33-120
Science & Science Fiction

Welcome!

Today…

Black Holes, Gravitational Waves and

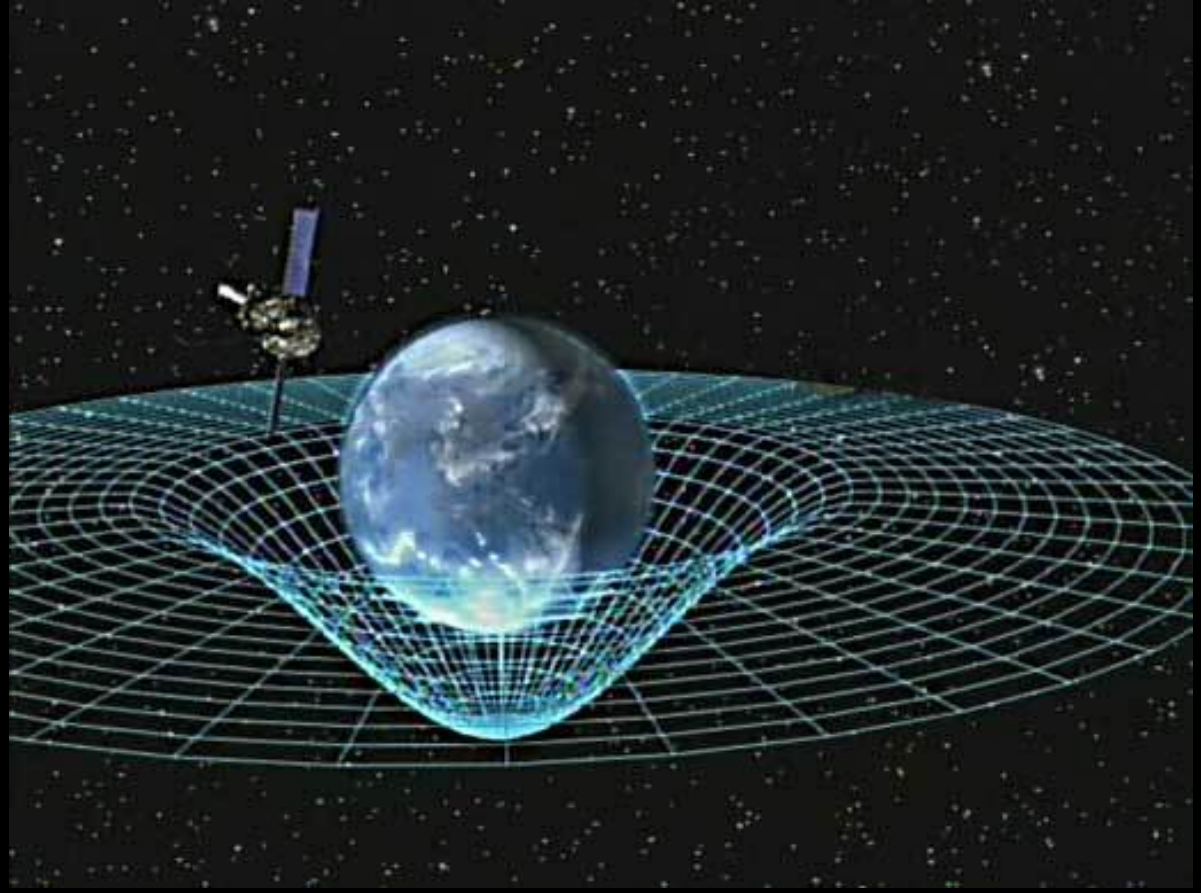
Warp Drive

- **Problem 2 due this Friday, Sept. 15**
  - **Time Dilation on ISS** (details on Canvas)
- **Spacetime Team Project next Monday, 9/18**
  - **Einstein's *Principle of Equivalence***
  - **No lecture – gather data for project**
  - **Team assignments on Canvas**
  - **Pick up equipment this week or Mon.**
  - **Results due on Wed. Sept. 20**

Announcements for Wednesday, Sept. 13

- **Exploration Paper 1** due Friday, Sept. 22
  - Your choice of topics on **Space & Time**
  - Min. 75% original writing (“Turnitin”)
  - Minimum 2 full pages of text
  - At least one reference
  - One Submission Only (don’t rush)
  - Details on Canvas

Coming Attractions…



https://www.ligo.caltech.edu/page/what-are-gw

Last time…
GPS: A Practical application of Relativity

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Global Positioning System (GPS)

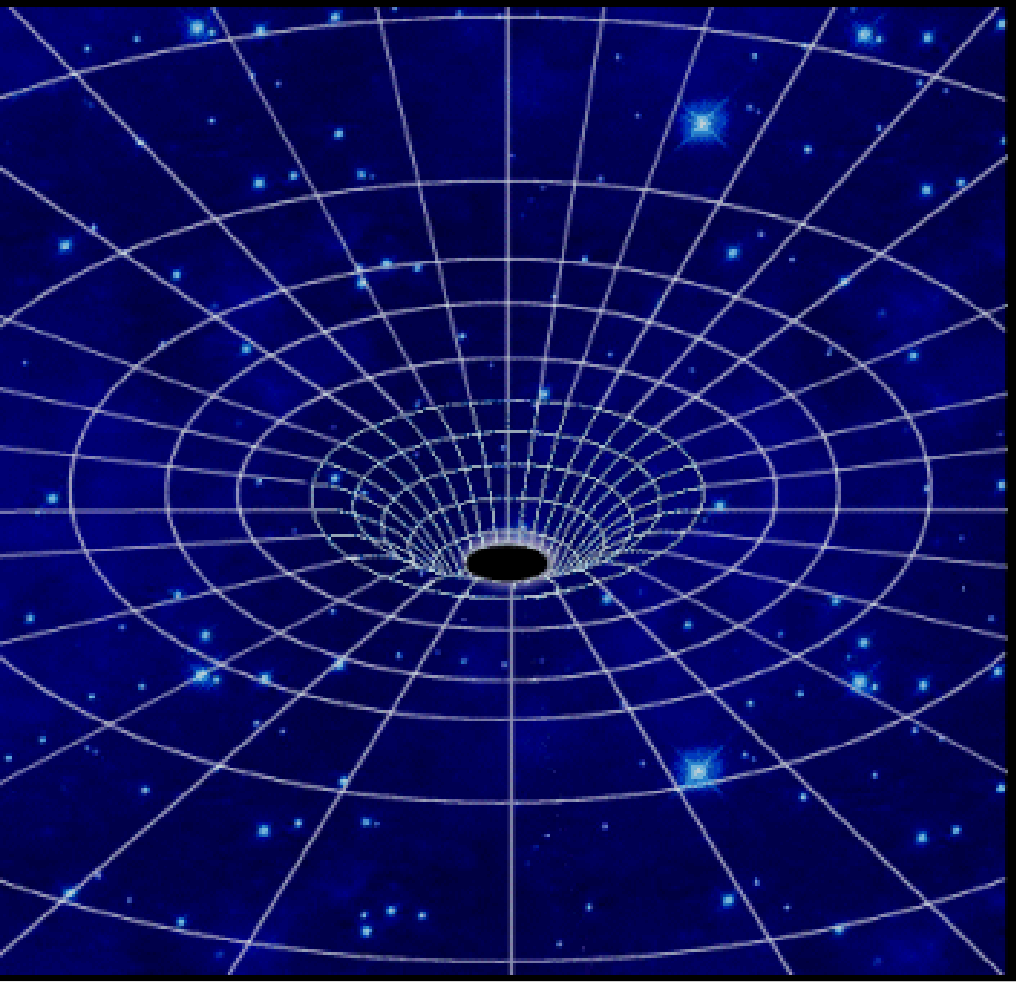
- GR: clocks on Earth run slower by 5 parts in 10^{10}

$$t_r = t_\infty \sqrt{1 - \frac{2Gm}{rc^2}}$$

- SR: clocks in orbit run slower by 1 part in 10^{10}

$$t' = t \sqrt{1 - \frac{v^2}{c^2}}$$

Practical application of Relativity:
Two competing effects for GPS



- Gravitationally completely collapsed object
- Event horizon: point of no return, beyond which not even light can escape (they will eat everything that comes close enough)
- Curvature of spacetime may be so severe that classical physics breaks down

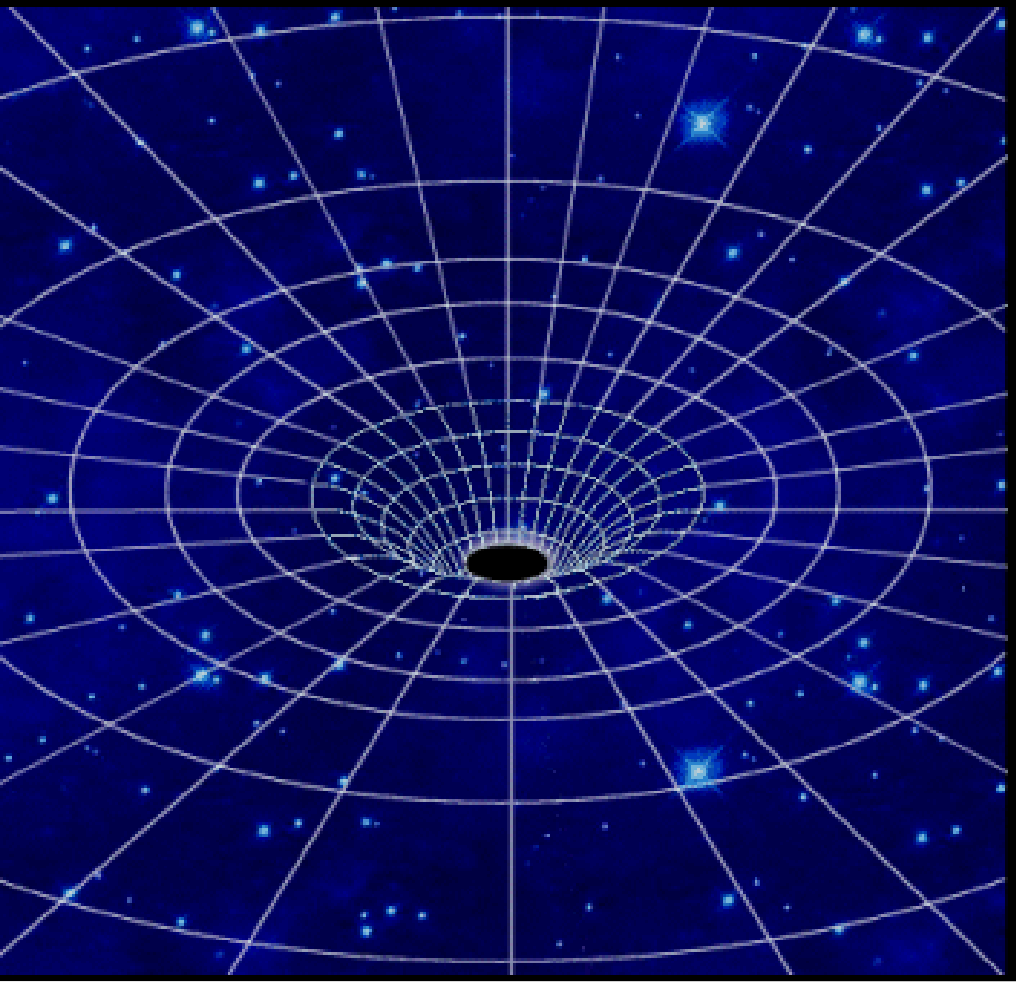
Last time…
Properties of Black holes

Start-up of the LHC: 10 Sept. 2008

Protests in Europe: fear of black holes

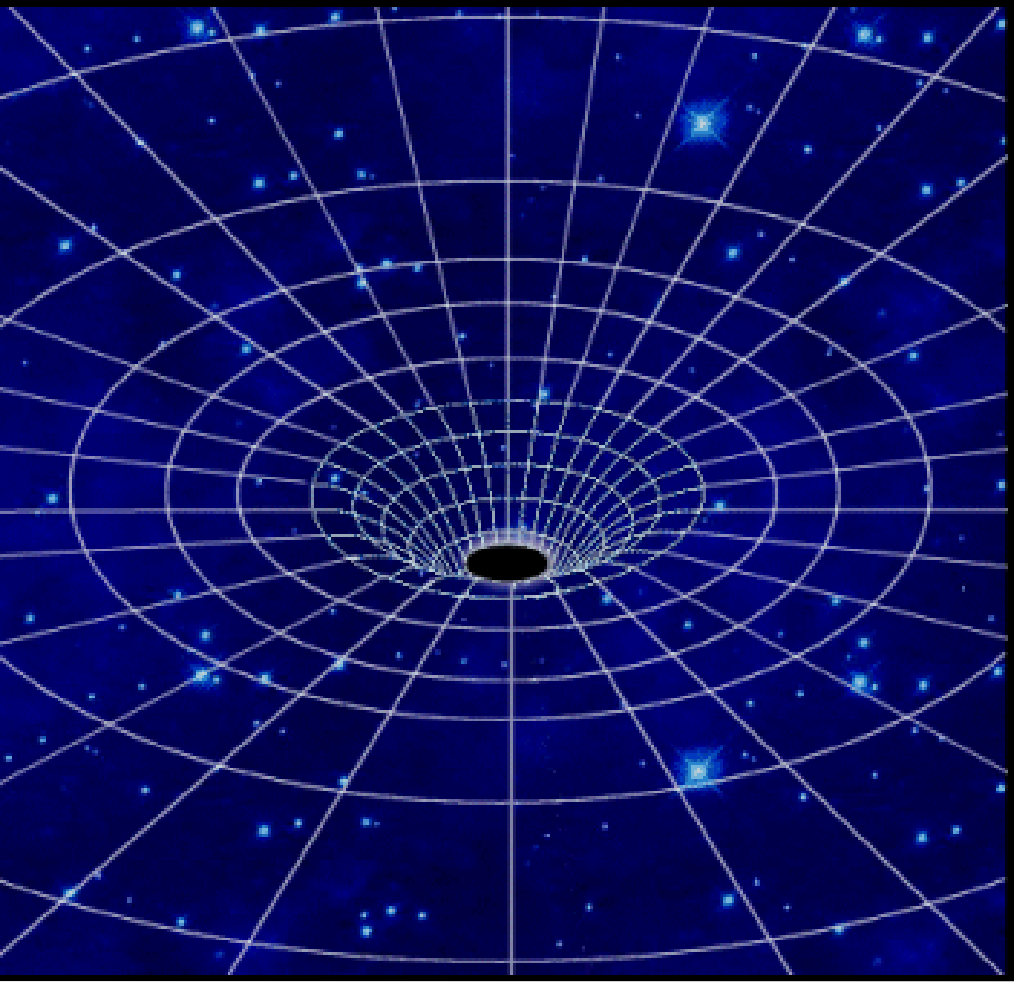
CMU Fence painted (by physics majors?)

Irrational fear of science…
The LHC and the end of the world as we know it



- Can a black hole be created by high-energy particle collisions? YES!
- Hawking Radiation: black holes are not completely black!
- They must feed or eventually evaporate.
- Timescale for evaporation depends on size (smaller will evaporate faster).

Properties of Black Holes



- **Event horizon: point of no return, beyond which not even light can escape**
- **Schwarzschild Radius:**

$$r_s = \frac{2Gm}{c^2}$$

Properties of Black Holes

- **Gravitational Time Dilation:**

$$t_r = t_\infty \sqrt{1 - \frac{2Gm}{rc^2}}$$

  - t_r = time at some distance r from a mass m
  - t_∞= normal time (infinitely far from the distortion)
  - G = Newton's gravitational constant

Origin of the Schwarzschild Radius:
Distance at which time stops!

Despicable Me

Directed by Chris Renaud & Pierre Coffin

Universal (2009)

Inspiration for Problem 3 (Due Wednesday, Sept. 27)
Calculate the Schwarzschild Radius for the Moon

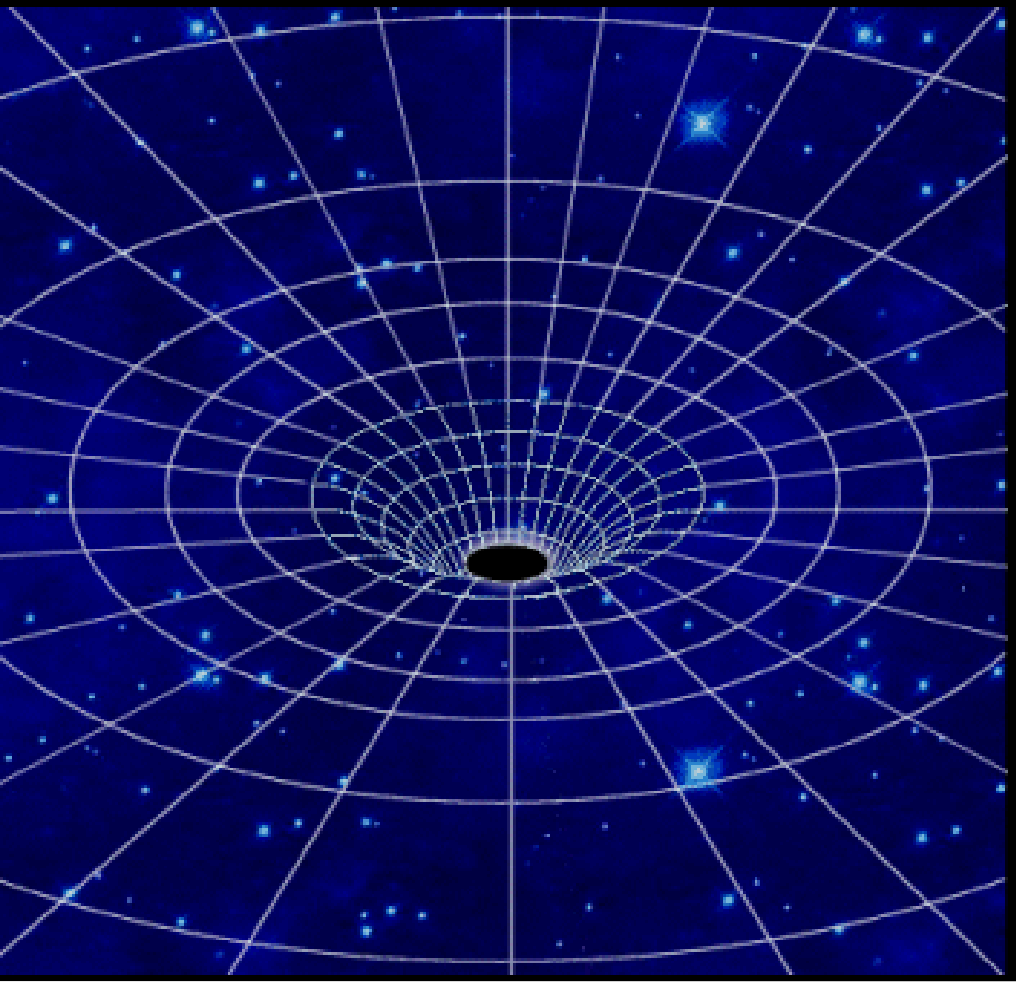
Despicable Me

Calculate the Schwarzschild Radius for the Moon

$$r_s = \frac{2Gm}{c^2}$$

If the Moon is shrunk to the size of a grapefruit, will it become a black hole?

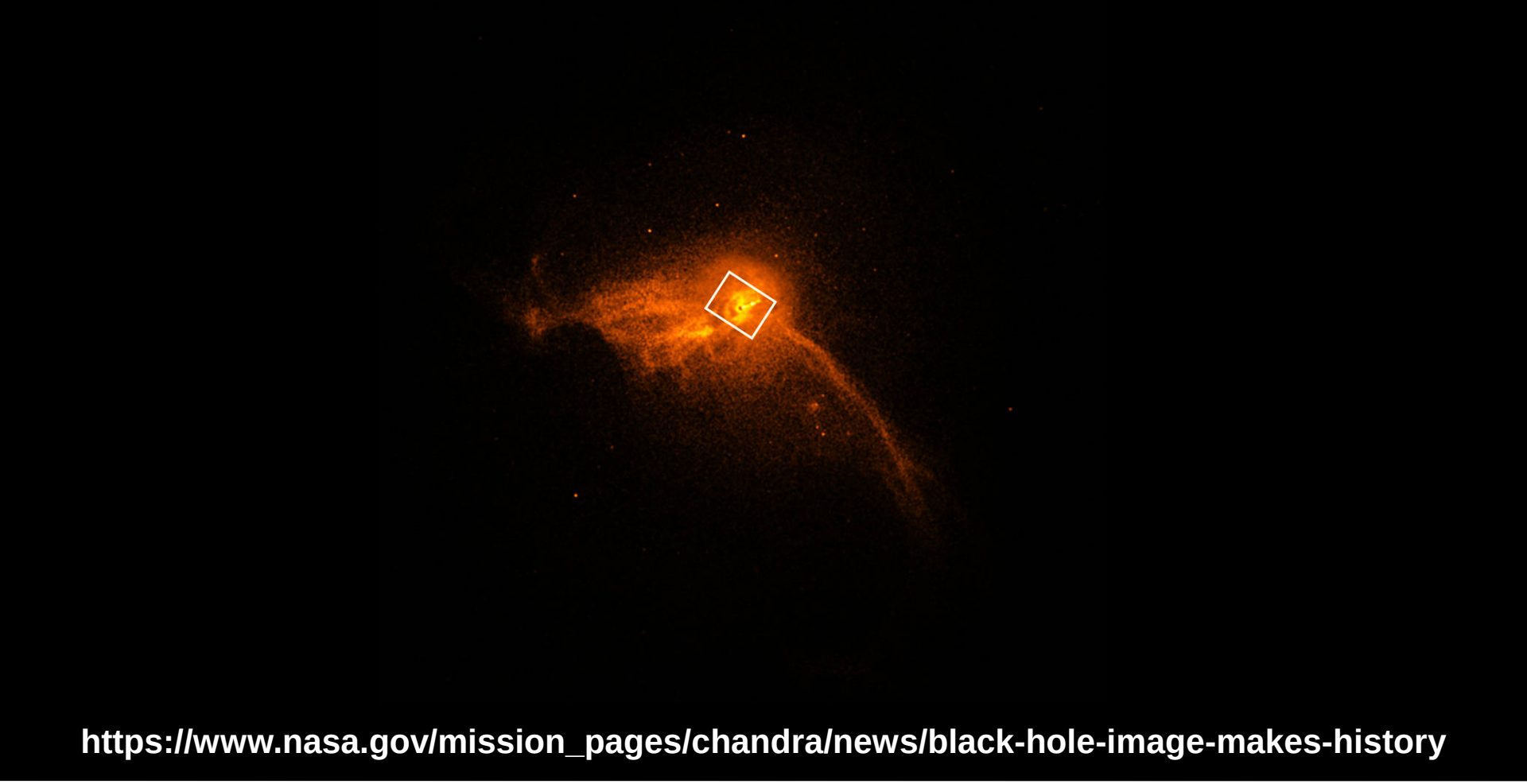
Inspiration for Problem 3 (Due Wednesday, Sept. 27)
Calculate the Schwarzschild Radius for the Moon



- Indirect evidence based on motion of nearby objects
- Gravitational lensing: bending of light from distant objects around a black hole
- First direct image of a black hole released April 2019

Properties of Black Holes (cont.)

Most important: Black Holes are real, not just sci-fi



https://www.nasa.gov/mission_pages/chandra/news/black-hole-image-makes-history

Image of M87
(in constellation Virgo)
from NASA's Chandra X-ray Observatory

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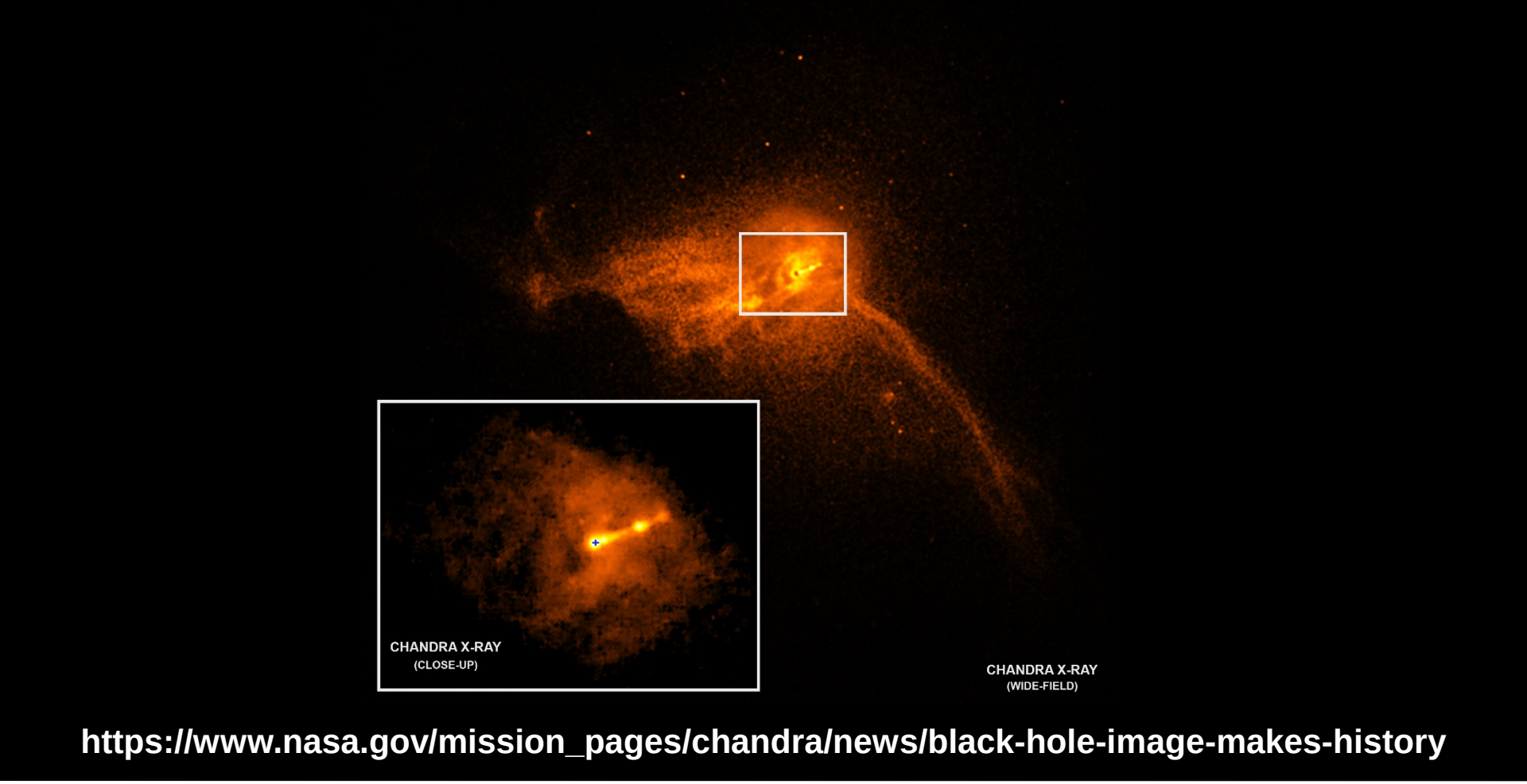

https://www.nasa.gov/mission_pages/chandra/news/black-hole-image-makes-history

Close-ups of previous image of M87 from NASA's Chandra X-ray Observatory

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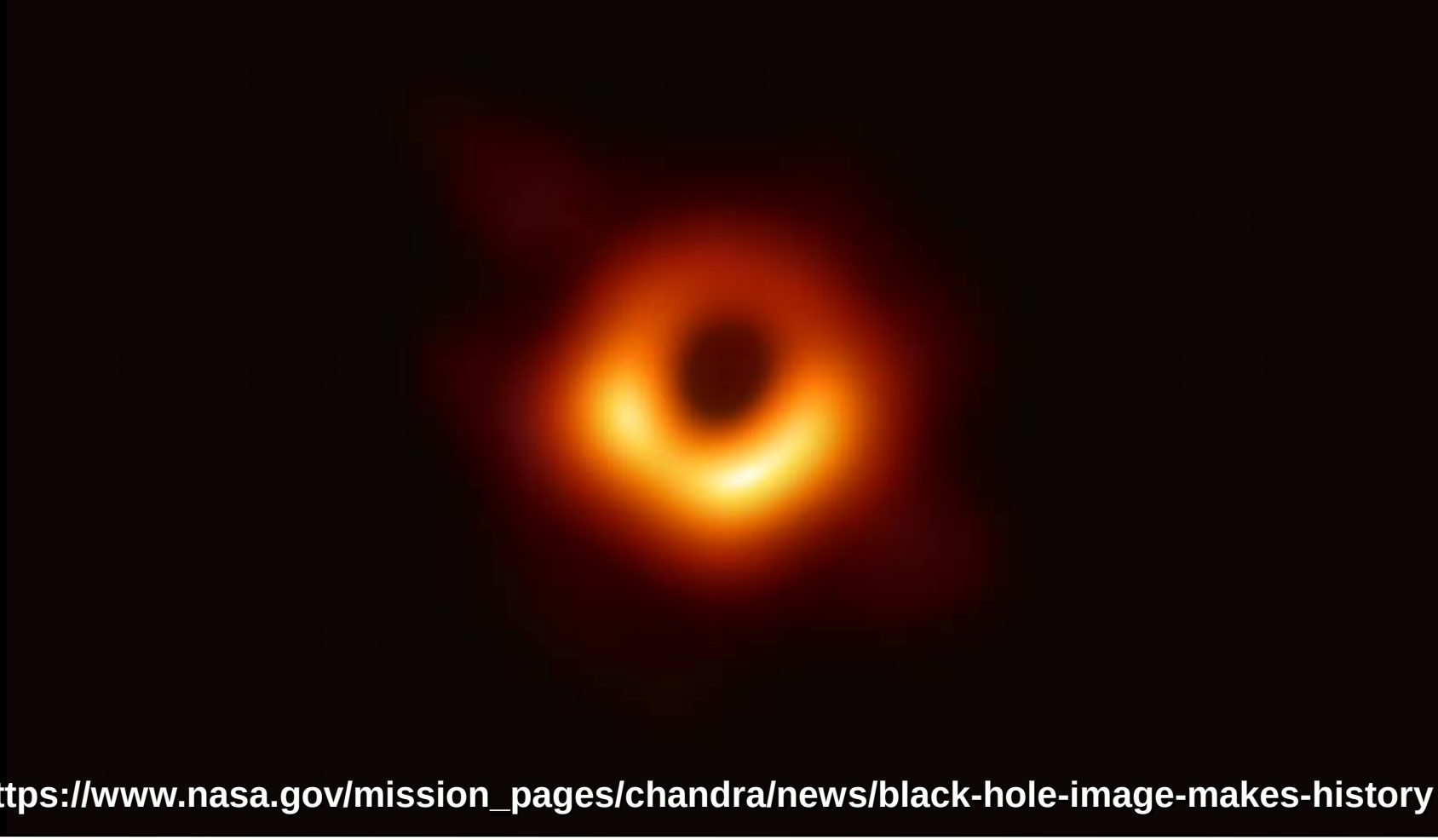

https://www.nasa.gov/mission_pages/chandra/news/black-hole-image-makes-history

First direct image of a black hole from NASA's Event Horizon Telescope April 2019

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Star Trek

Directed by J.J. Abrams

Paramount (2009)

Time Travel by going through a Black Hole: Science says NO!

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Interstellar

Directed by Christopher Nolan

Warner Brothers (2014)

Best movie depiction of a Black Hole so far!
Gravitational Time Dilation

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- **Gravitational Time Dilation:**

$$t_r = t_\infty \sqrt{1 - \frac{2Gm}{rc^2}}$$

  - t_r = time at some distance r from a mass m
  - t_∞= normal time (infinitely far from the distortion)
  - hours near black hole = years back on Earth

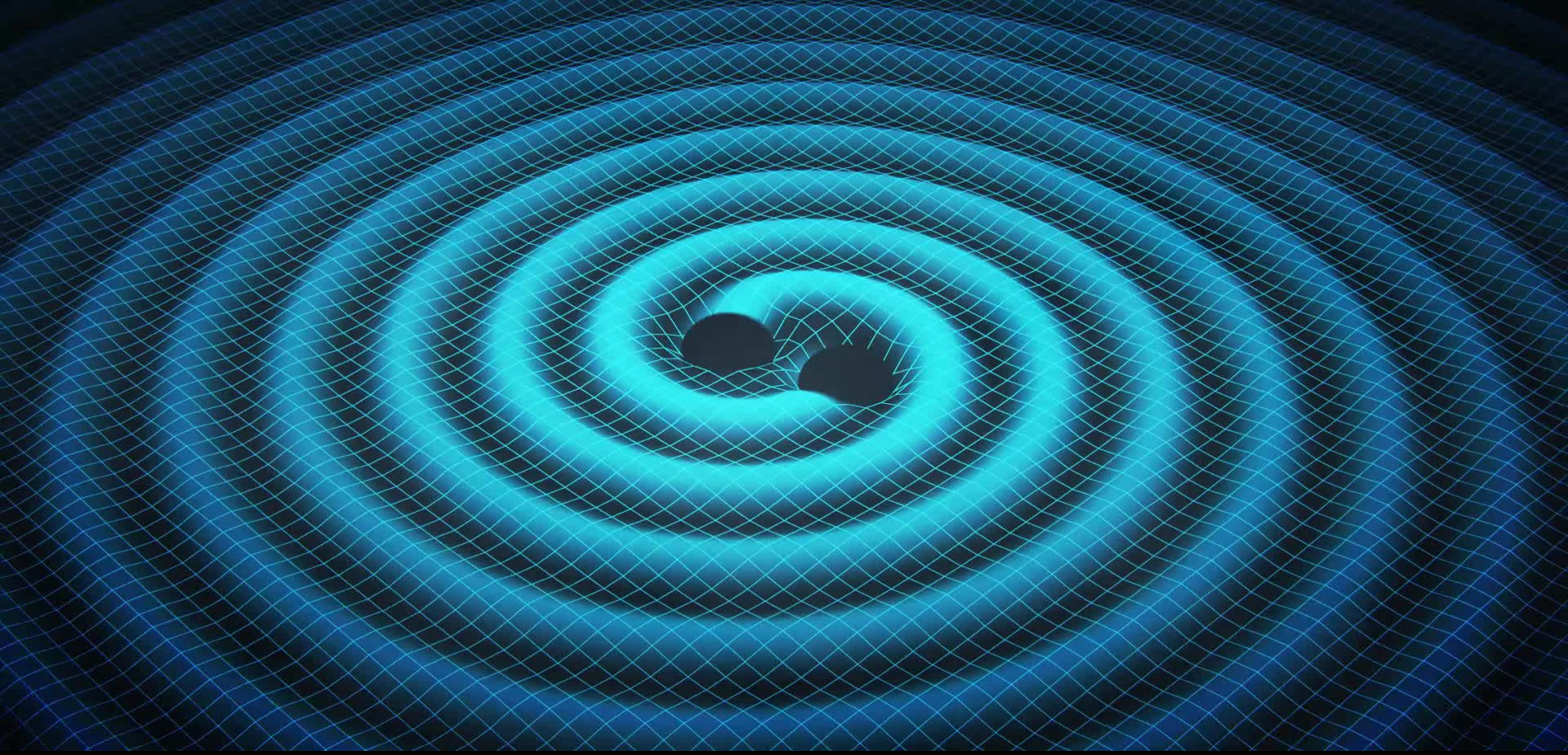
General Relativity:
Clocks run more slowly when closer to large mass.
(allows for time travel into the <u>future</u>)

Star Trek VI: The Undiscovered Country

Directed by Nicholas Meyer

Paramount (1991)

Another Prediction of General Relativity: Gravitational Waves



https://www.extremetech.com/extreme/222852-what-are-gravitational-waves-and-where-does-physics-go-from-here-now-that-weve-found-them

Another Prediction of General Relativity: Gravitational Waves

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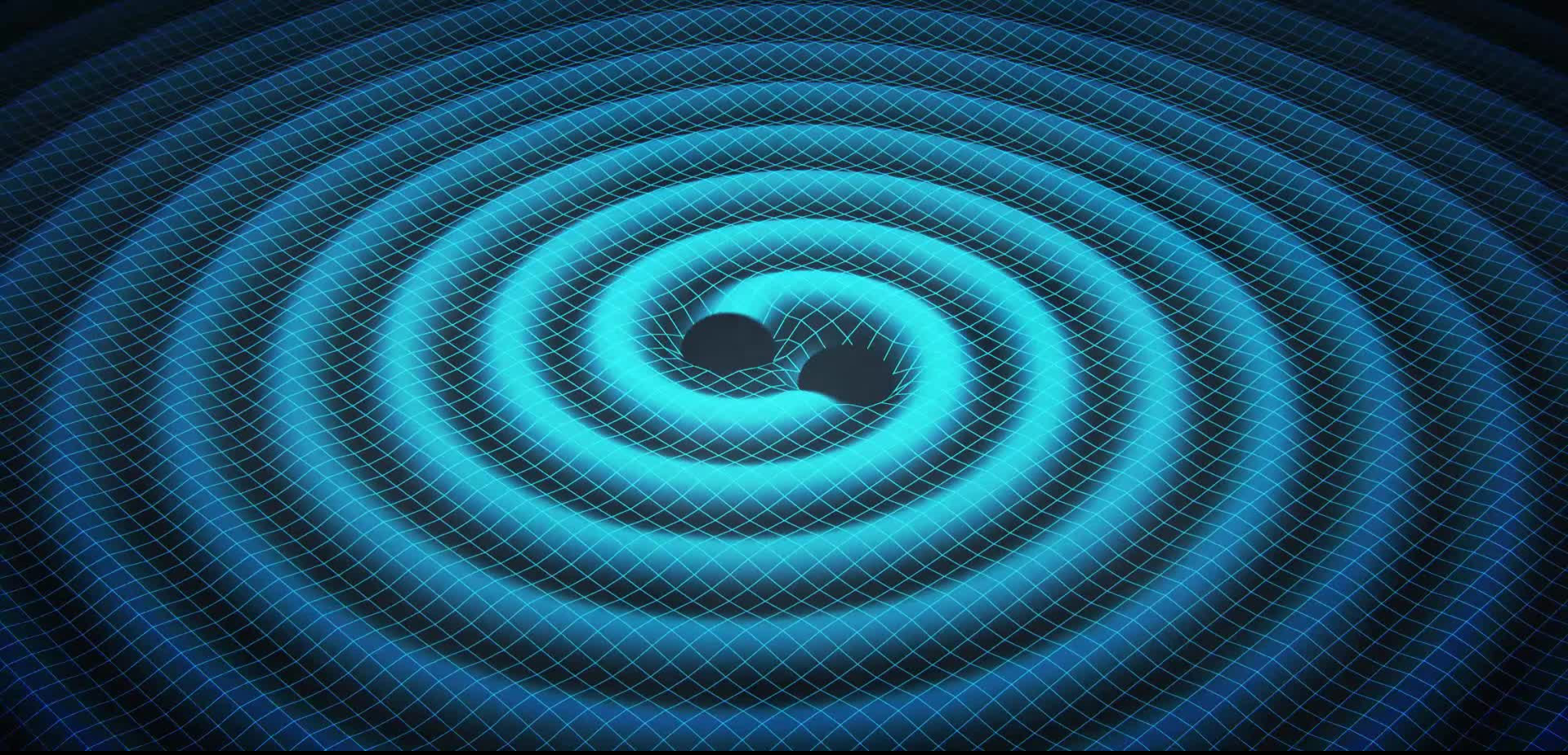
- **Timeline for Gravitational Waves:**
  - **Predicted by Einstein's General Theory of Relativity (published 1916; written 1915)**
  - **First detected by LIGO (September 2015)**
  - **LIGO collaboration convinced results were real (December 2015)**
  - **Paper delivered to PRL (21 Jan 2016)**
  - **Press release + publication (11 Feb 2016)**

Gravitational Waves:
The big physics announcement of 2016



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How do you detect Gravitational Waves?

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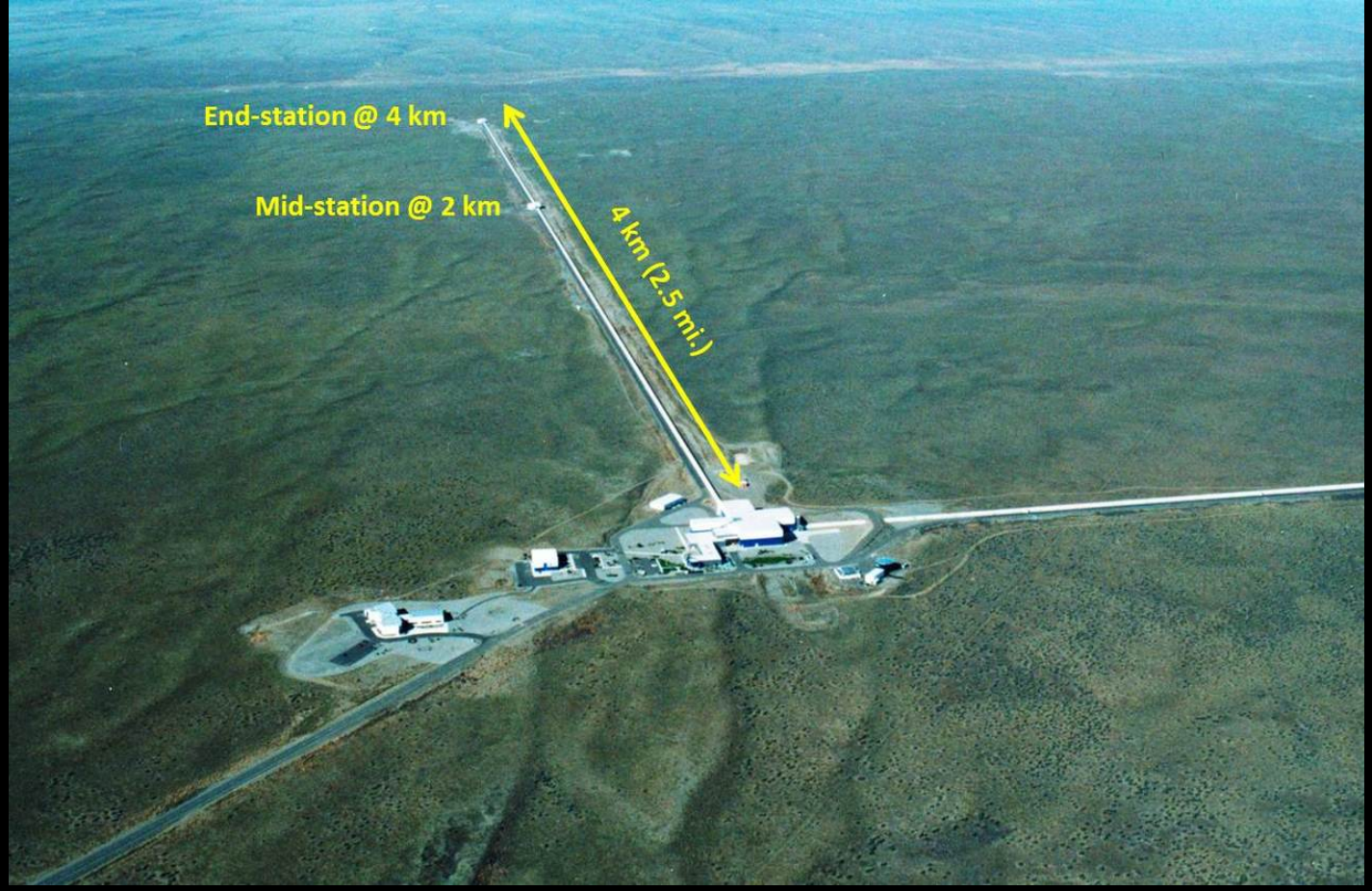

https://www.ligo.caltech.edu/page/ligo-detectors

LIGO…

Laser Interferometer Gravitational-Wave Observatory

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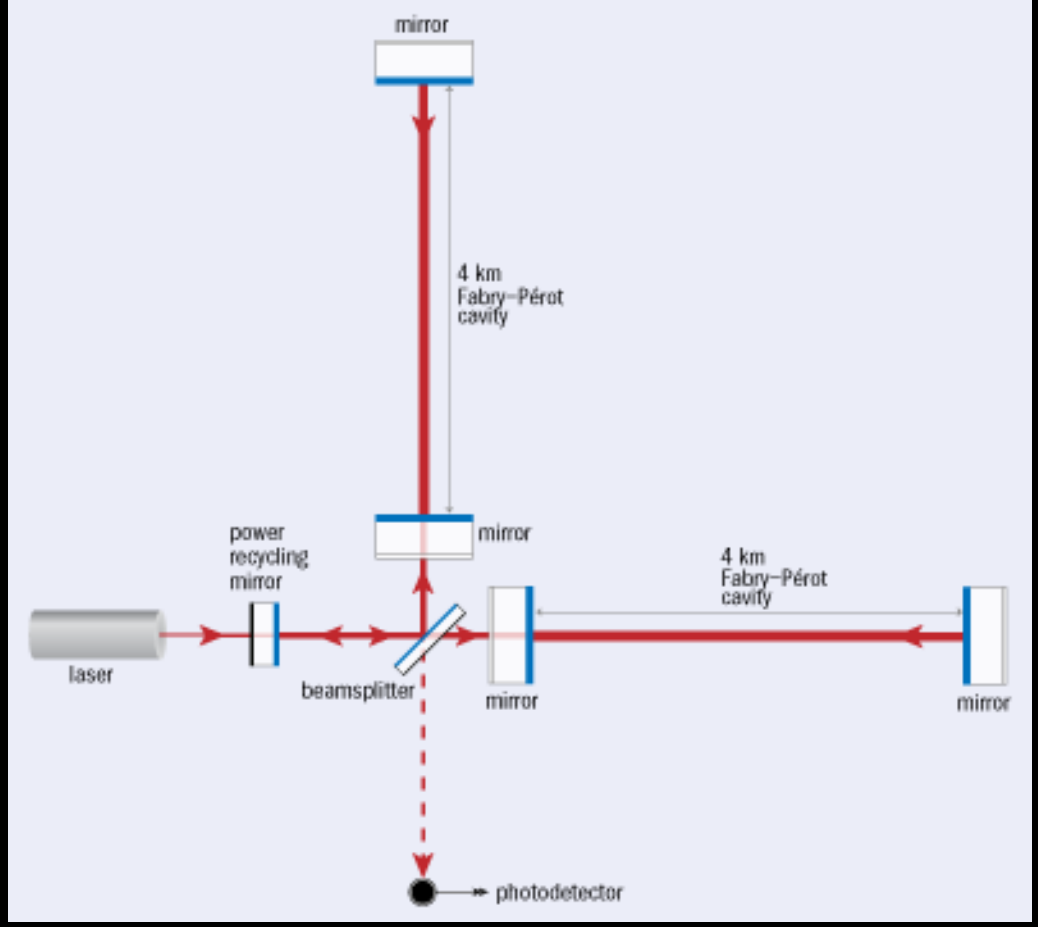
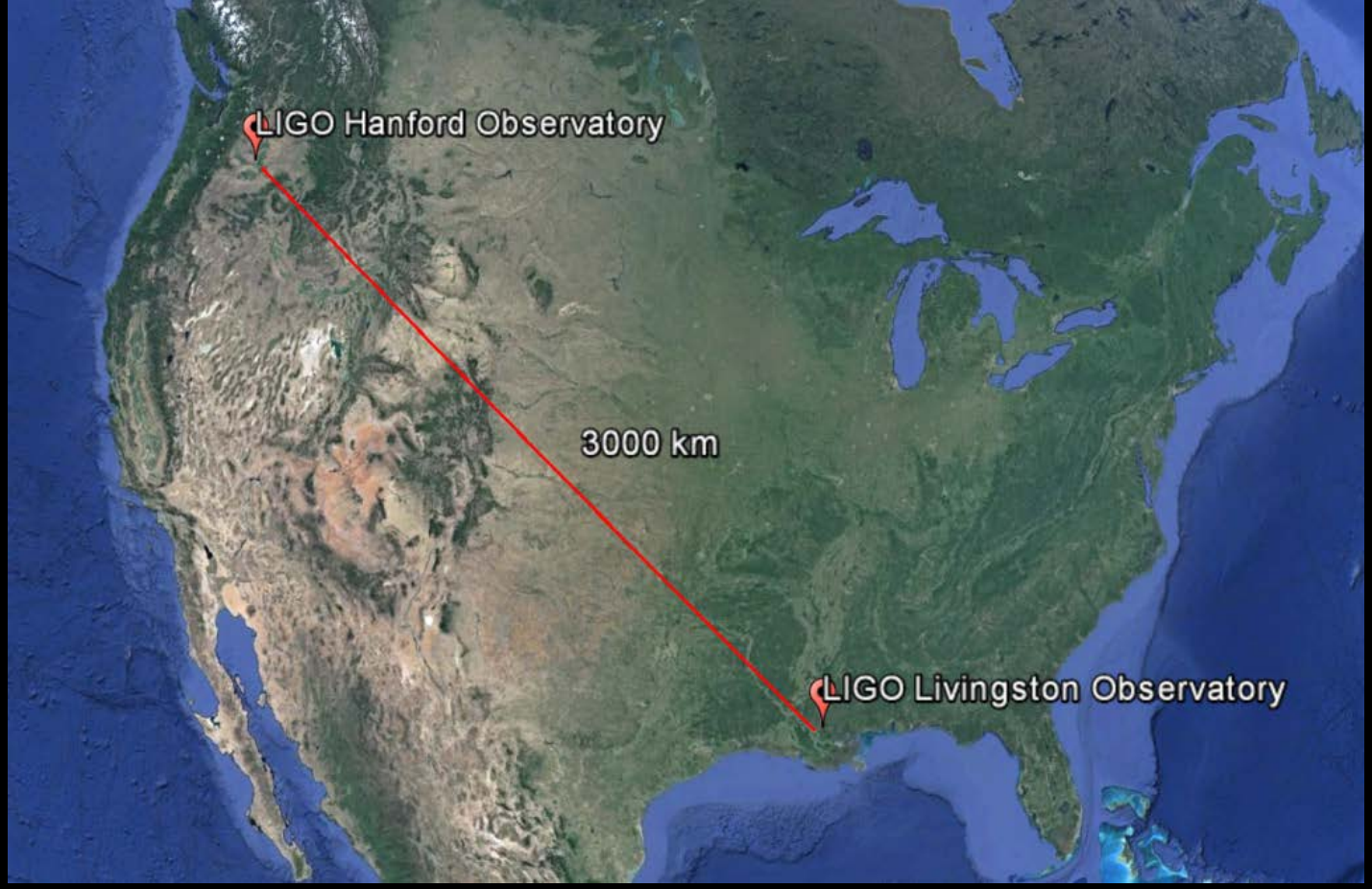


http://physicsworld.com/cws/article/news/2016/feb/11/ligo-detects-first-ever-gravitational-waves-from-two-merging-black-holes/

LIGO…

Interference pattern shifts if either arm changes length



http://www.vofoundation.org/blog/gravitational-waves-detected/

LIGO…

Two facilities: Hanford, WA and Livingston, LA

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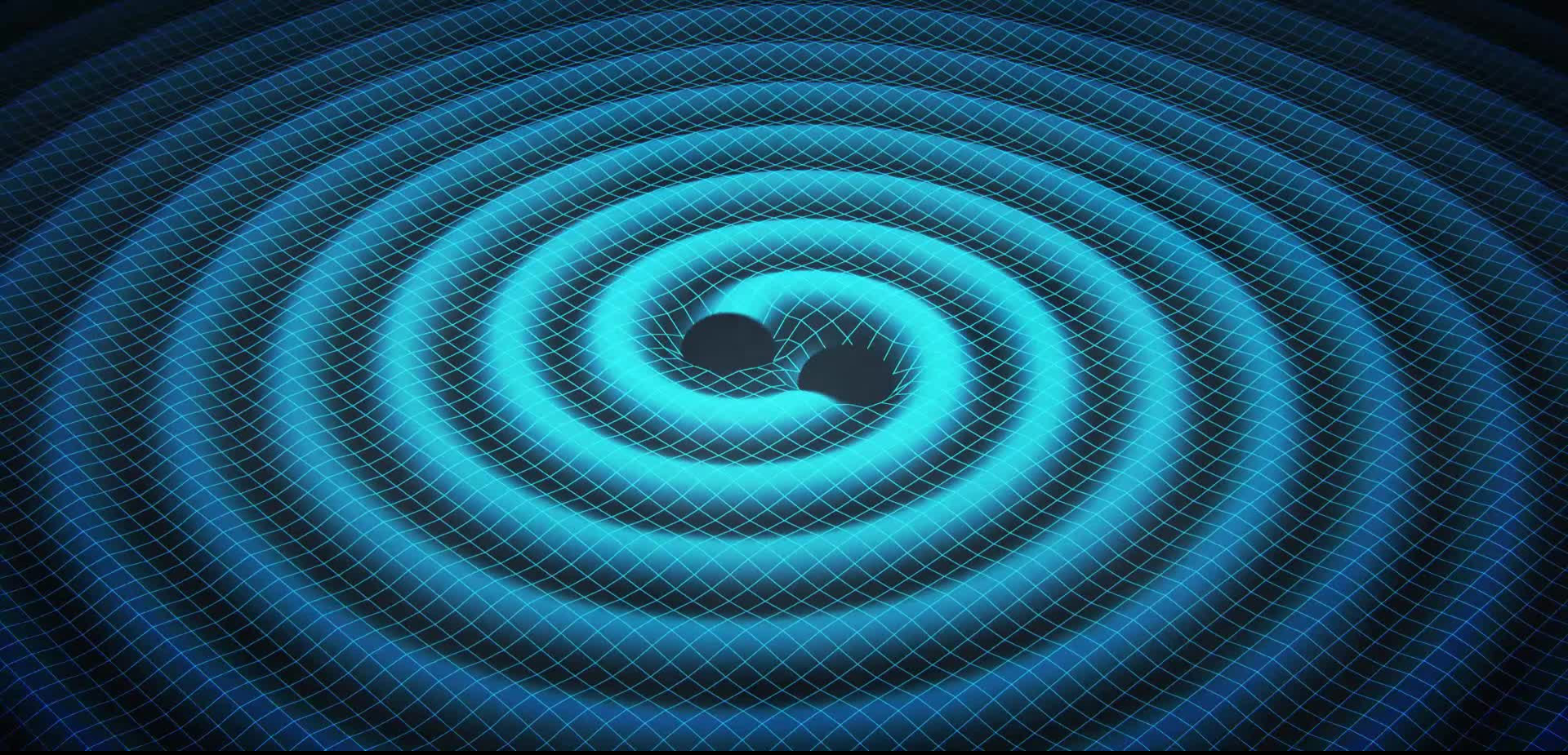

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LIGO…

Gravitational Waves are ripples of distortion in space

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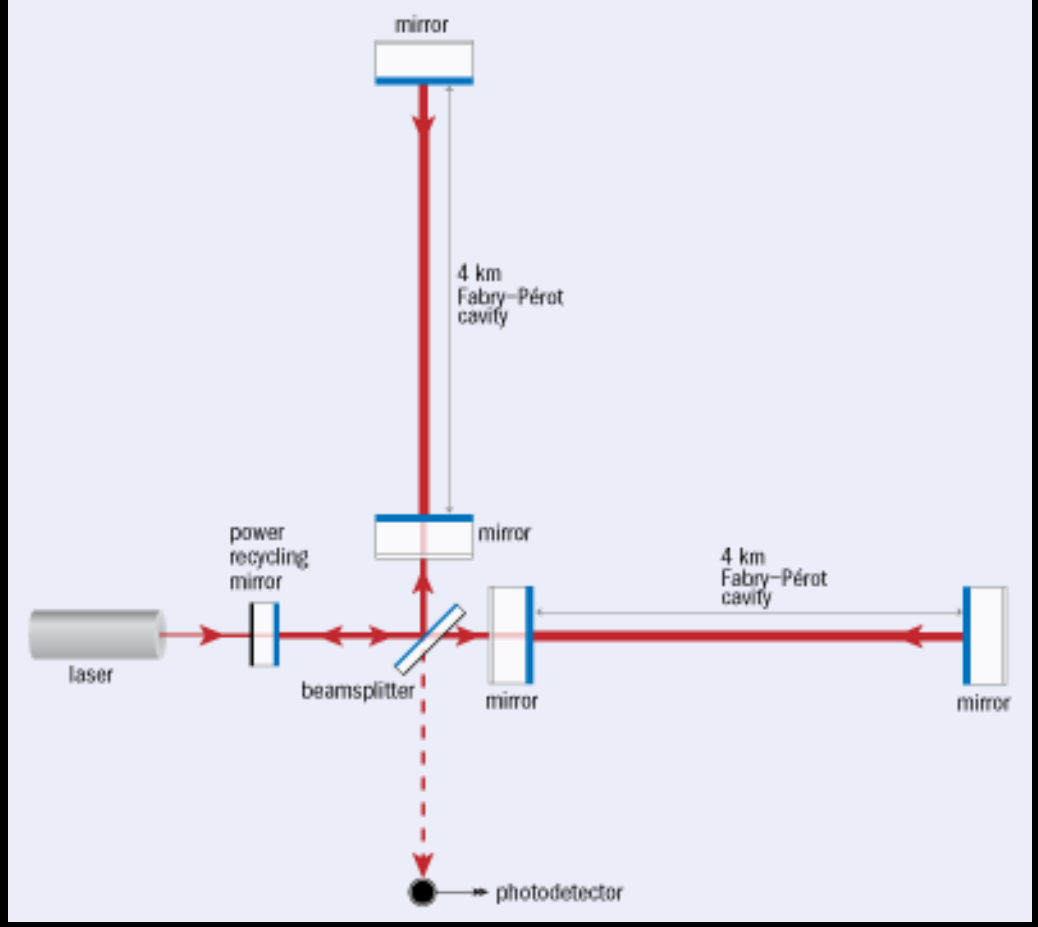
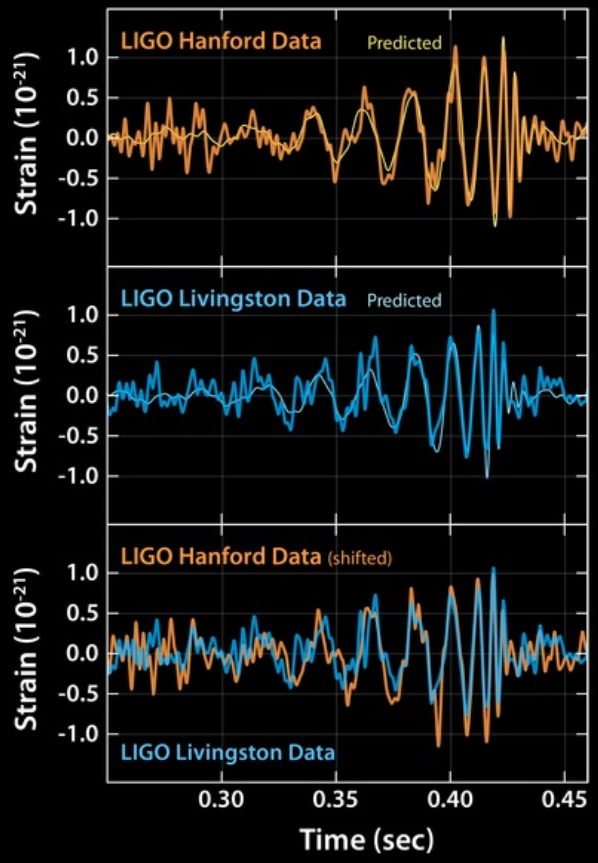


http://physicsworld.com/cws/article/news/2016/feb/11/ligo-detects-first-ever-gravitational-waves-from-two-merging-black-holes/

LIGO…

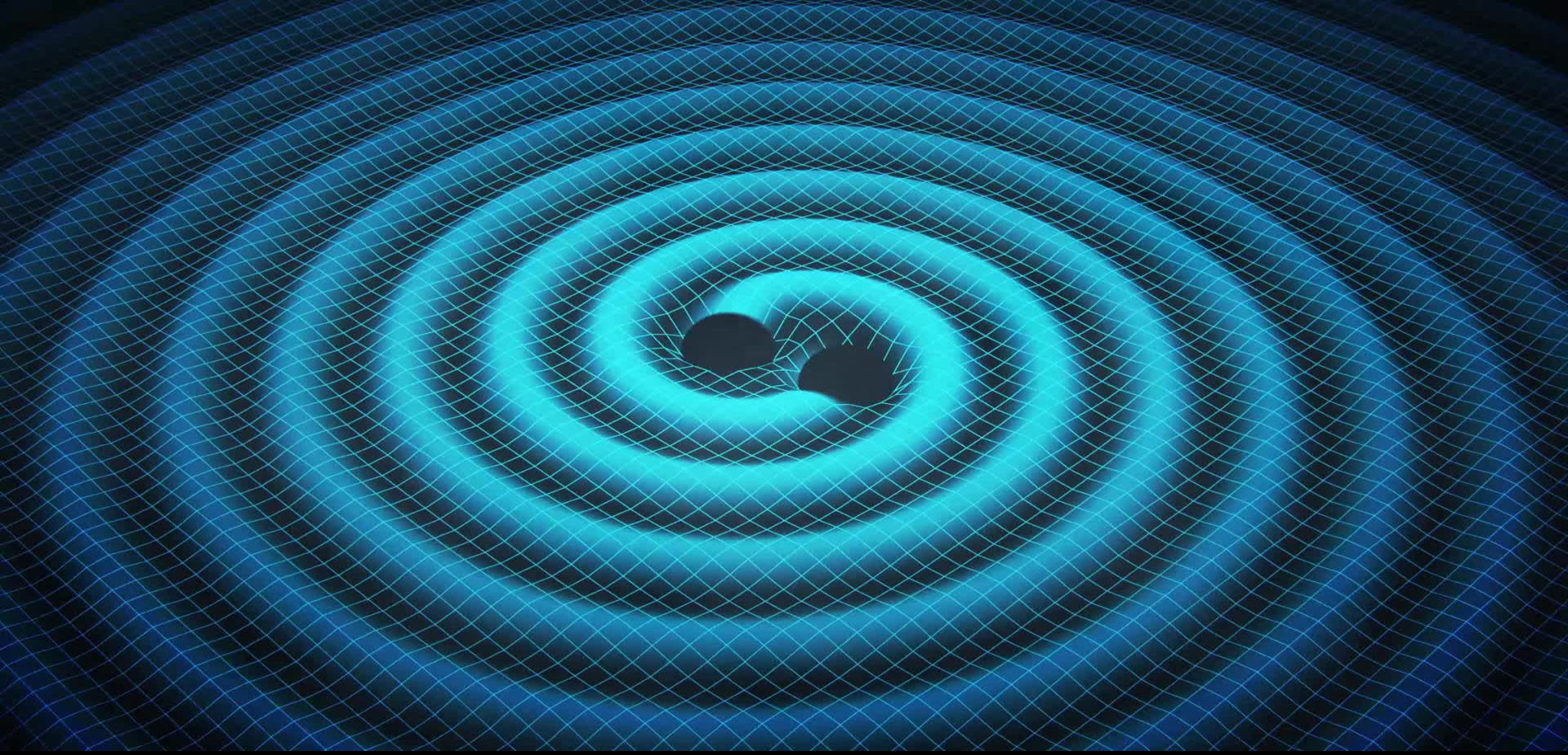
Ripples of distorted space affect the two arms differently



https://www.ligo.caltech.edu/image/ligo20160211a

LIGO…

Data from both facilities match each other and theoretical fit



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Warp Drive:
Could distorted space be used to travel globally faster than light, but not locally faster than light?

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Special Relativity: $E=mc^2$

Equivalence of Energy and Mass

General Relativity:

Fabric of spacetime distorted by large mass

The basic idea of warp drive:
Not just Sci-Fi but a hypothetical possibility!

Curvature of Spacetime = **Configuration of Matter and Energy**

“Space tells matter how to move.”
“Matter tells space how to curve.”

The basic idea of warp drive:
Not just Sci-Fi but a hypothetical possibility!

The warp drive: hyper-fast travel within general relativity

Miguel Alcubiere

Department of Physics and Astronomy, University of Wales

Class. Quantum Grav. **11** (1994)

Warp Drive:

Travel globally faster than light, but not locally.

Not just Sci-Fi but a hypothetical possibility!

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Next time…
Further discussion of “warp drive”;
Begin discussion of “Future Physics”

Barry Luokkala

Teaching Professor of Physics

Carnegie Mellon University