# *33-120*
# *Science & Science Fiction*

**Welcome!**

**Today:**

***Modern Physics* – Einstein & Relativity (continued)**

- **Problem 2** due this Friday, September 15
  - Time dilation on the ISS
  - Details on Canvas

# Announcements for Monday, September 11

- **Spacetime Field Project Day: Monday, 9/18 (one week from today)**
  - **Einstein's *Principle of Equivalence***
  - **No lecture – gather data for project**
  - **Team assignments on Canvas (soon)**
  - **Pick up equipment this week**

**Previews of coming attractions…**

- **Special Theory of Relativity**
  - ***Spacetime* as a 4-dimensional "fabric"**
  - **Perception of space and time depend on relative motion**
    - **Moving clocks run slow relative to clocks at rest.**
    - **Time travel is possible! (into the future but not the past)**

**Review of Special Relativity so far…**

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

- Moving clocks run slow relative to clocks at rest.
- Take a round trip at close to the speed of light.
- Come home after 6 months (ship time) and arrive hundreds of years in the future (Earth time).

**Is time travel possible?**
**YES! (into the future but not the past)**

- **Special Theory of Relativity, continued:**
  - **Speed of light constant for everyone**
    - **Only *massless* particles can travel at the speed of light.**
    - **Nothing can travel faster than light.**

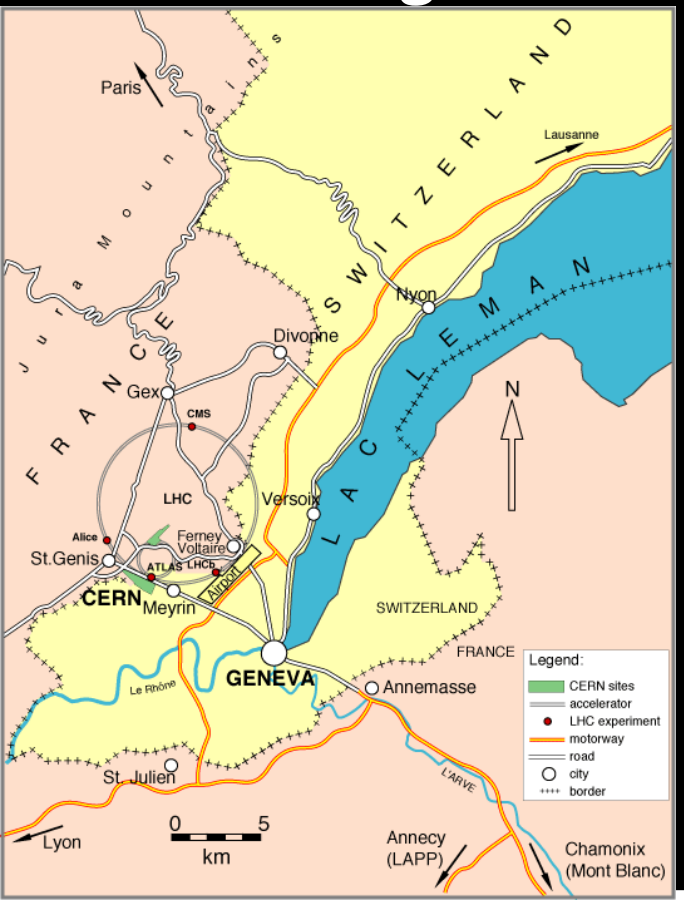
**The constancy of the speed of light**

# *The Big Bang Theory*
# "The Isolation Permutation"

**Directed by Mark Cendrowski**
**Warner Brothers (2011)**

**Can anything travel faster than light?**

# Breaking News from CERN, 23 September 2011




***Neutrinos from Large Hadron Collider (LHC)***

***Detected at Gran Sasso (Rome)***

***in less time than expected.***

***v > c ???***


**“Faster-than-light particles at CERN: paradigm-shifting discovery, or just another Swiss export, as full of holes as their cheese?”**

**- Sheldon Cooper, 11/03/2011**

- Neutrino speed apparently exceeded speed of light by few parts per million.
- Einstein says nothing can travel faster than light.
- Is this a paradigm shift? (Was Einstein wrong?)

**"Faster-than-light particles at CERN: paradigm-shifting discovery, or just another Swiss export, as full of holes as their cheese?"**

**- Sheldon Cooper, 11/03/2011**

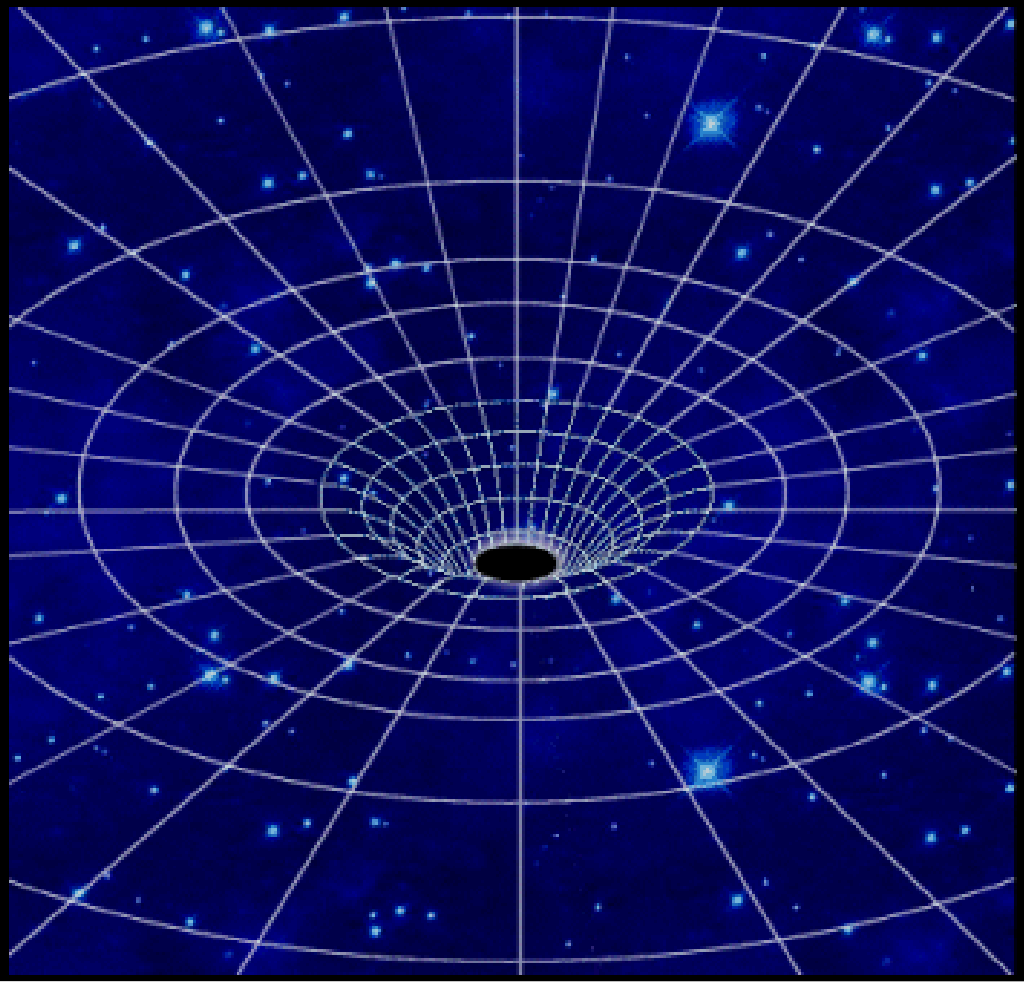
- **Papers published to explain it…**
  - **Claimed support for quantum gravity**
- **Or was there a simpler explanation?**
  - **YES! An identifiable mistake**
    **(faulty connection in timing system)**
- **The laws of physics are safe (for now).**
- **Quantum gravity papers retracted**

**"Faster-than-light particles at CERN: paradigm-shifting discovery, or just another Swiss export, as full of holes as their cheese?"**

**- Sheldon Cooper, 11/03/2011**

- **General Theory of Relativity**
  - **Gravity = distortion of *spacetime* near a large mass**
    - **gravitational time dilation**
  - **Black Holes (extreme distortion)**
  - **Gravitational waves**
    - **Effects of gravity propagate at speed of light, NOT instantaneously**

**General Relativity:**
**Another way to mess with your perception of time**



# General Relativity:
# Fabric of spacetime distorted (stretched) near large mass

*33-120 Science & Science Fiction*

- **Gravitational Time Dilation:**

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

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

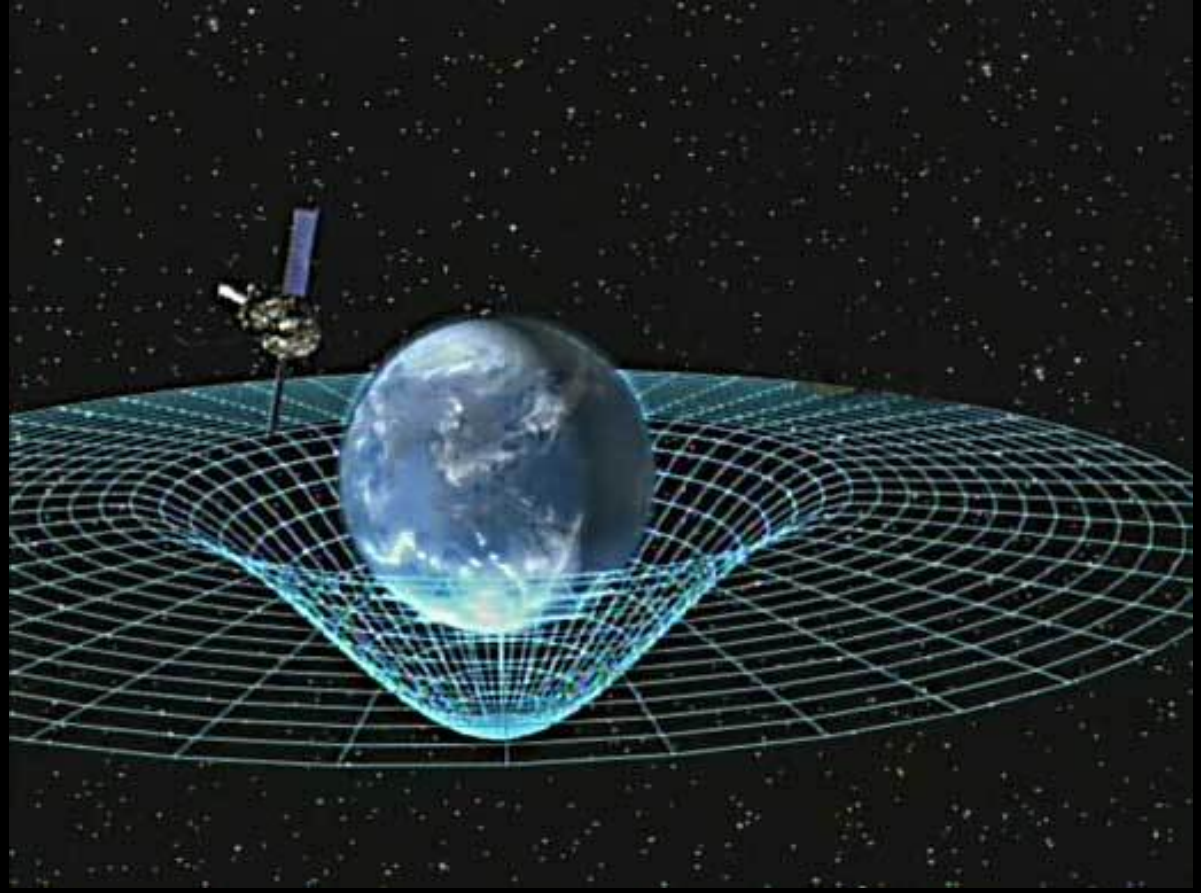
**General Relativity:**
**Clocks run more slowly when closer to large mass**

# *Tomorrow Never Dies*

**Directed by Roger Spottiswoode**

**MGM/United Artists (1997)**

**Practical application of Relativity**



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

# Today…
# GPS: A Practical application of Special Relativity and General Relativity

***33-120 Science & Science Fiction***

# Global Positioning System (GPS)

- General Relativity: clocks run slow near large mass

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

- Special Relativity: moving clocks run slow

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

**Practical application of Relativity:**
**Two competing effects for GPS**

# 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 $10^{10}$

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

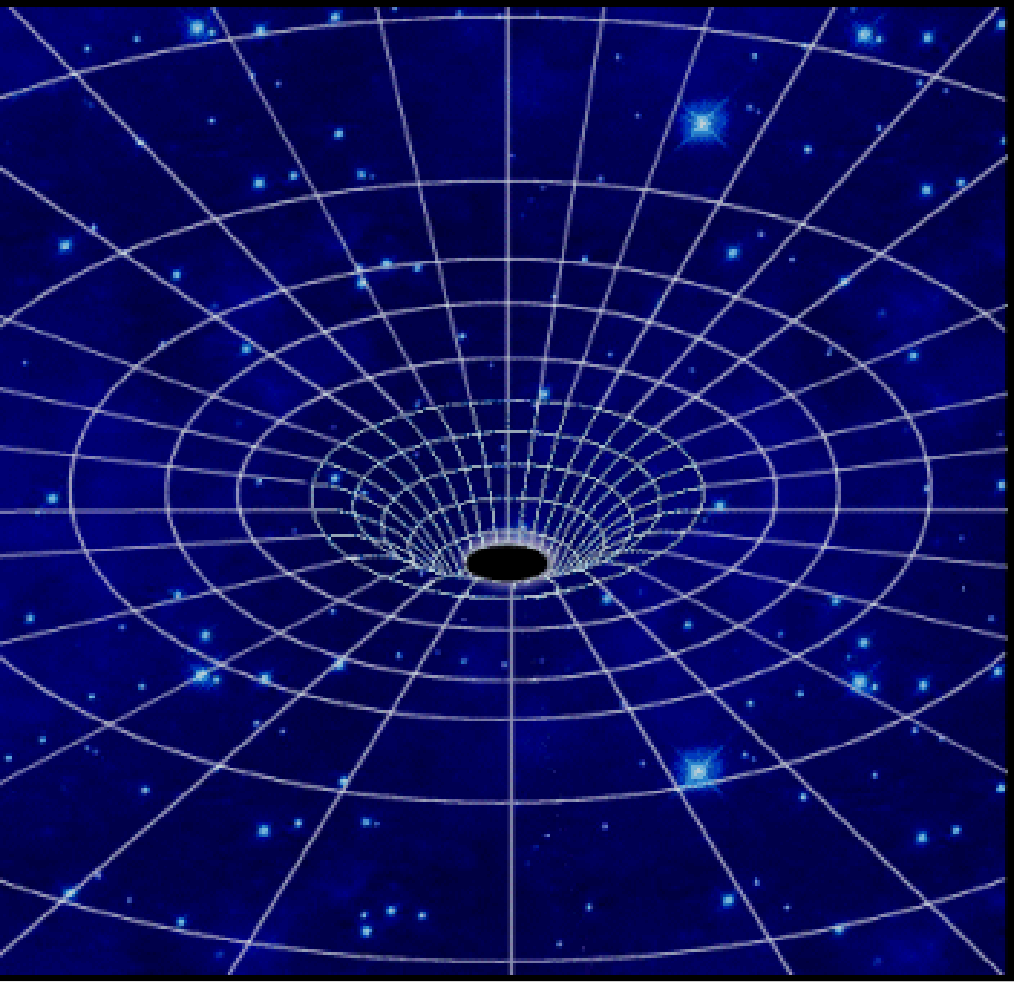
**Practical application of Relativity:**
**Two competing effects for GPS**

**What happens to the fabric of *spacetime* in the presence of a gravitationally completely collapsed object (a.k.a. a black hole)?**

**What happens to the fabric of *spacetime* when two such objects meet in space?**

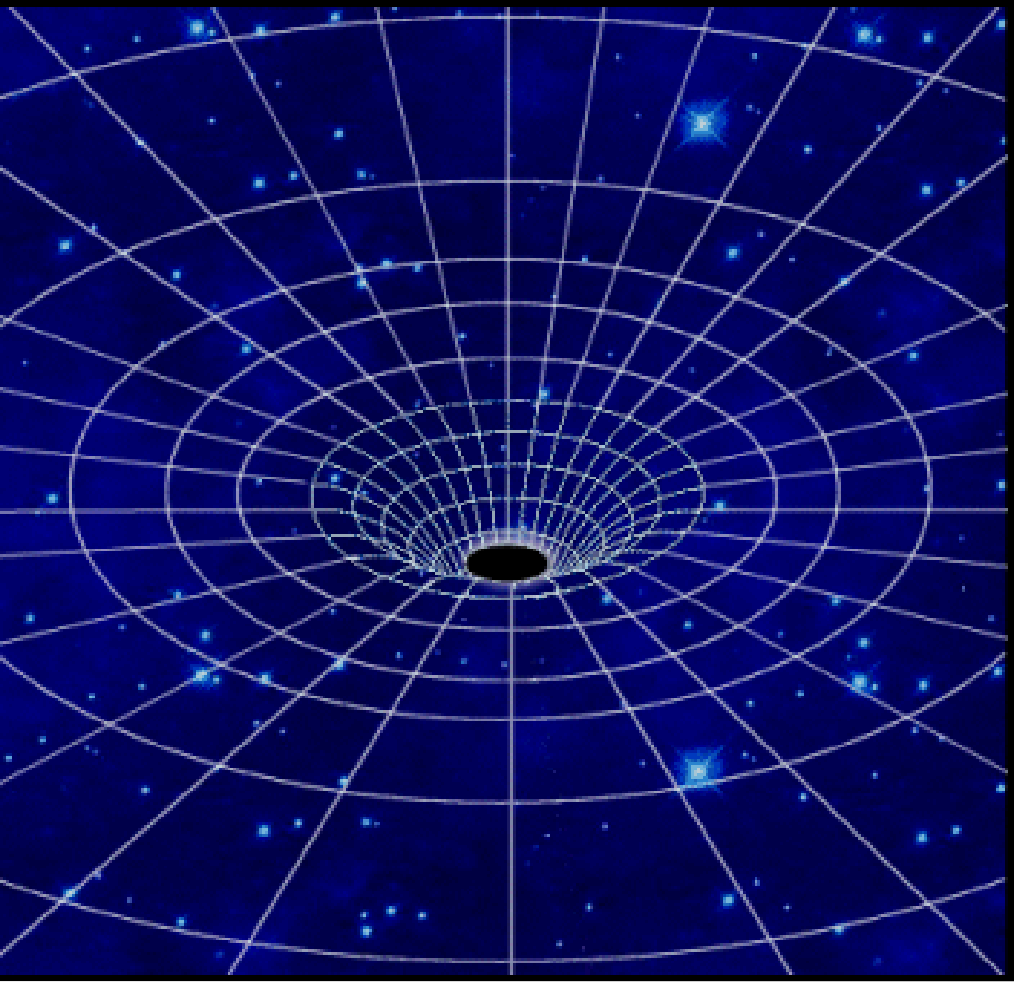
**Is something like a *Star Trek* "warp drive" hypothetically possible?**

**More applications of General Relativity…**
**Black Holes, Gravitational Waves, Warp Drive**



- Gravitationally completely collapsed object
- Event horizon:  point of no return, beyond which not even light can escape
- Curvature of spacetime may be so severe that classical physics breaks down

# Black holes



- The term “black hole” (*black star*) foreshadowed in Sci-Fi (January 1967)
- “Black hole” first used by John Wheeler (Dec. 1967)
- Easier to say than “gravitationally completely collapsed object”

# Black holes

# *Star Trek (original series)*
# "Tomorrow is Yesterday"

**Written by D.C. Fontana**

**Paramount (1967)**

**Origin of the term "black hole"…**
**Foreshadowed in sci-fi months before first use in scientific discussions**

# *The Black Hole*

**Directed by Tibor Takacs**

**Equity Pictures (2005)**

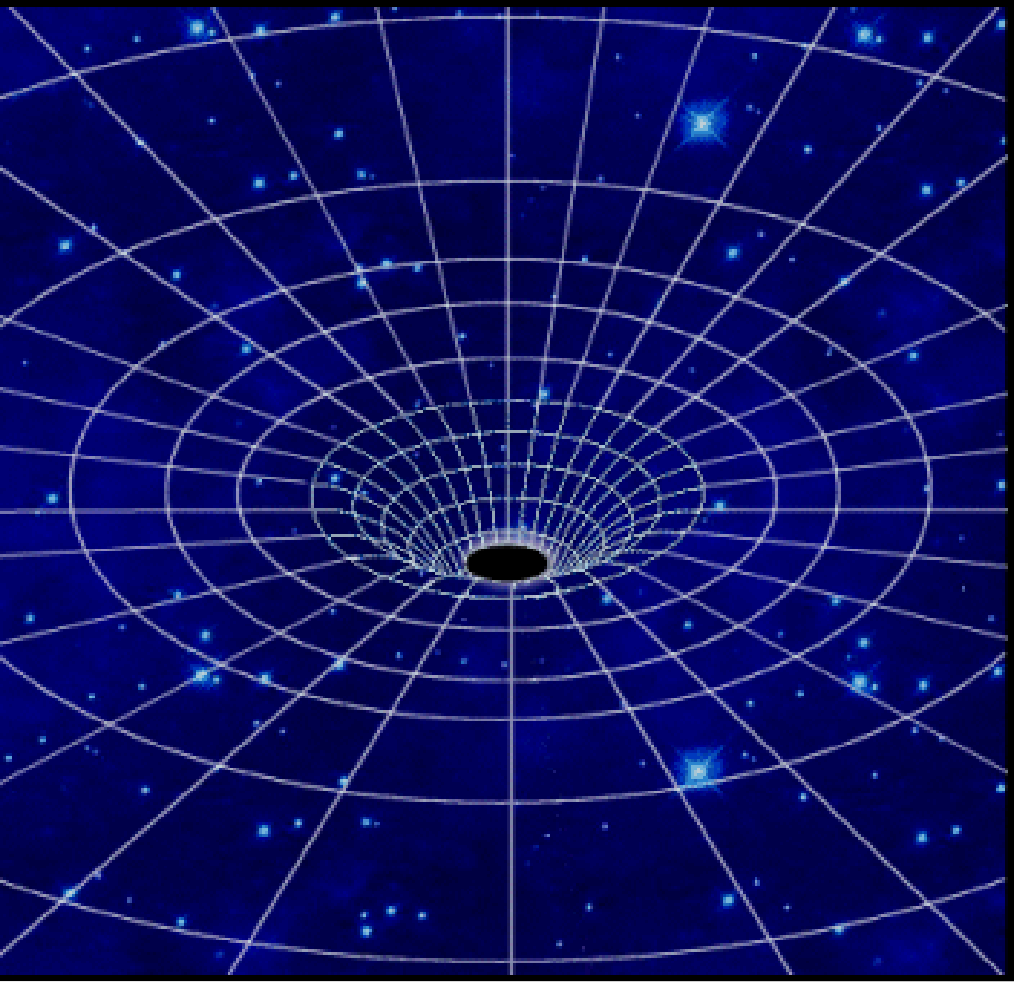
**Movie depiction of a black hole…**
**(doesn’t get much worse than this)**

# Start-up of the LHC: 10 Sept. 2008

# Protests in Europe:  fear of black holes

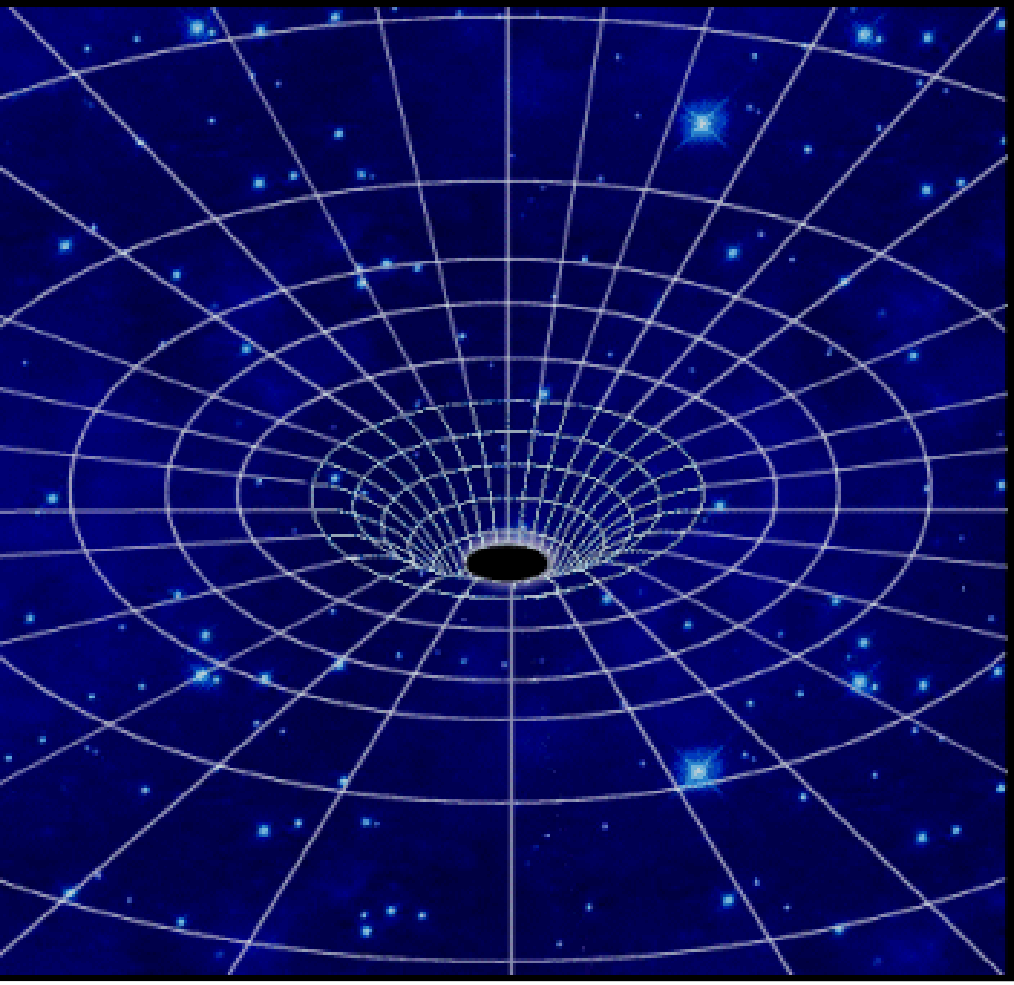

# CMU Fence painted (by physics majors?)

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



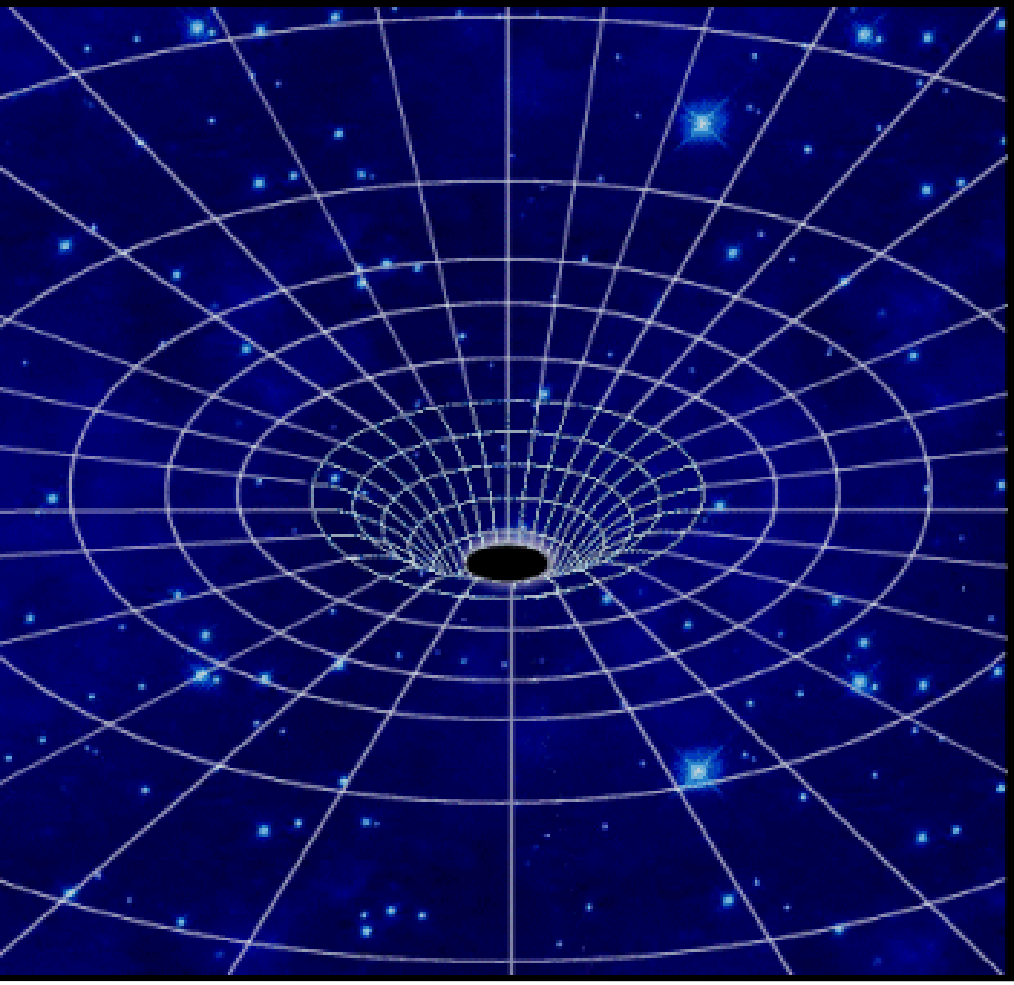
- Gravitationally completely collapsed object
- Event horizon:  point of no return, beyond which not even light can escape (they will eat everything that comes close enough)
- Hawking Radiation: black holes are not completely black!

# Properties of Black Holes



- **Hawking Radiation: black holes are not completely black!**
- **A black hole must *feed* or it will eventually *evaporate*.**
- **Timescale for evaporation depends on size (smaller ones evaporate faster)**

# Properties of Black Holes



- **Gravitationally completely collapsed object**
- **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

# *Despicable Me*

**Directed by Chris Renaud & Pierre Coffin**

**Universal (2009)**

**Inspiration for Problem 3 (Due September 27)**
**Calculate the Schwarzschild Radius for the Moon**

***33-120 Science & Science Fiction***

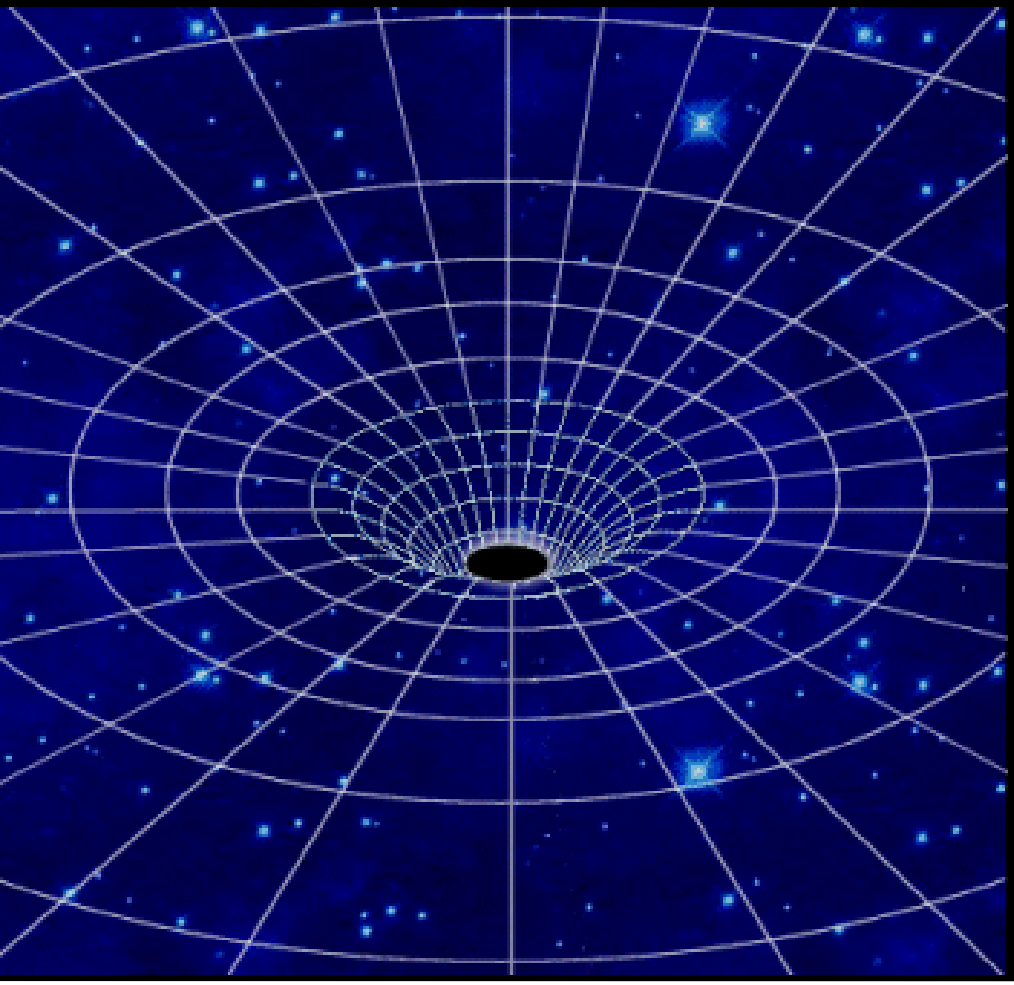
# *Despicable Me*

**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 Feb. 15)**
**Calculate the Schwarzschild Radius for the Moon**

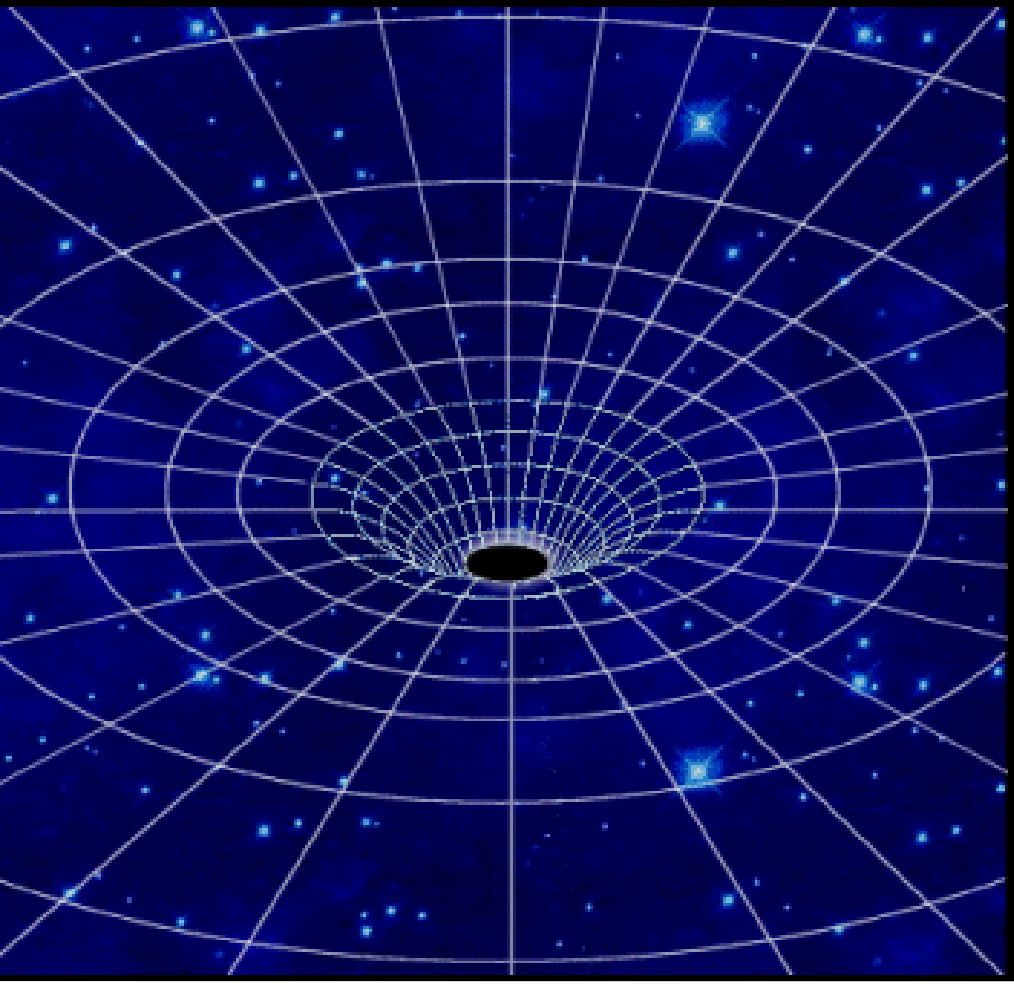


- **Event horizon: point of no return, beyond which not even light can escape**
- **Schwarzschild Radius:**

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

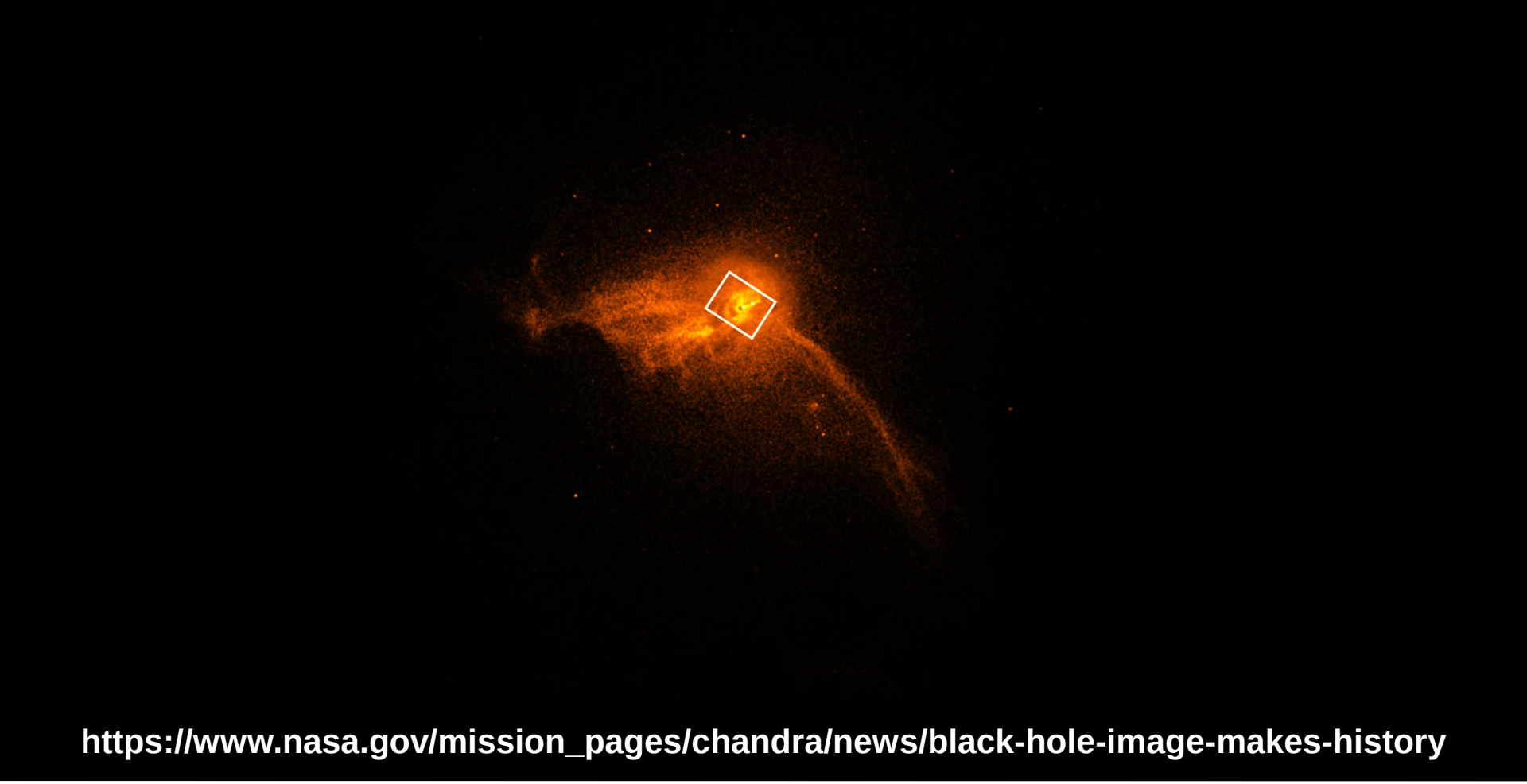
- **A Black Hole has a Schwarzschild Radius larger than its actual physical radius**

# Properties of Black Holes



- **Gravitationally completely collapsed object**
- **Most important: Black holes are <u>real</u>, not just sci-fi**

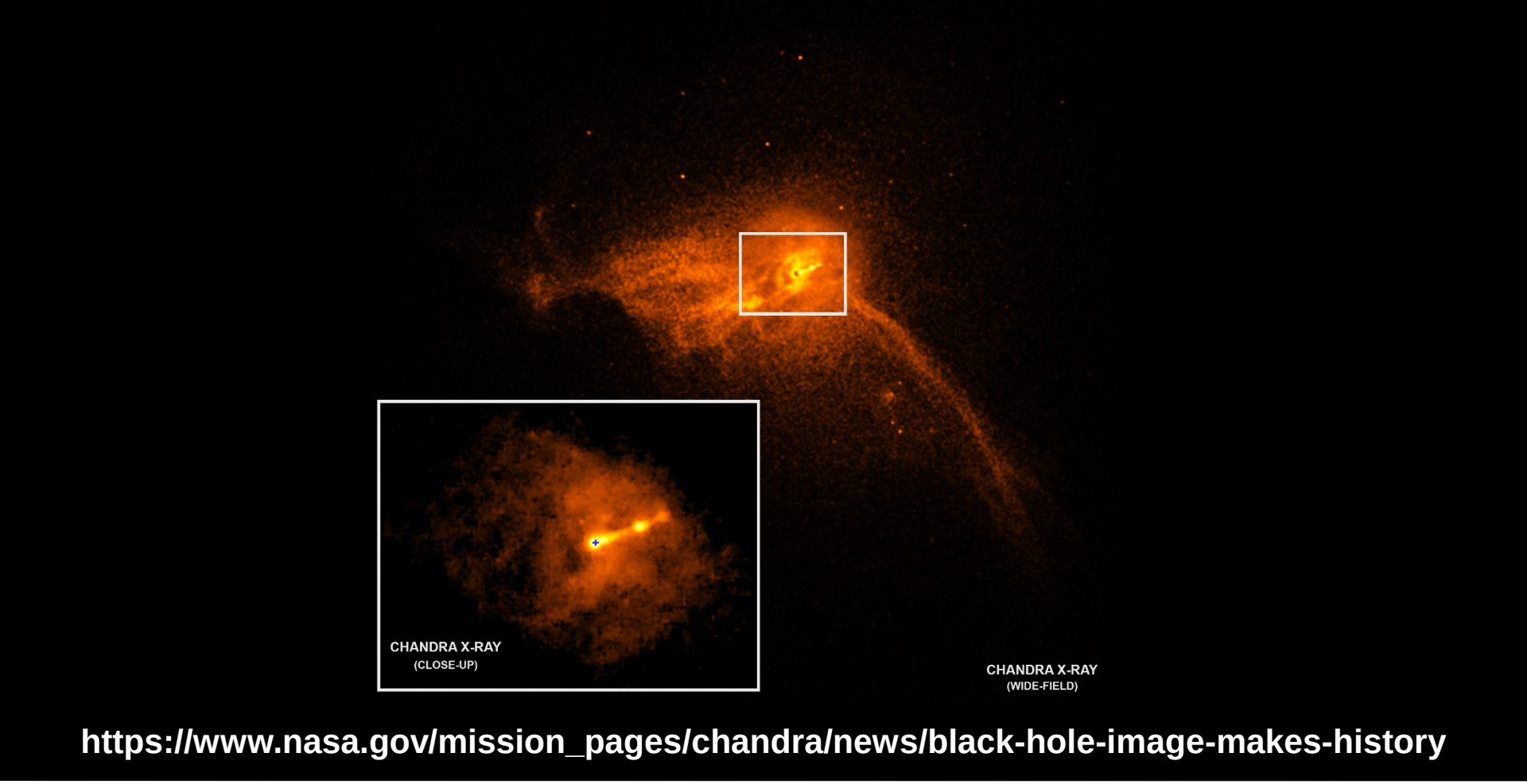
# Properties of Black Holes



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

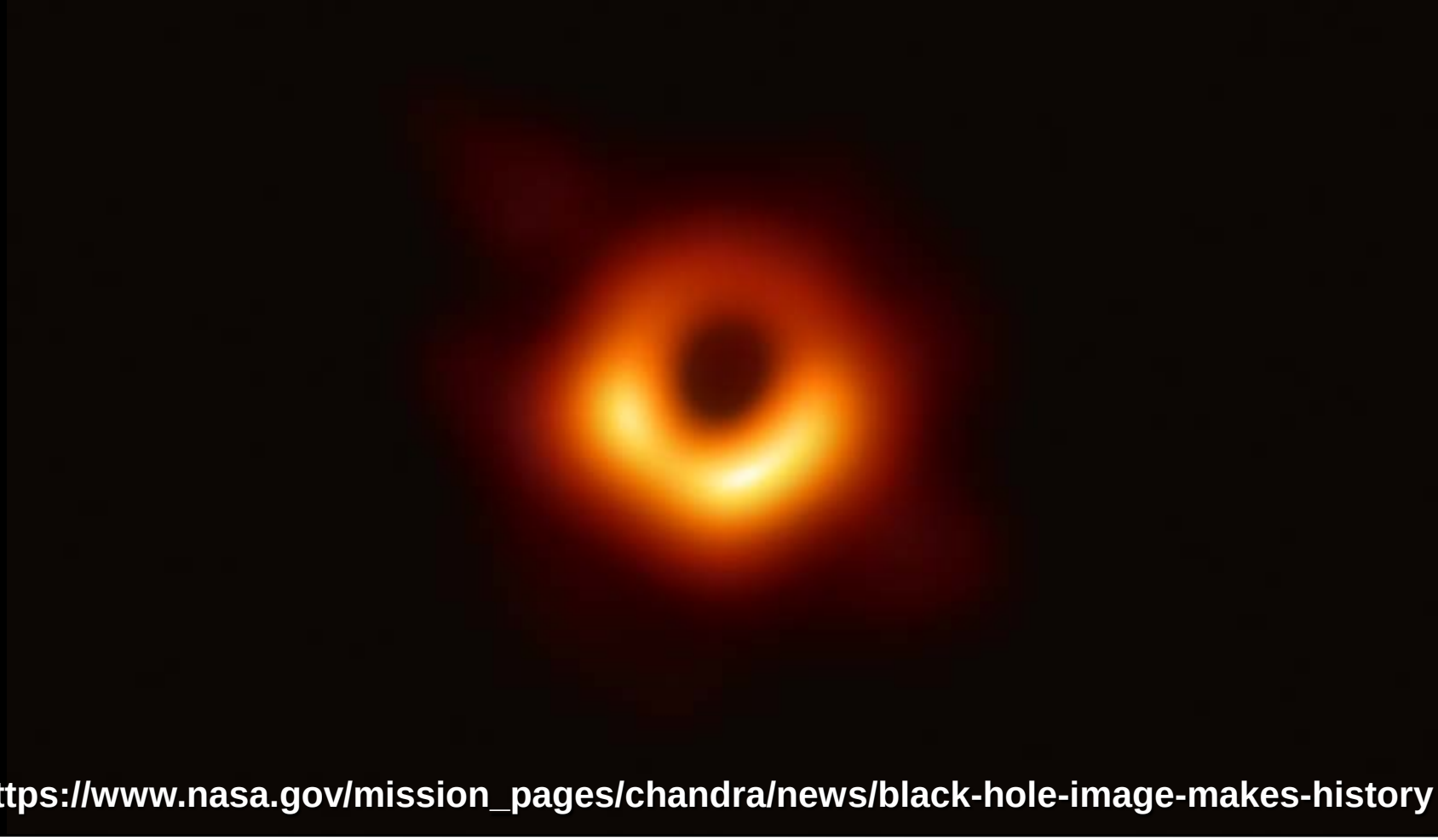
*33-120 Science & Science Fiction*




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

*33-120 Science & Science Fiction*



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

*33-120 Science & Science Fiction*

## *Next time…*
## *Can a black hole be used for time travel?*
## *Gravitational Waves and Warp Drive*

*Barry Luokkala*

*Teaching Professor of Physics*

*Carnegie Mellon University*

*Q&A…*