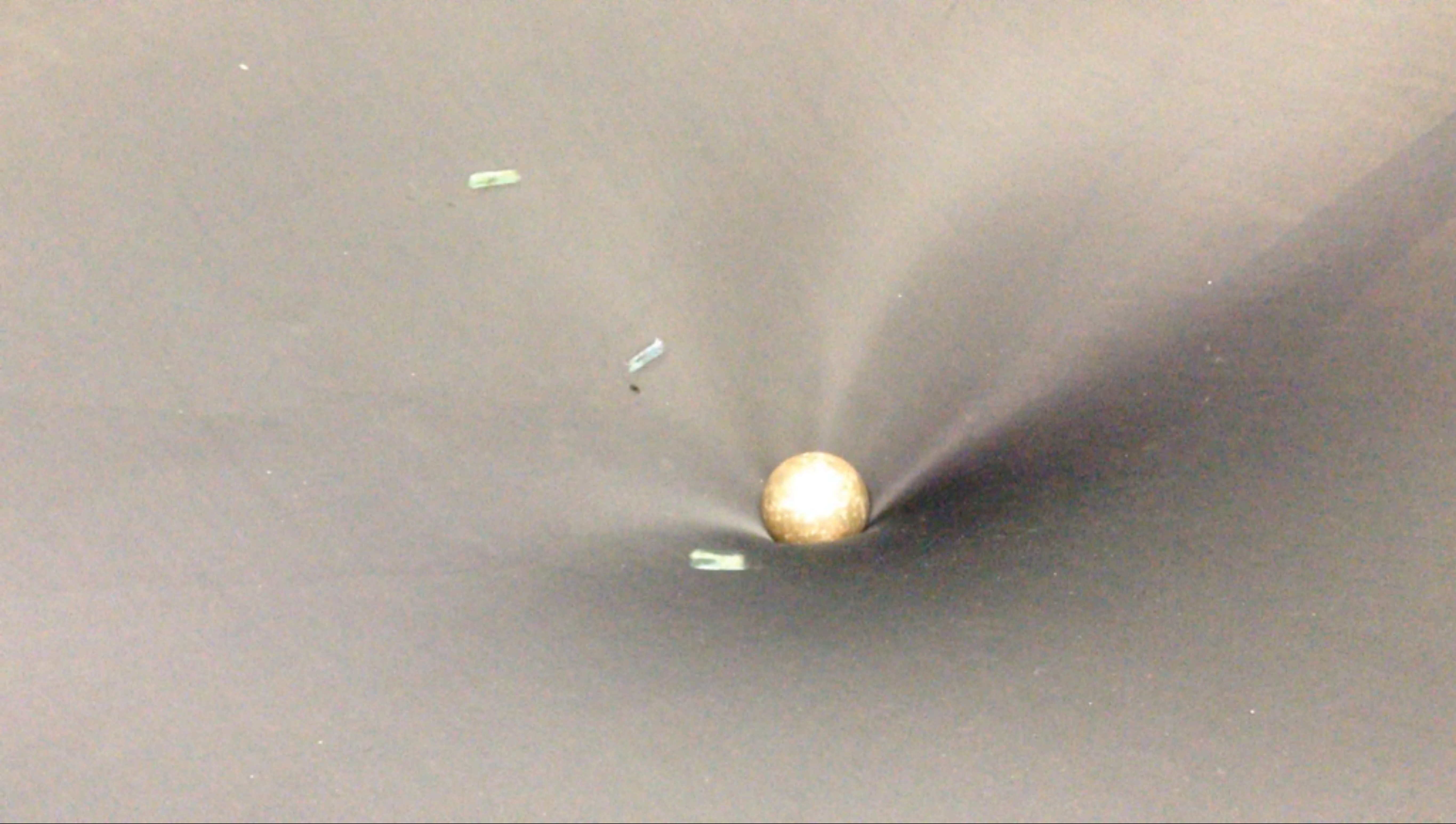


Credit: The Library of Congress

Curved Space-Time

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

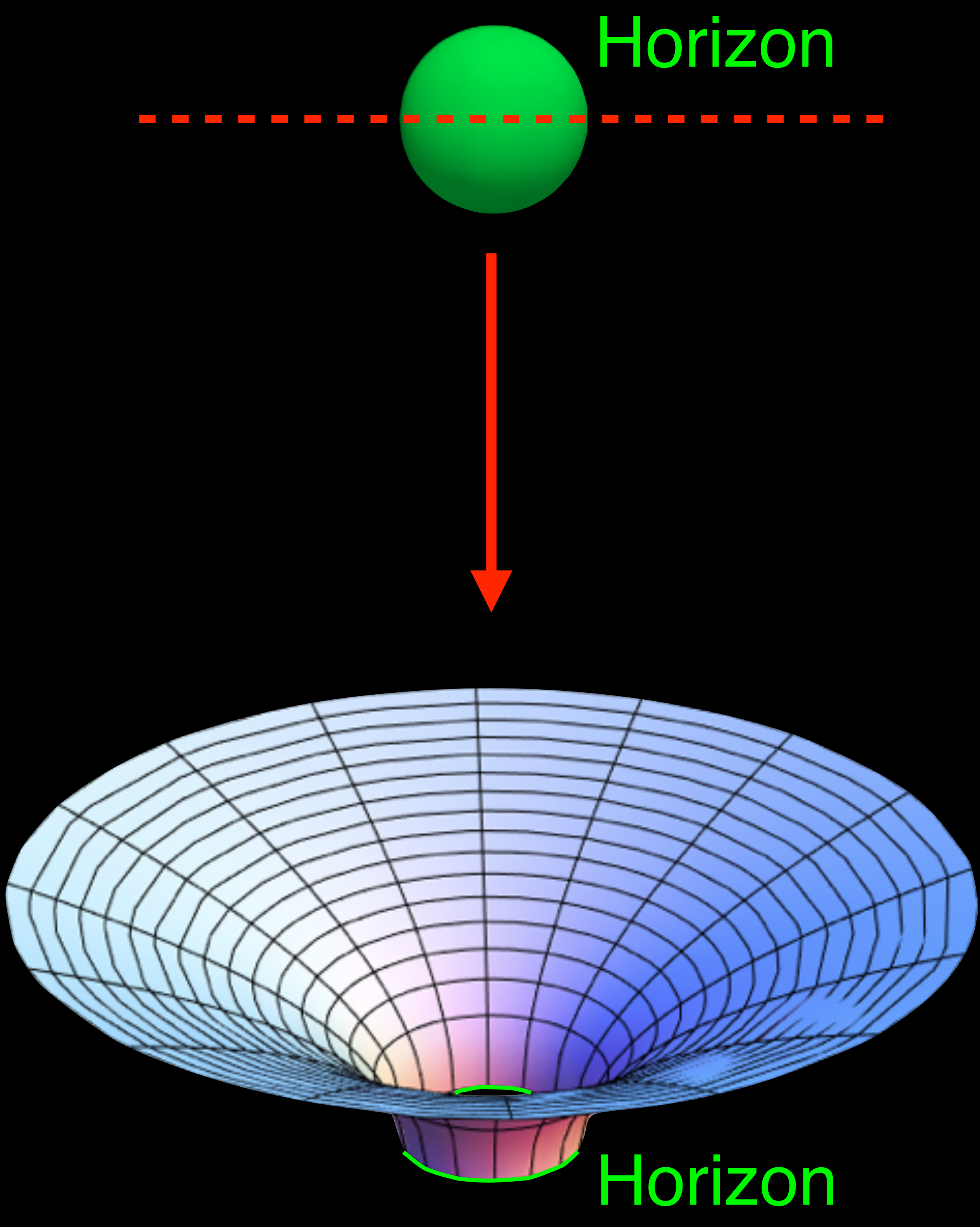




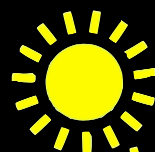
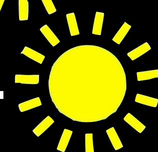
Larry Kiwano, Astrocamp, November 7, 2013

What are black holes?

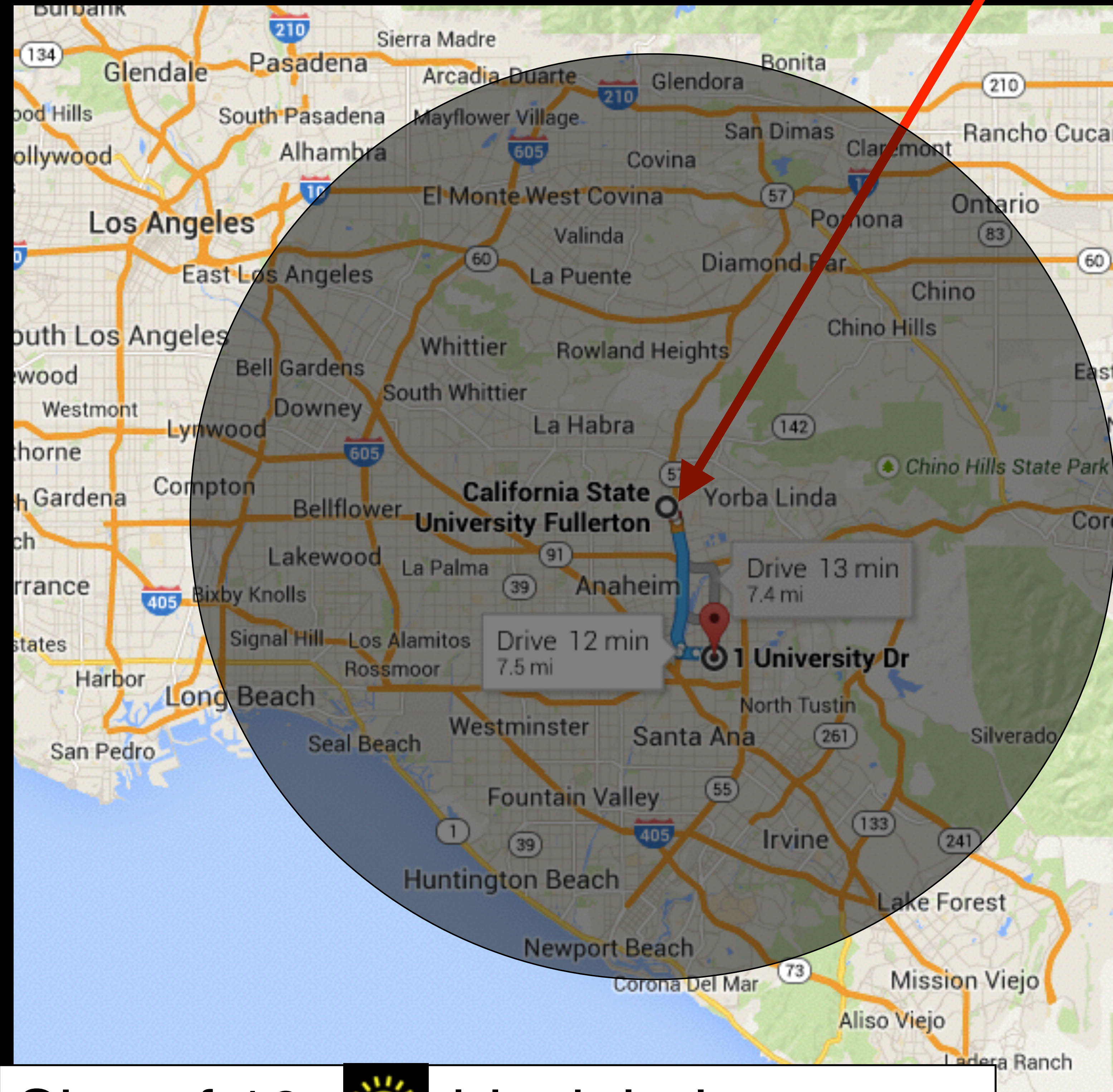
- Gravity so strong...
  - Nothing (even light) can escape from inside hole's horizon (surface)
  - Singularity inside horizon: infinitely strong gravity
- Formed when the most massive stars die



How big are black holes?

- Mass: huge!
  - Two kinds
  - 3 to 30 
  - Millions+ 
- Radius: small!

Size of earth-mass black hole



Size of 10-  black hole

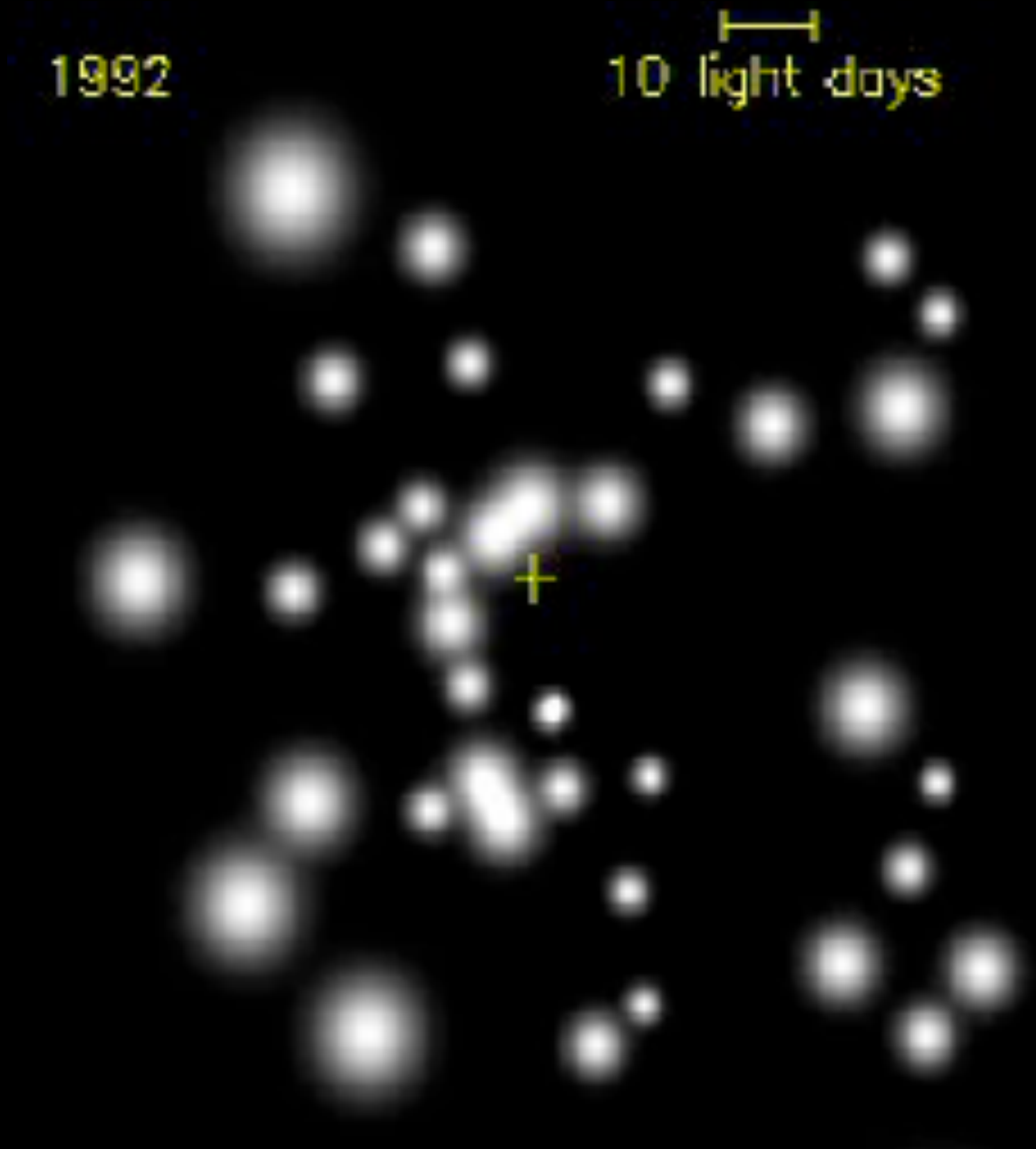
Image courtesy Google maps

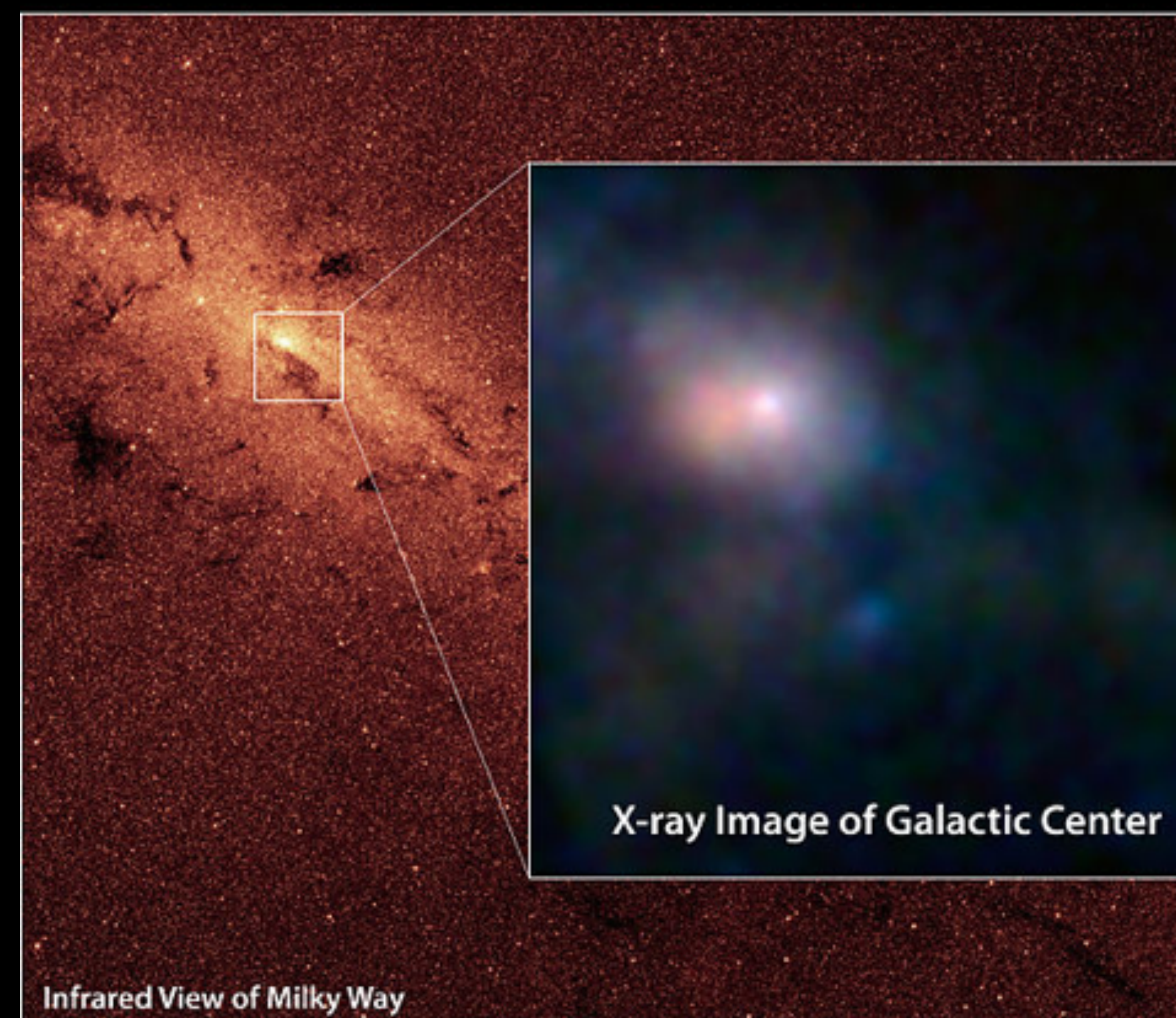
If black holes don't give off any light, how do we find them?

By observing their gravitational effects on other objects:

- Orbit of stars
- Gravitational lensing
- Heated matter falling into a black hole

Supermassive black hole (SGRa*) at the center of our galaxy!

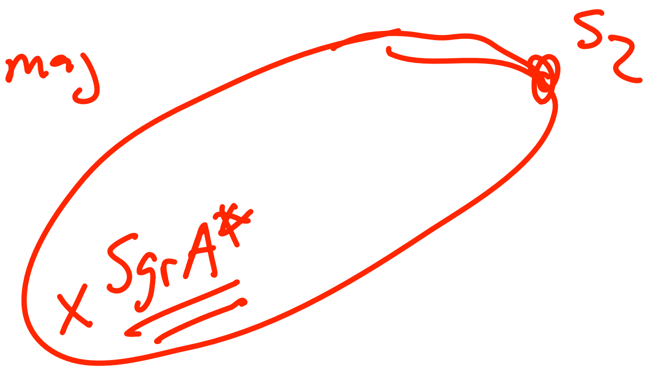




S2 orbits SgrA* with a period of 15.2y and with a semi-major axis of 1.4×10^{14} m. What is the mass of Sagittarius A*? How does it compare to the mass of the sun (1.99×10^{30} kg)?

$$T^2 = \frac{4\pi^2}{GM} r^3$$

(r: semi-maj)



$$T = 15.2\,y \cdot \frac{365\,d}{1\,y} \cdot \frac{24\,h}{1\,d} \cdot \frac{3600\,s}{1\,h} = 4.79 \cdot 10^{8}\,s$$

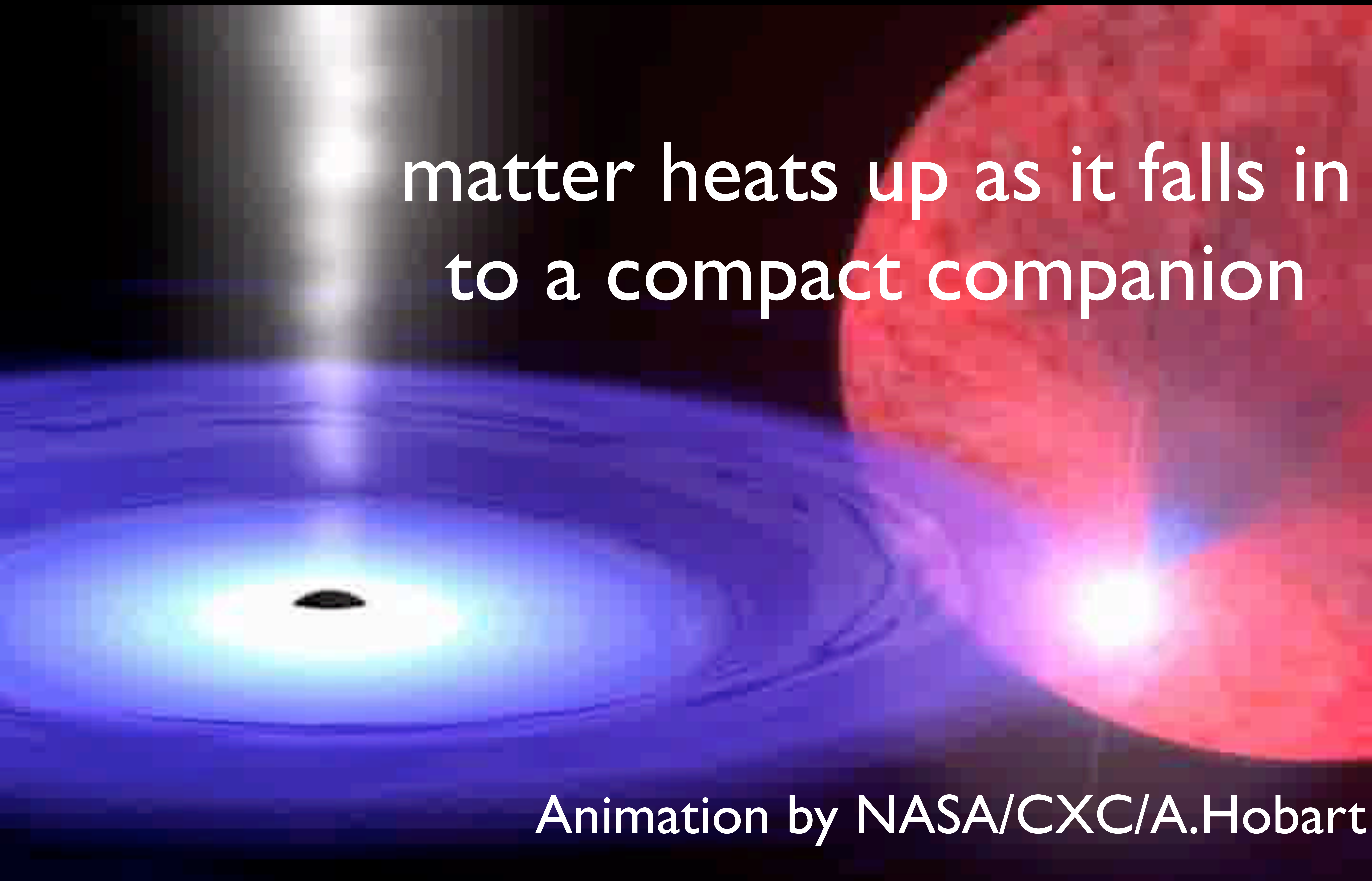
$$M = \frac{4\pi^2 r^3}{GT^2} = \frac{4\pi^2 (1.4 \cdot 10^{14}\,m)^3}{(6.67 \cdot 10^{-11}\,Nm^2/kg^2)(4.79 \cdot 10^{8}\,s)^2} = 7.078 \cdot 10^{36}\,kg$$

$$M_\odot = 1.99 \cdot 10^{30}\,kg$$

$$\frac{M_{SgrA^*}}{M_\odot} = \frac{7.078 \cdot 10^{36}}{1.99 \cdot 10^{30}} = 3.56 \cdot 10^{6}\,M_\odot$$

Example Physics 225 question!

Black holes also seen in “X-ray binaries”



20 billion solar mass black holes discovered!

Los Angeles Times | SCIENCE

LOCAL U.S. WORLD BUSINESS SPORTS ENTERTAINMENT HEALTH LIVING TRAVEL OPIN

BREAKING VIDEO CRIME OBITUARIES COMMUNITY WEATHER TRAFFIC CROSSWORDS

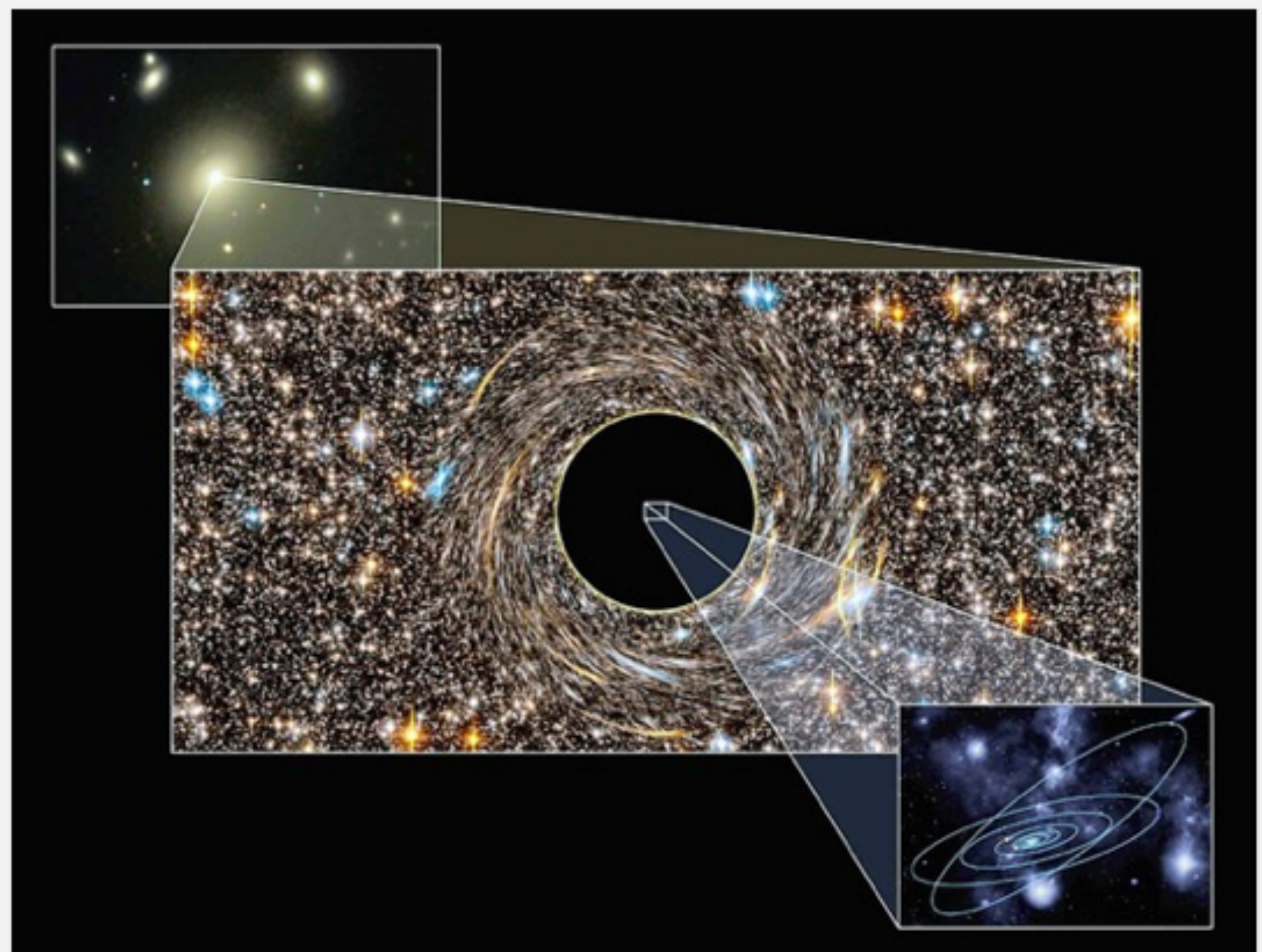
By Amina Khan, Los Angeles Times

December 5, 2011 | 8:30 p.m.

Astrophysicists find biggest black holes yet

Two monsters, one of which may be about 20 billion times the mass of our sun, could provide important clues to the formation of galaxies.

Comments 34 Share 2841 +1 21 Tweet 116 Recommend 502



A graphic conception of the immense size of a newly discovered black hole, shown in the background. Our solar system,

http://www.latimes.com/news/science/la-sci-black-holes-20111206,0,3092833.story

If a planet is in a circular orbit,1 A.U. away from a neutron star of 1 Solar mass, it will...

A. Orbit once each Earth year, the same as Earth.

B. Orbit much faster than Earth, circling many times in each Earth year.

C. Orbit much slower than Earth, taking many Earth years to complete one cycle

If the Sun was suddenly replaced with a black hole of the same mass, what would happen to Earth?

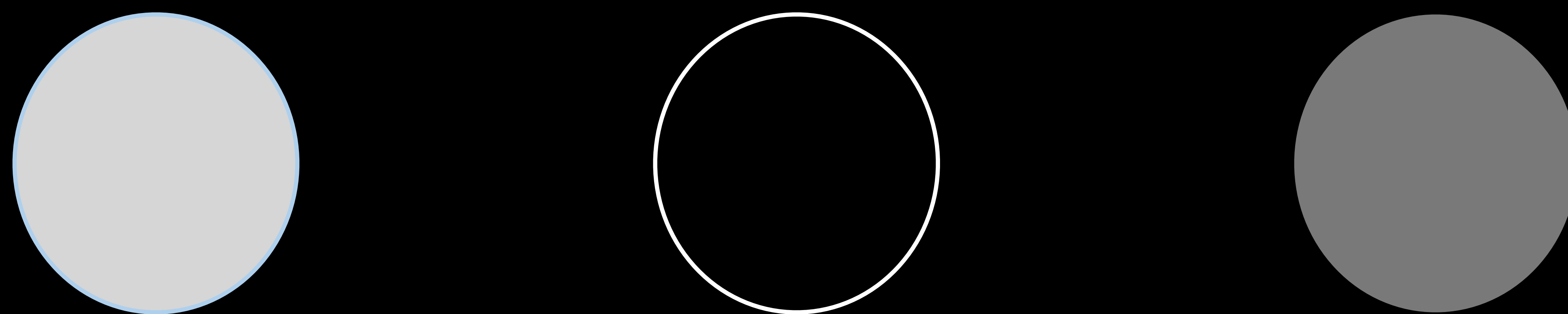
A. It would be ejected from the solar system

B. It would continue in its orbit exactly as before

C. It would spiral into the black hole

D. It would continue to orbit, but the orbit would be much smaller

Assume that the following objects have the same surface area:



Which object would have the largest mass?

A. Neutron Star

B. Black hole

C. Comet

D. All would have the same mass

Gravitational Waves

GW PAC GRAVITATIONAL WAVE Physics and Astronomy Center

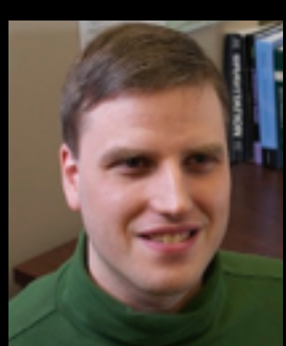
CALIFORNIA STATE UNIVERSITY FULLERTON

Joshua Smith

Gravitational-wave (GW) measurement

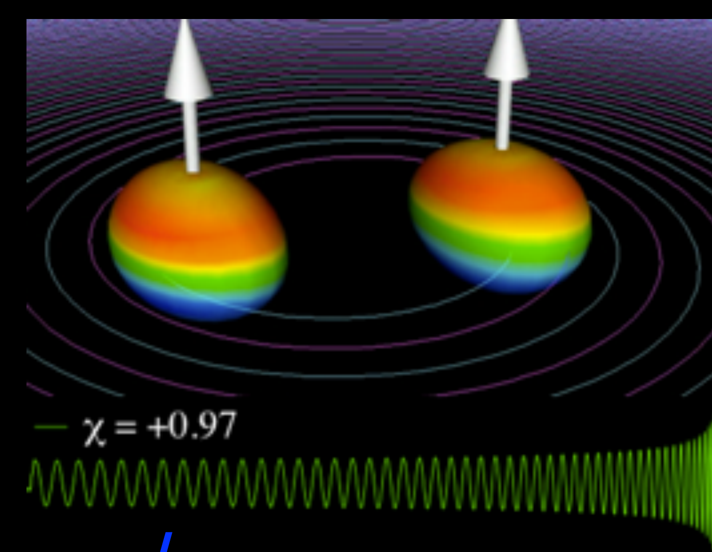
Jocelyn Read

Neutron star astrophysics and GWs



Geoffrey Lovelace

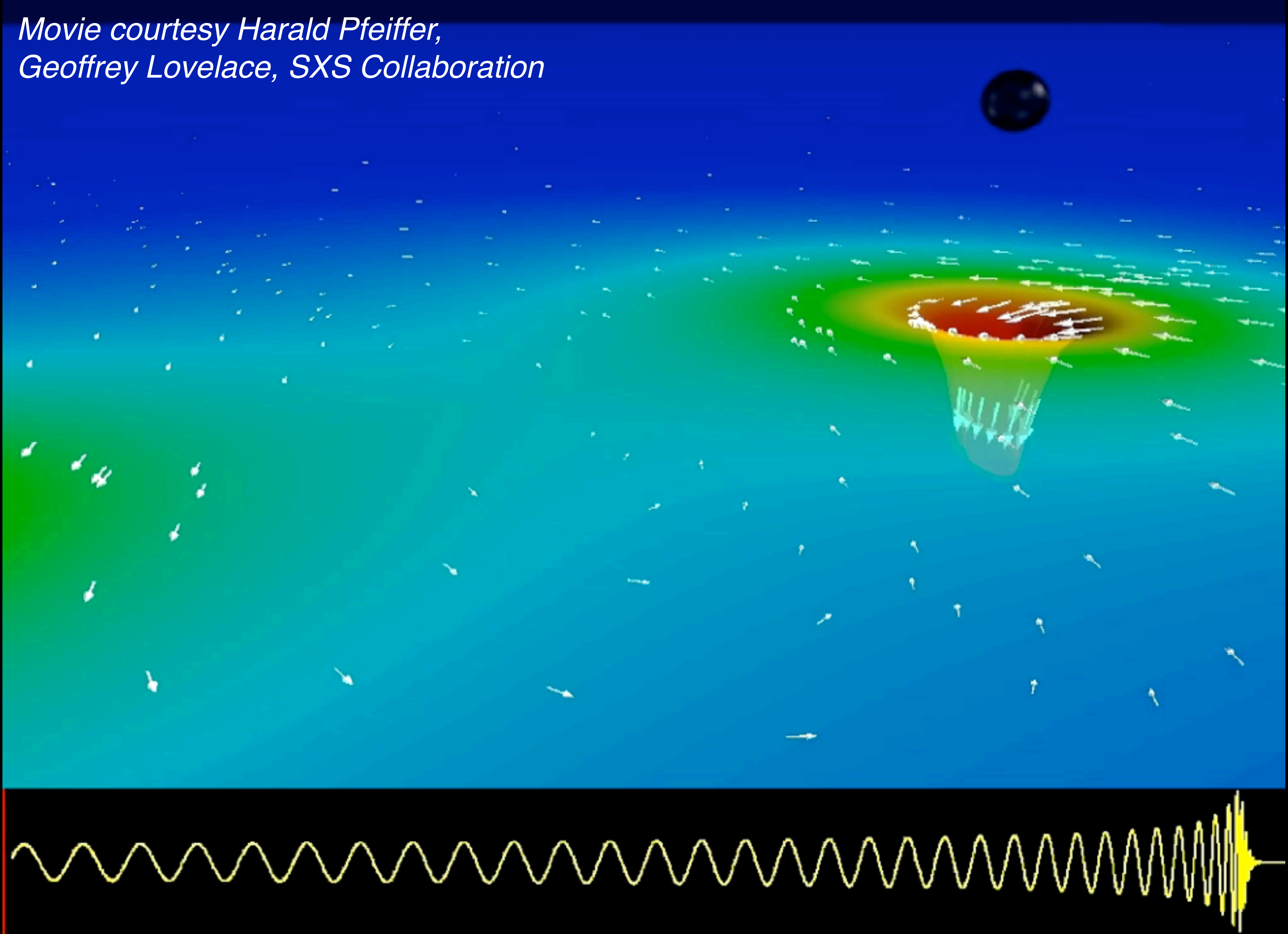
Computational relativist merging black holes & neutron stars



http://physics.fullerton.edu/gwpac/

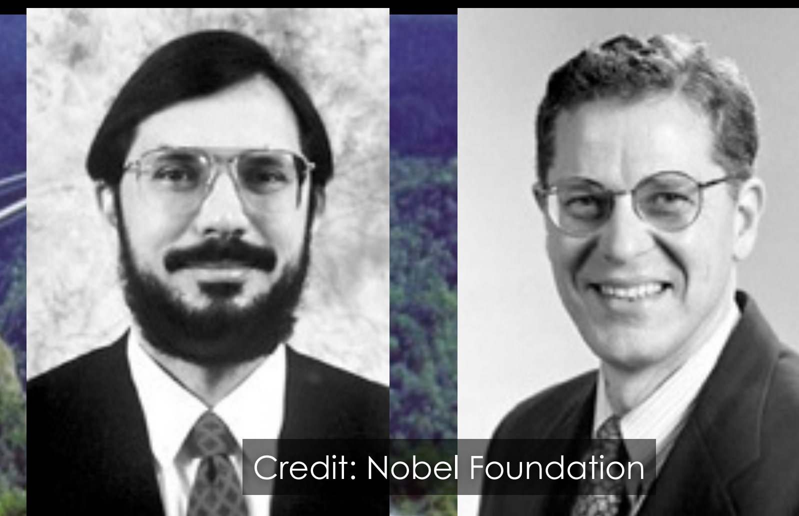
Gravitational waves

- Ripples in space-time that travel at speed of light
- Predicted by Einstein's theory of gravity, General Relativity in 1916
- Generated by co-orbiting objects, spinning asymmetric objects
- Interact weakly with matter - densest systems transparent to gravitational waves
- A new spectrum in which to explore the universe



depth: spacetime curvature, colors: flow of time, arrows: flow of space

How do we know gravitational-waves exist?



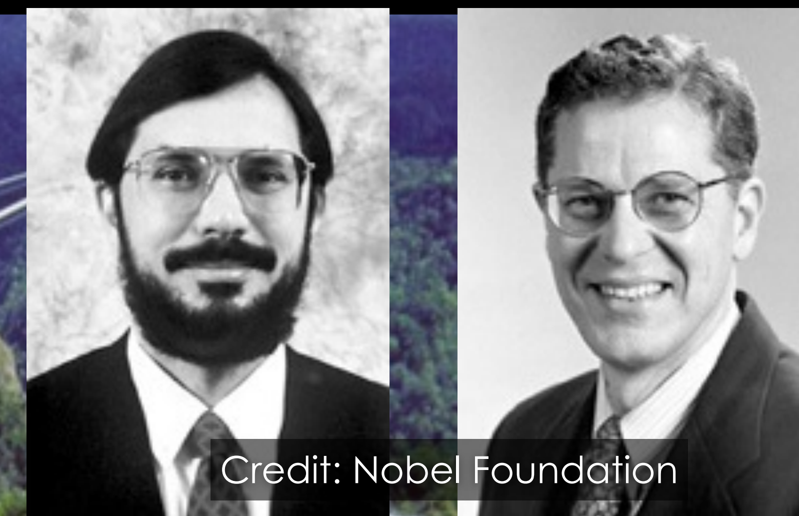
- Visible light is just one part of the electromagnetic spectrum - using observatories like Arecibo we can observe the universe in radio waves

- Russell Hulse and Joe Taylor studied binary system of neutron stars in Arecibo data

Binary neutron star PSR B1913+16

- Two 1.4 $\odot$ neutron stars
- Orbit every 8 hours
- Orbit is 80 microseconds shorter per year
- Stars will collide in 300 million years

How do we know gravitational-waves exist?



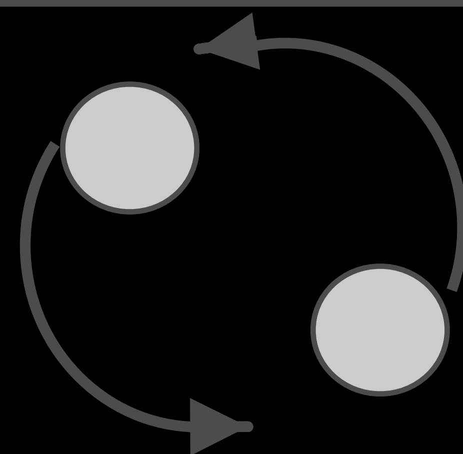
Russell Hulse, Joe Taylor

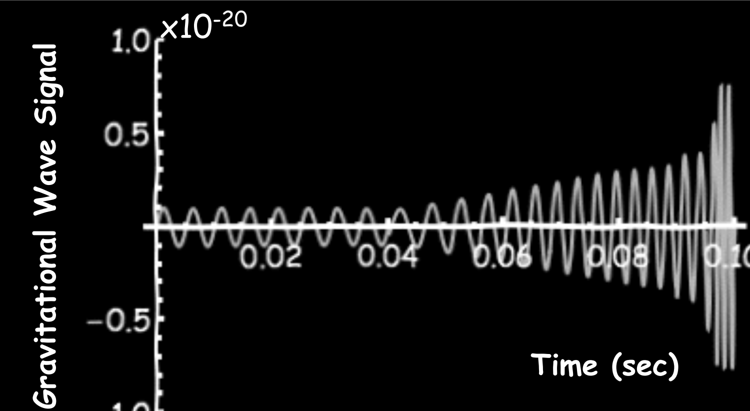
- Observed neutron star binary for decades
- Found that orbit is slowly shrinking
- Agrees precisely with Einstein's predictions
  - Gravitational waves carry away energy
- 1993 Nobel Prize

Gravitational-wave sources

Sources of gravitational waves

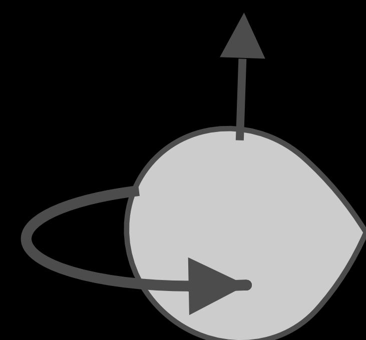
Colliding neutron stars & black holes

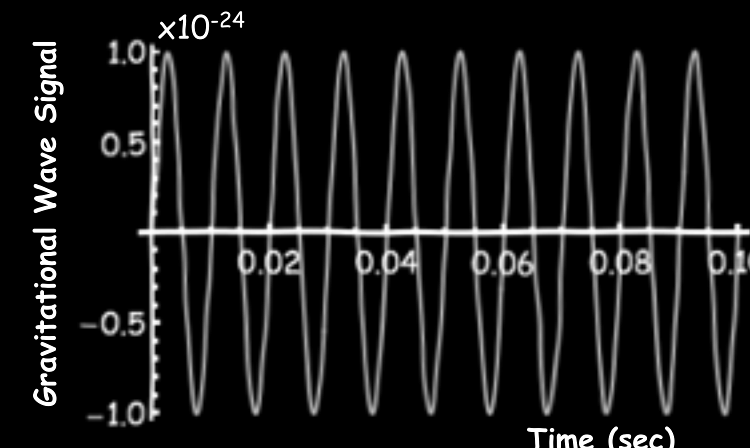




Chirp

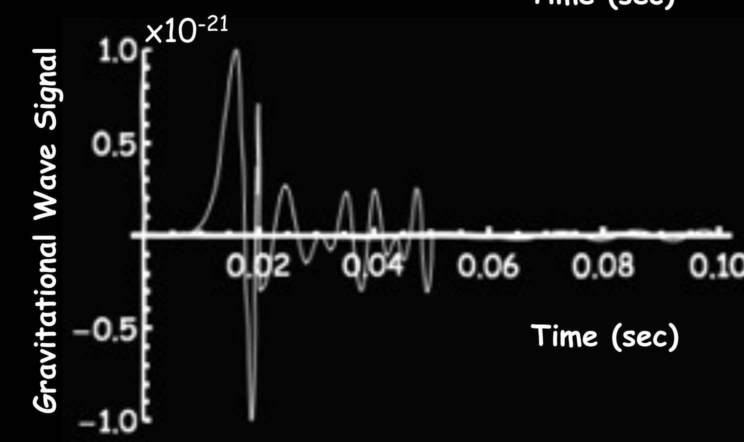
Spinning neutron star with a mountain (image not to scale)





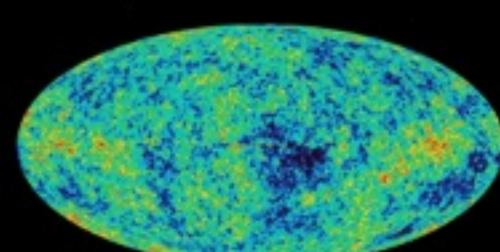
Sine wave

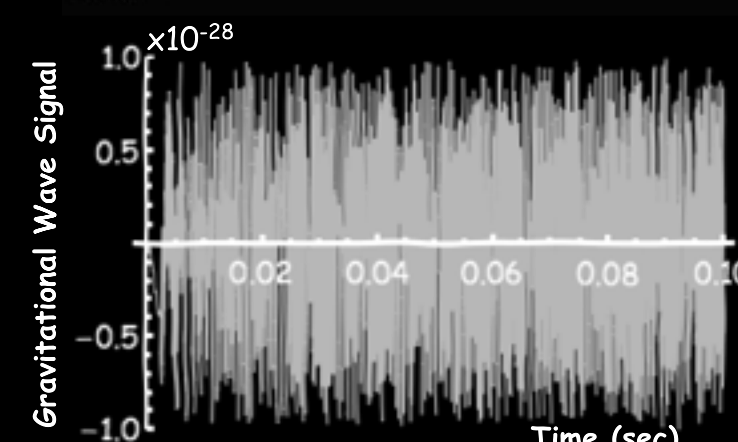
Non-spherical Supernova



Burst

Cosmic Gravitational wave background (BICEP2 results)

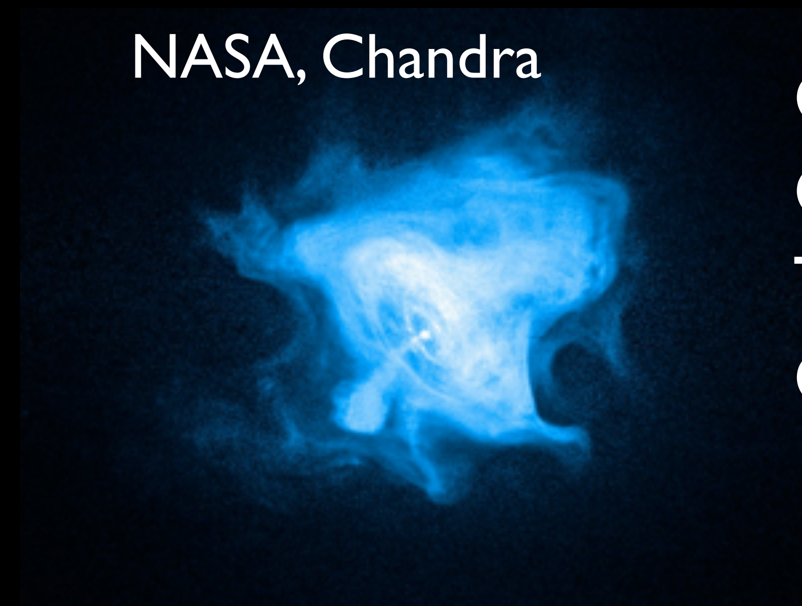




Random noise

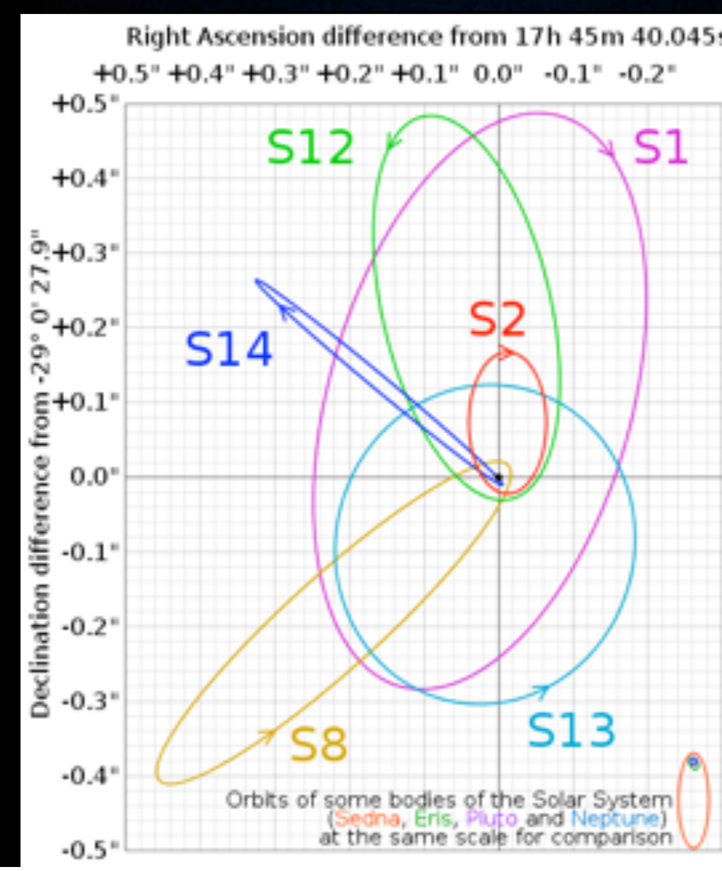
Gravitational-wave sources you might know: Extreme Systems in the Night Sky

Supernova 1987A,
Magellanic Clouds,
(Southern Hem)



Crab Pulsar,
Crab Nebula,
Taurus
Constellation

Betelgeuse, late stage star, future core collapse supernova, 642ly, Orion Constellation



cmglee, wikimedia commons

Sagittarius A*, 4 Million solar mass black hole at center of our galaxy, Sagittarius Constellation

Information courtesy Martin Hendry, Glasgow

A few questions these sources could answer...

fundamental Physics

- What are the properties of gravitational waves?
- Is GR the correct theory of gravity, and is it valid in strong-gravity conditions?

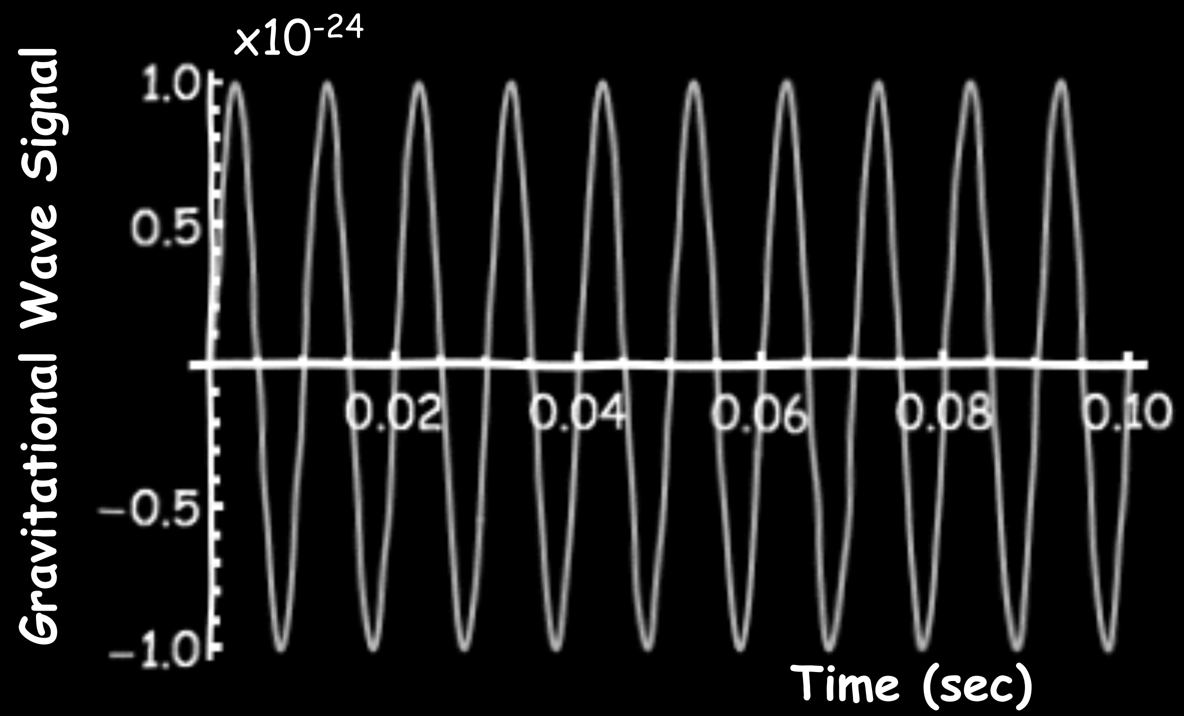
Astronomy and astrophysics

- How abundant are stellar-mass black holes?
- What causes gamma-ray bursts?
- What are the masses and internal structures of neutron stars?
- What happens in a core-collapse supernova?

Which of the following does not emit gravitational waves?

A. A spinning spherical star
B. The Earth orbiting the Sun
C. A professor waving his or her hands
D. All of the above would emit gravitational waves

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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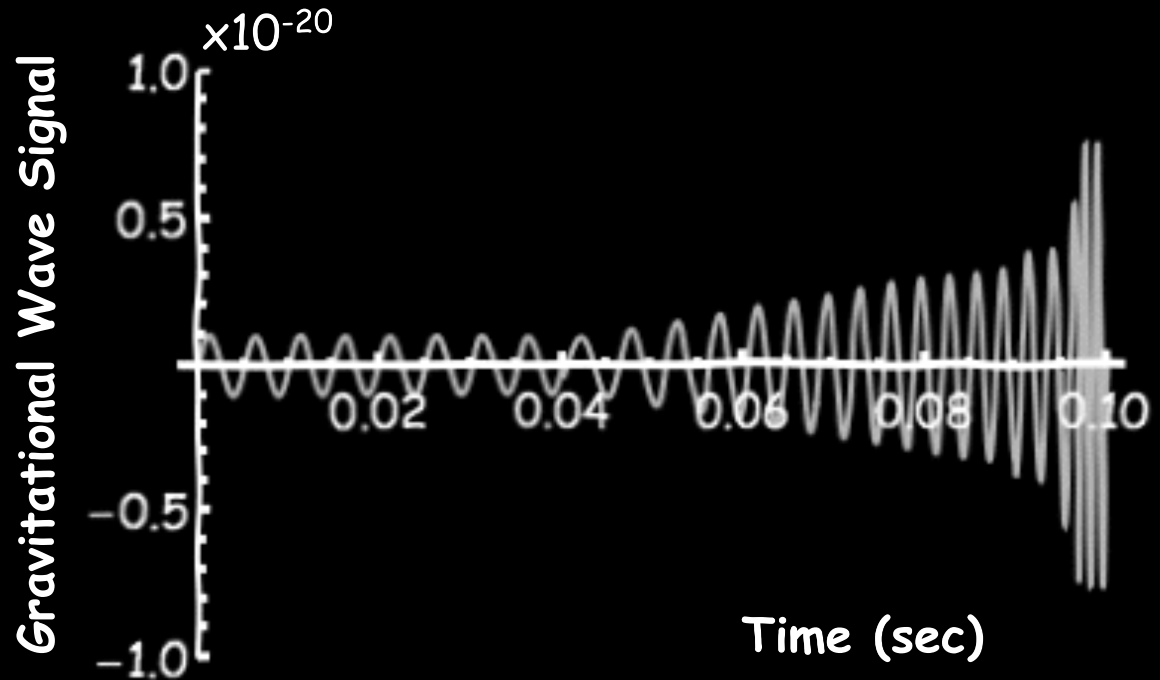

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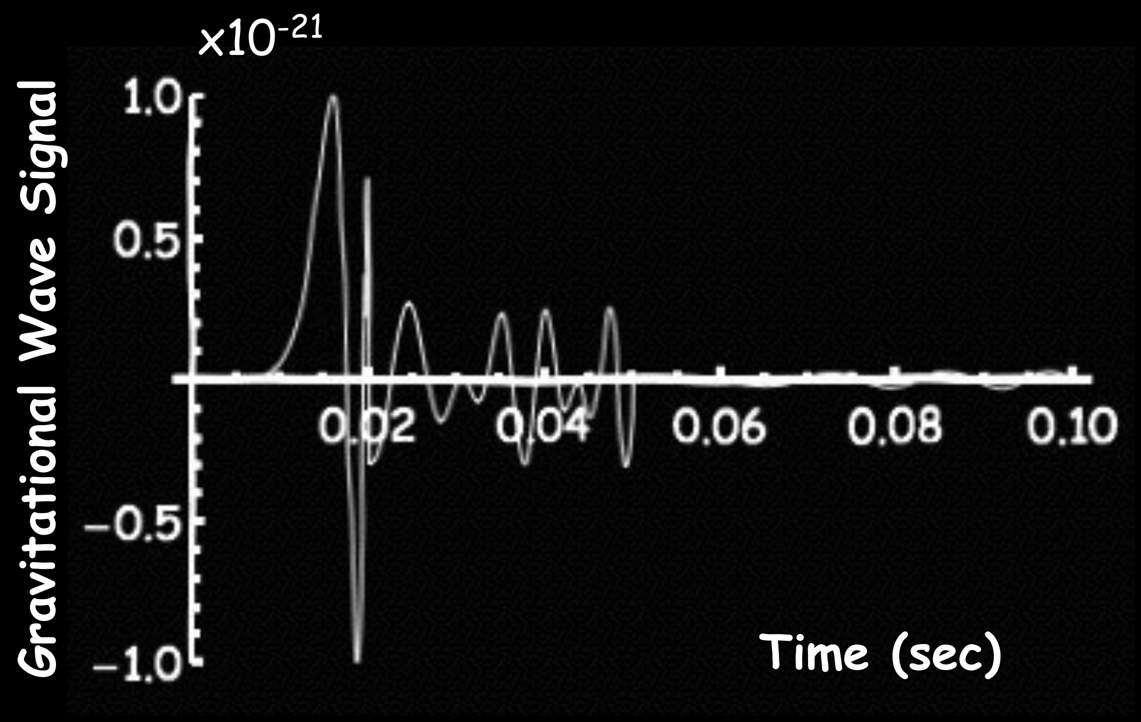

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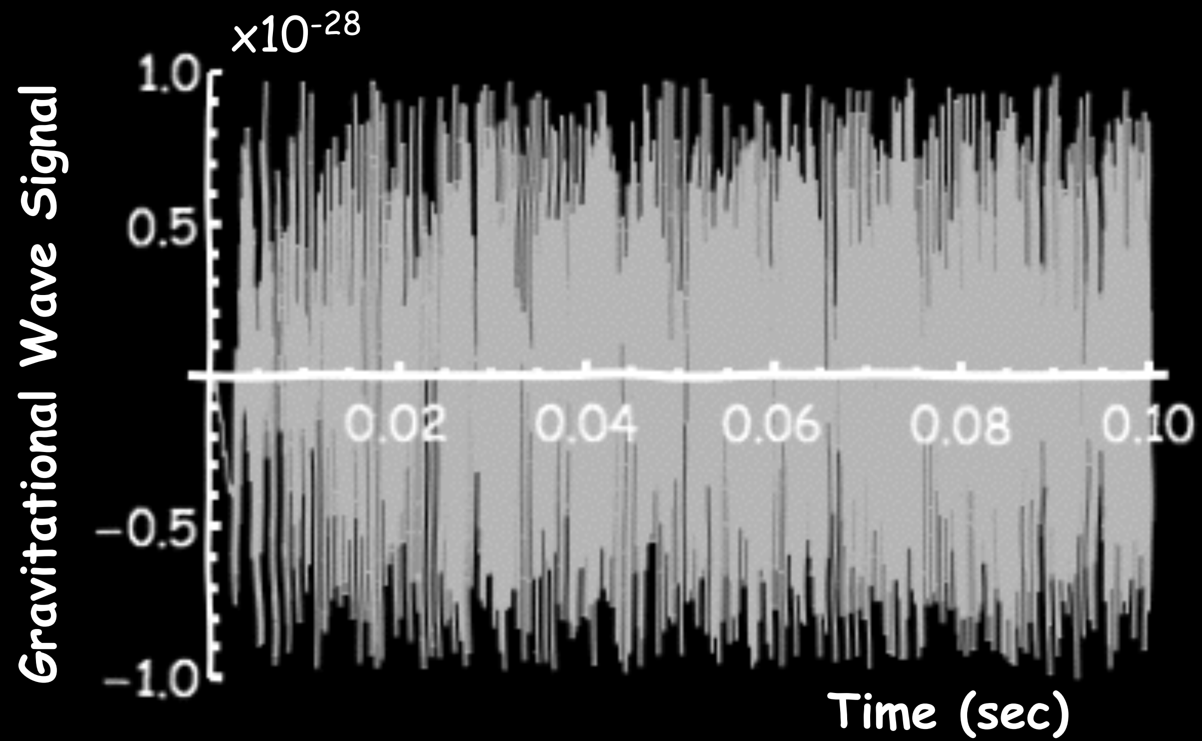

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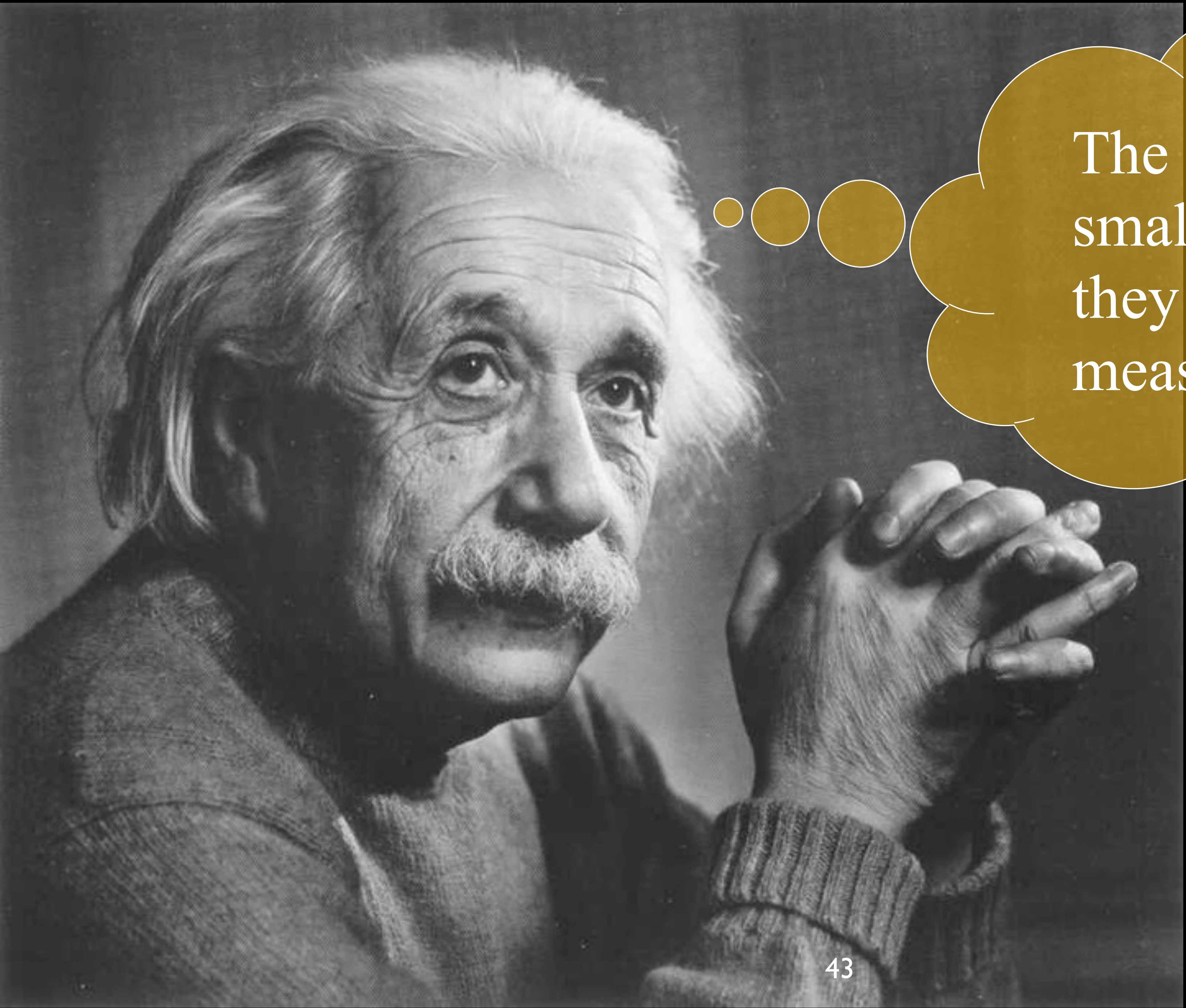
Gravitational-wave detectors

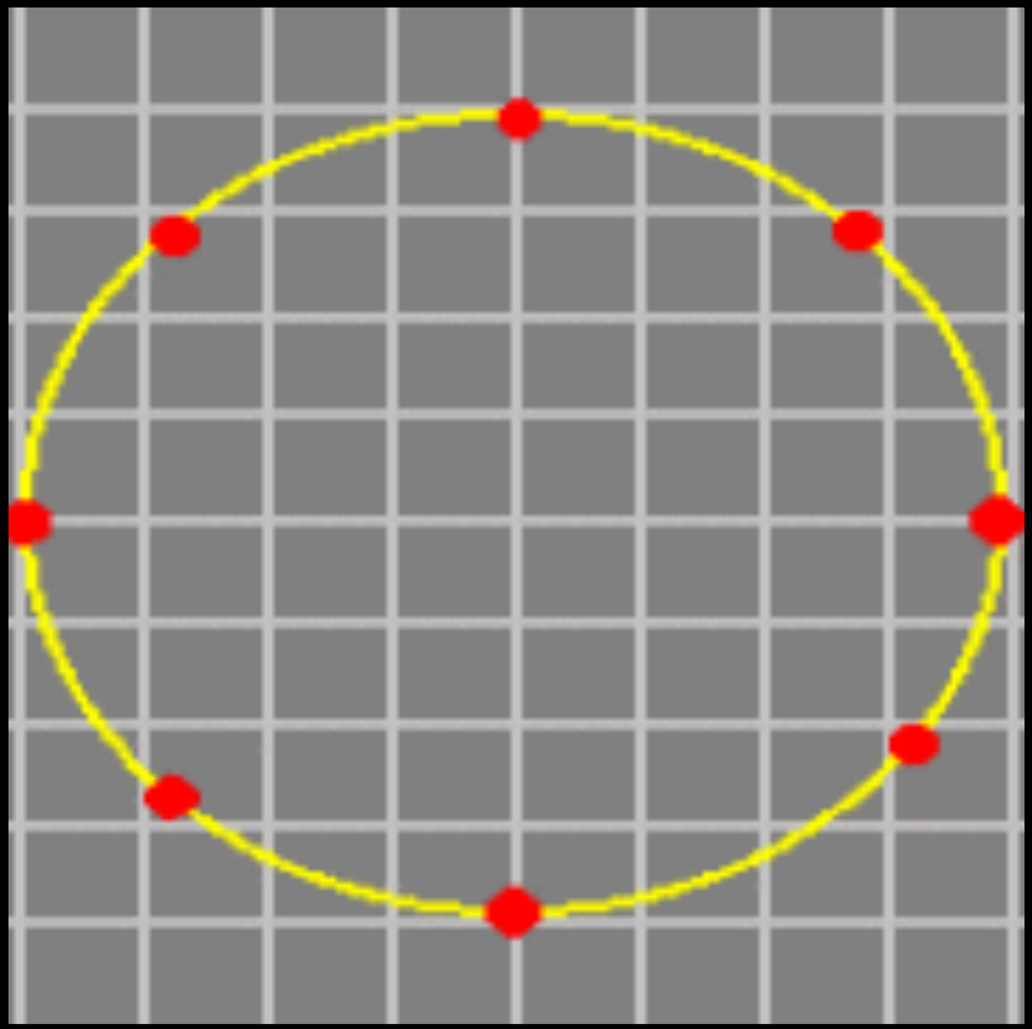
Are gravitational waves detectable?



The effects are so small it’s doubtful they will ever be measured.

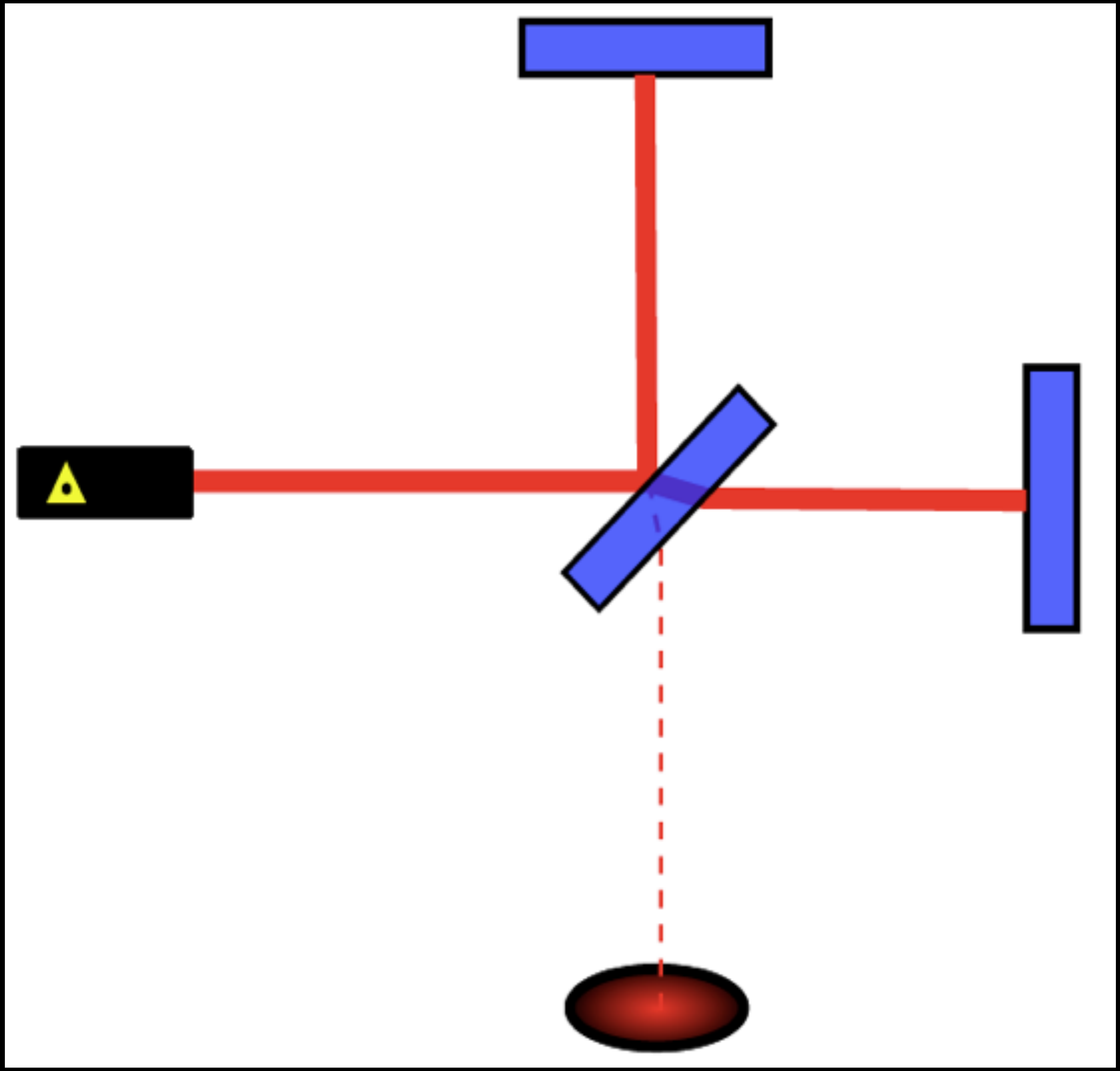
Effects of gravitational waves

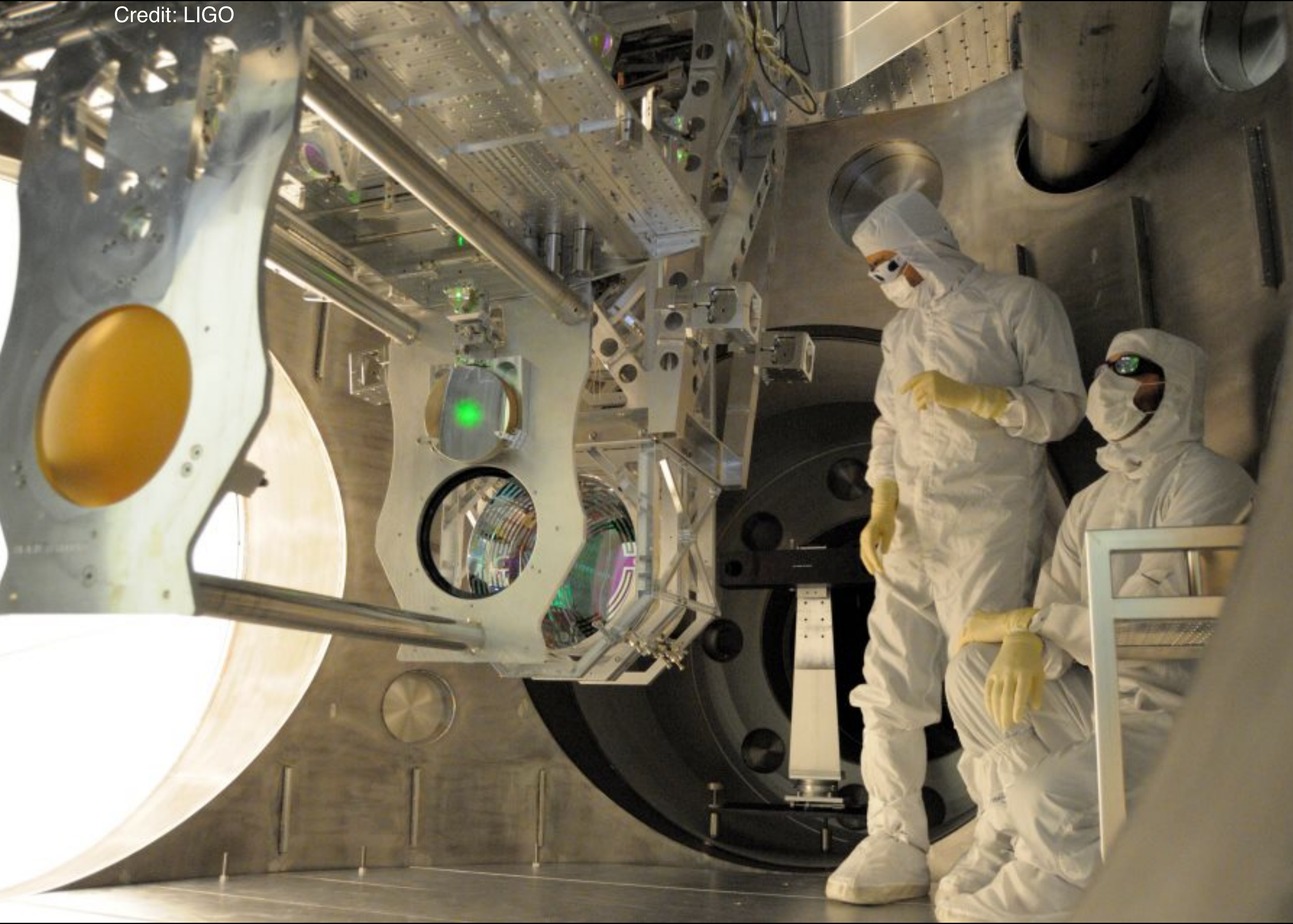
- Cause the distance between objects to change
- Fractional change shown 10%
- Fractional change from gravitational waves arriving at Earth 0.000000000000000 00001%



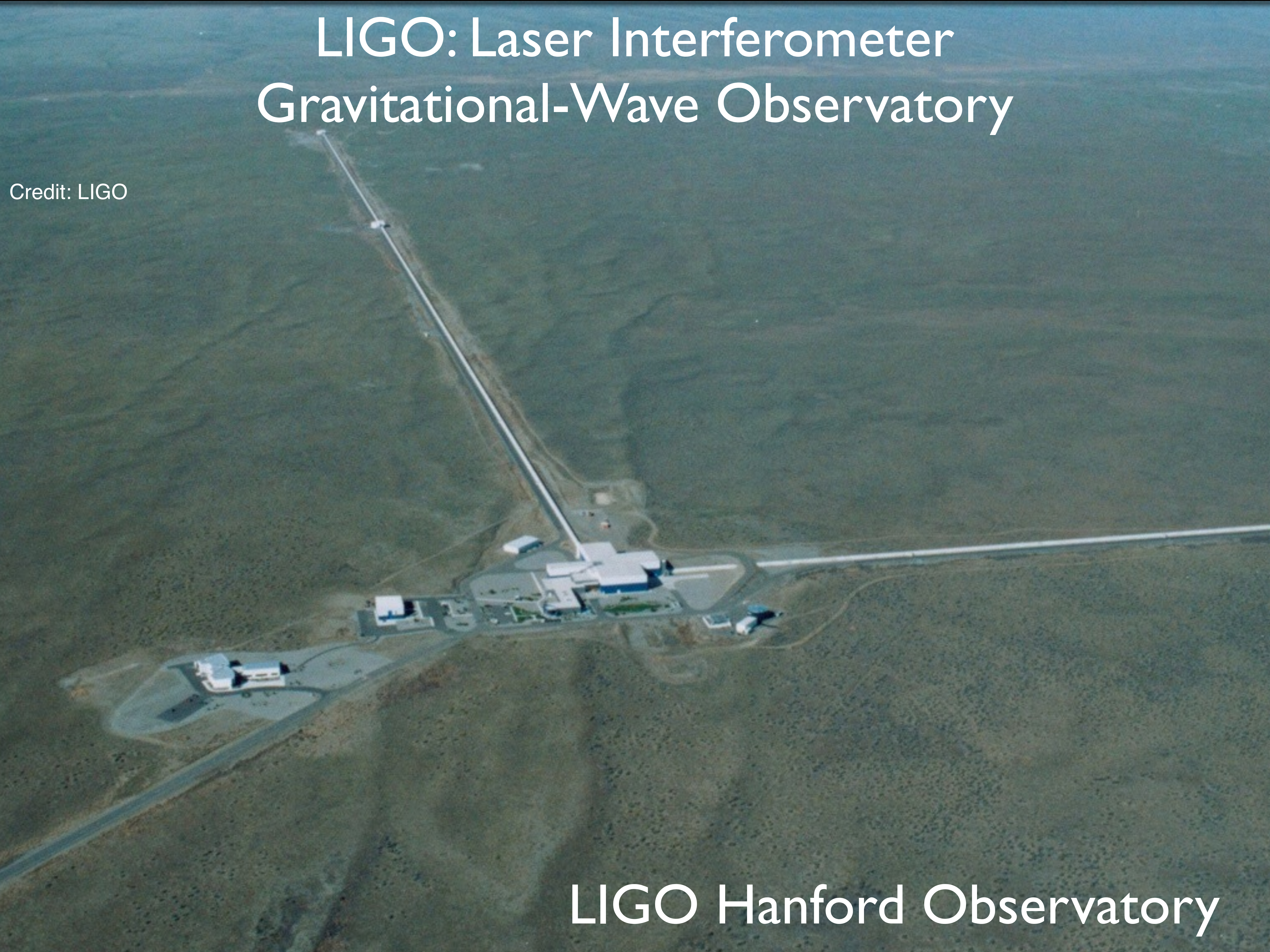
How a gravitational-wave detector works

- Arms placed so light cancels
- Transforms stretching and squeezing into more/less light
- Longer arms and more laser power to see farther

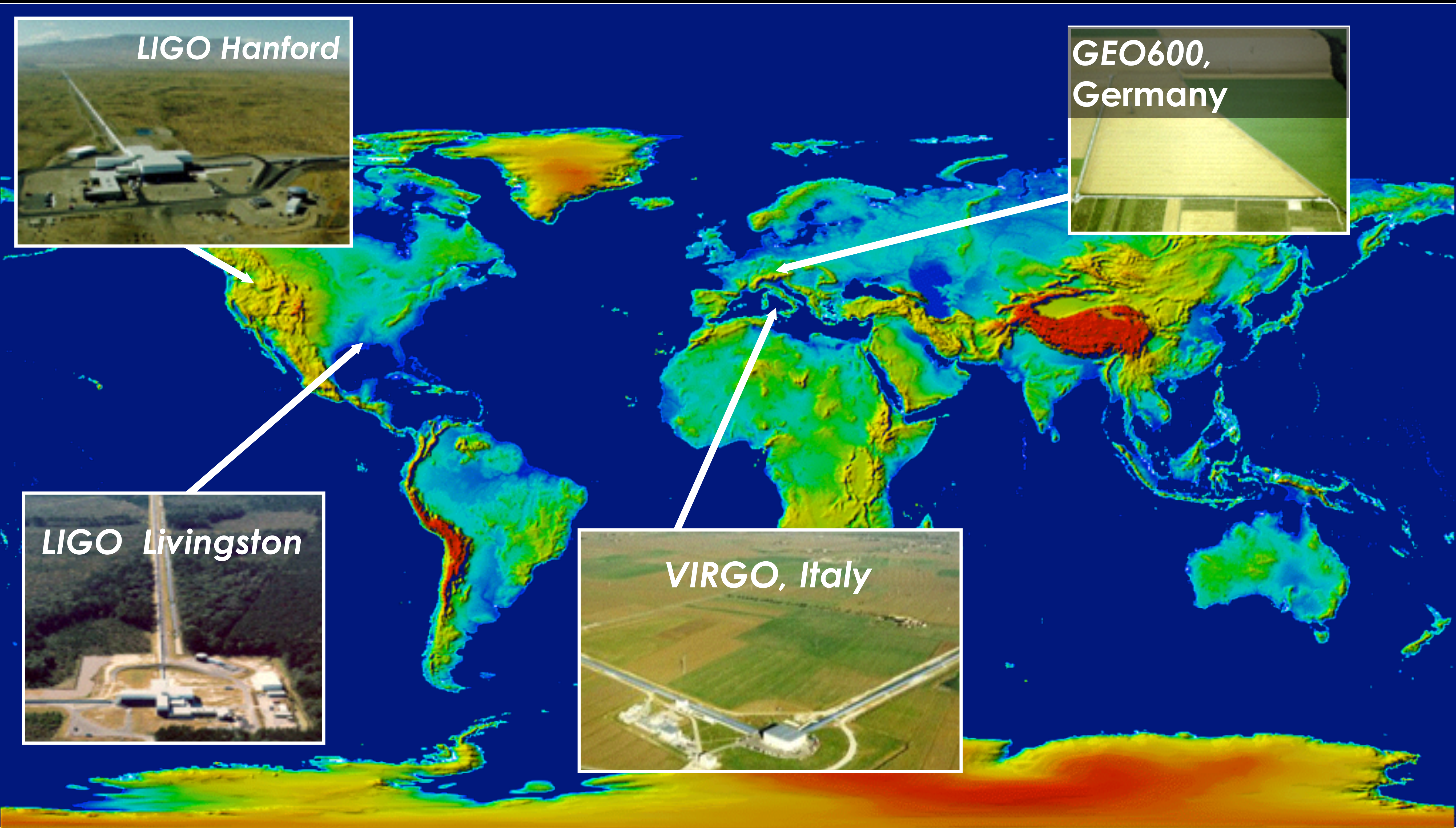



Credit: LIGO

LIGO: Laser Interferometer Gravitational-Wave Observatory


LIGO: Laser Interferometer
Gravitational-Wave Observatory
Credit: LIGO
LIGO Hanford Observatory

Worldwide laser GW detector network, 2010



Current Status, GW detection

- Initial LIGO detectors reached their designed sensitivity allowing the most sensitive searches ever - no detections yet
- Advanced LIGO construction well underway. Several detections per year expected to begin as soon as 2016 - one century after Einstein's GR!
- The future of gravitational-wave astronomy is bright!

If a gravitational wave and an electromagnetic wave were both emitted at the same time from 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

If a gravitational wave and an electromagnetic wave were both emitted from the same source near the center of our galaxy, which wave would be affected the most by the matter (gas, dust, etc.) between the source and Earth?

A. Gravitational Wave
B. Electromagnetic Wave
C. Both
D. Neither

Which of the following sources of gravitational waves could LIGO conceivably detect?

A. The Sun orbiting the Milky Way
B. Two black holes orbiting very close to each other
C. Two neutron stars orbiting very close to each other
D. The Moon orbiting the Earth
E. Both B and C

Simulation of colliding black holes and gravitational radiation released
Image courtesy Albert Einstein Institute

Thanks for being a great class!

Good luck on the Final!

LIGO Livingston Observatory
LIGO