

# Today's Topics

Monday, March 30, 2026 (Week 9, lecture 24) – Chapter 24.

A. Special Relativity review.

B. General Relativity.

C. Gravitational redshift.

D. Gravitational Waves.

E. Black holes.

**Problem Set #8** is due on ExpertTA on Friday, April 3, 2025, by 9:00 AM

**Midterm #2** will be on Monday, April 6, 2025.

# Today's Topics

Monday, March 31, 2025 (Week 9, lecture 23) – Chapter 24.

## A. Special Relativity review.

What happens when you travel close to the speed of light “ $c$ ”

## B. General Relativity.

## C. Gravitational redshift.

## D. Gravitational Waves.

## E. Black holes.

# Today's Topics

Monday, March 31, 2025 (Week 9, lecture 23) – Chapter 24.

## A. Special Relativity review.

What happens when you travel close to the speed of light “ $c$ ”

## B. General Relativity.

What happens when you have very strong gravity

## C. Gravitational redshift.

## D. Gravitational Waves.

## E. Black holes.

# Special Relativity (REVIEW)

## Principle of Relativity

The laws of physics are the same in all inertial reference frames.

## Corollary #1

You cannot tell if you are moving (based on local measurements) in an inertial frame.

## Corollary #2: Universal speed of light

The speed of light in vacuum is the same in all inertial frames, regardless of the motion of the source.

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Length contraction & time dilation

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Length contraction & time dilation

# General Relativity

## Equivalence Principle

A coordinate system that is falling freely in a gravitational field is (equivalent to) an inertial frame.

## Corollary

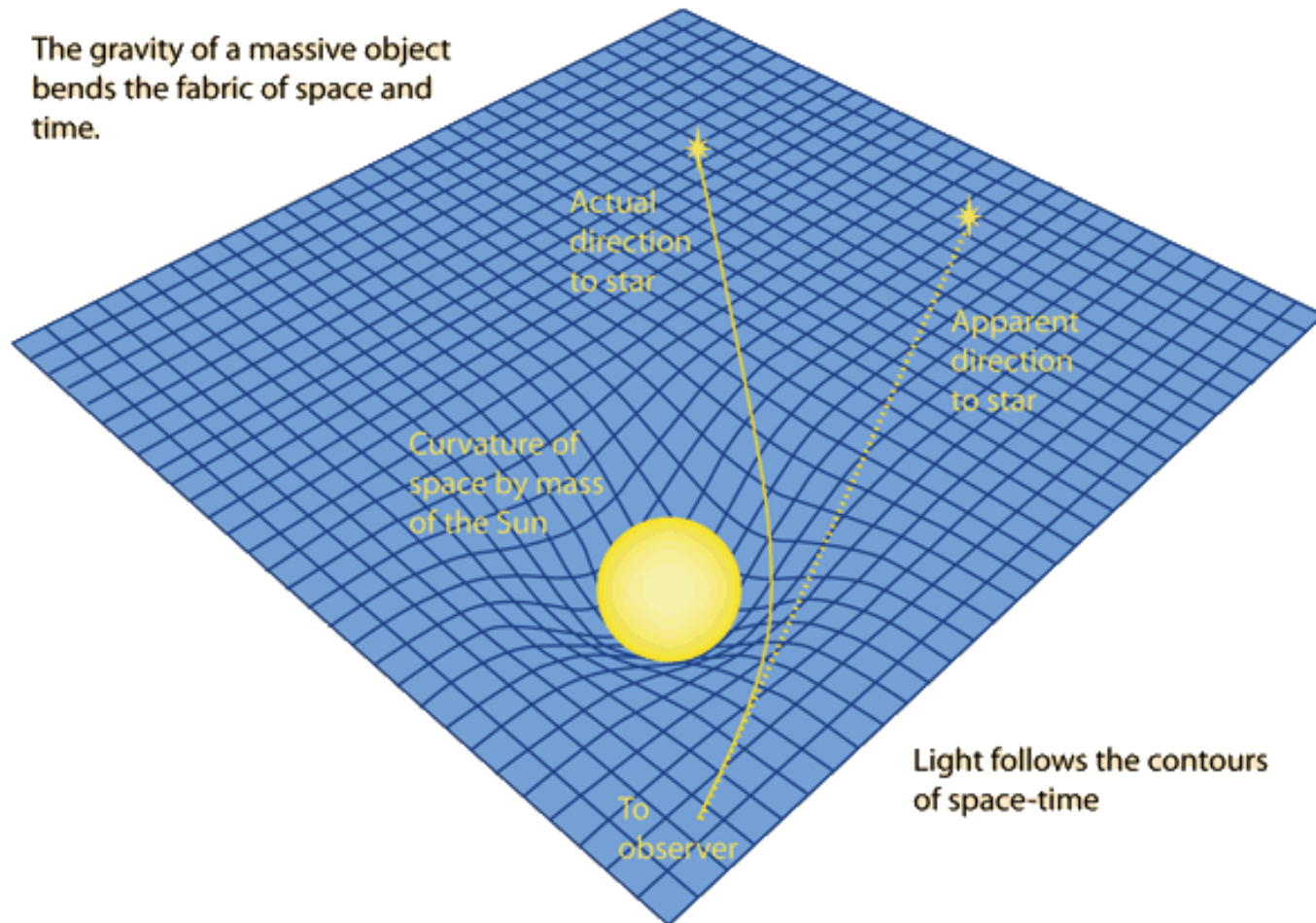
You cannot tell if you are at rest in a non-gravitational field (i.e. in a standard inertial frame) or freely falling under gravity based on local measurements.

# Equivalence Principle on ISS



# Curved Space-Time: light rays in 2D

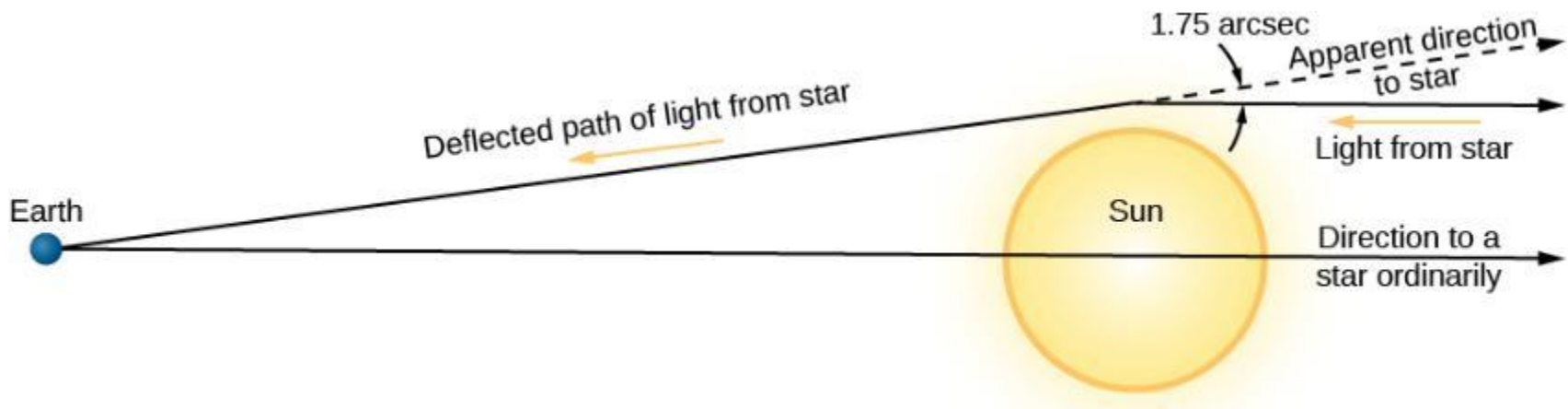
The gravity of a massive object bends the fabric of space and time.



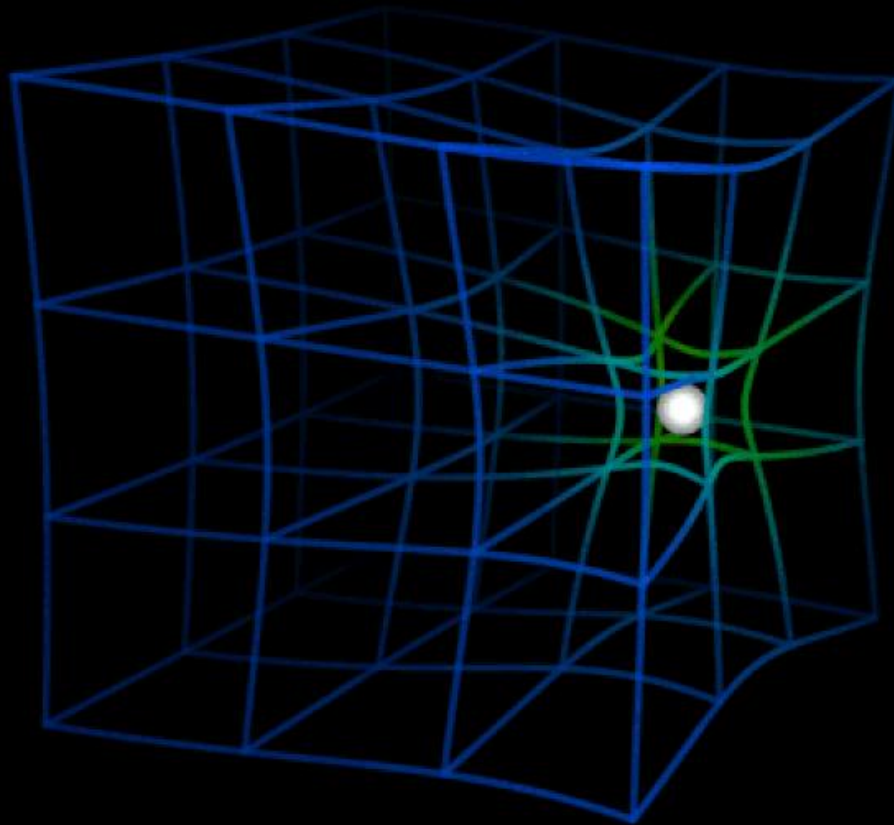
# Curved Space-Time

## *Eddington's measurement of deflection of light*

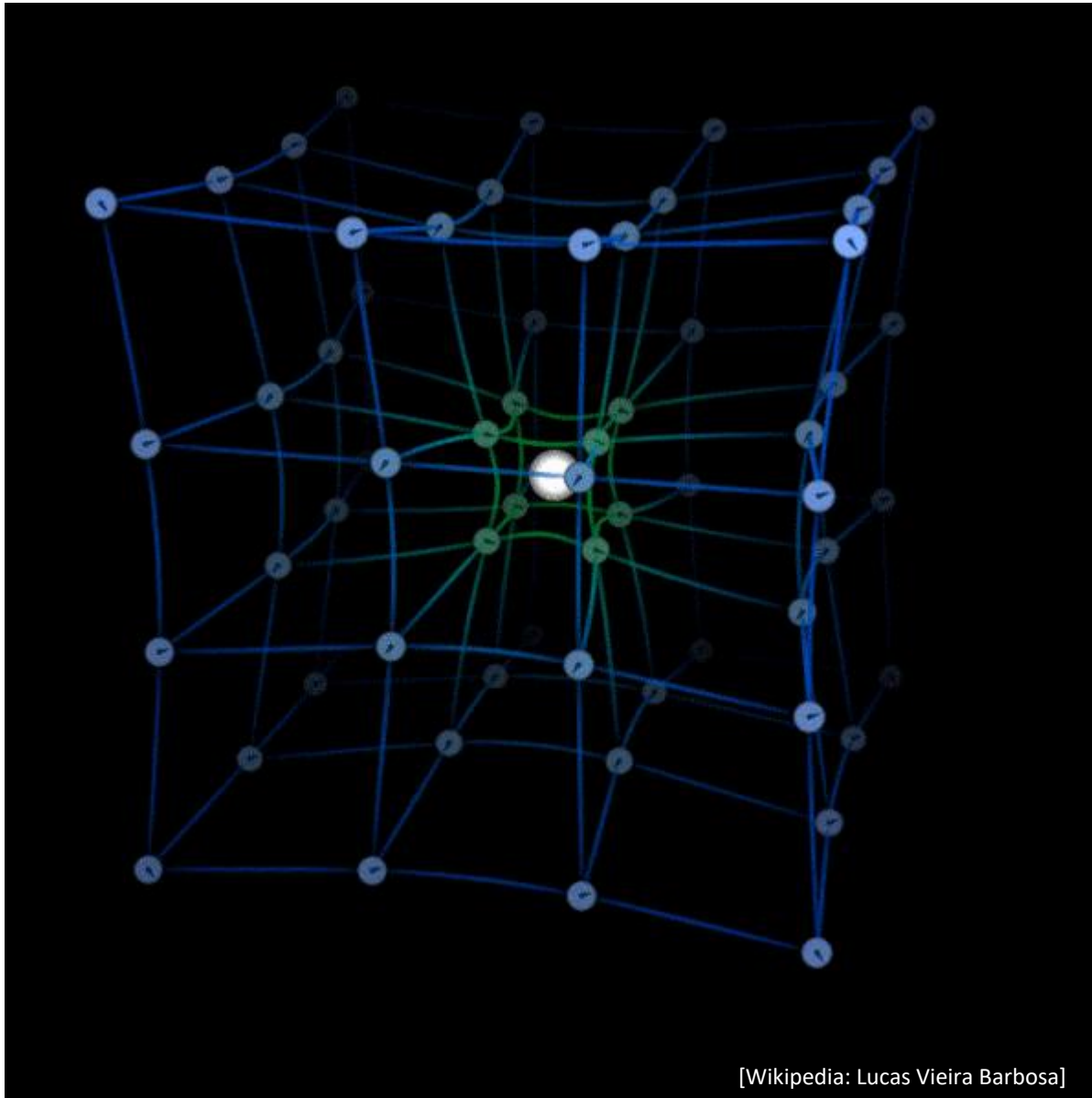
- Arthur Eddington measures the deflection of starlight by the Sun.
- 1919 solar eclipse: West Africa & Brazil.
- The star appears shifted: Measurements show deflection that agrees with General Relativity.



# Curved Space-Time



# Curved Space-Time



# Gravitational Time Dilation: small heights

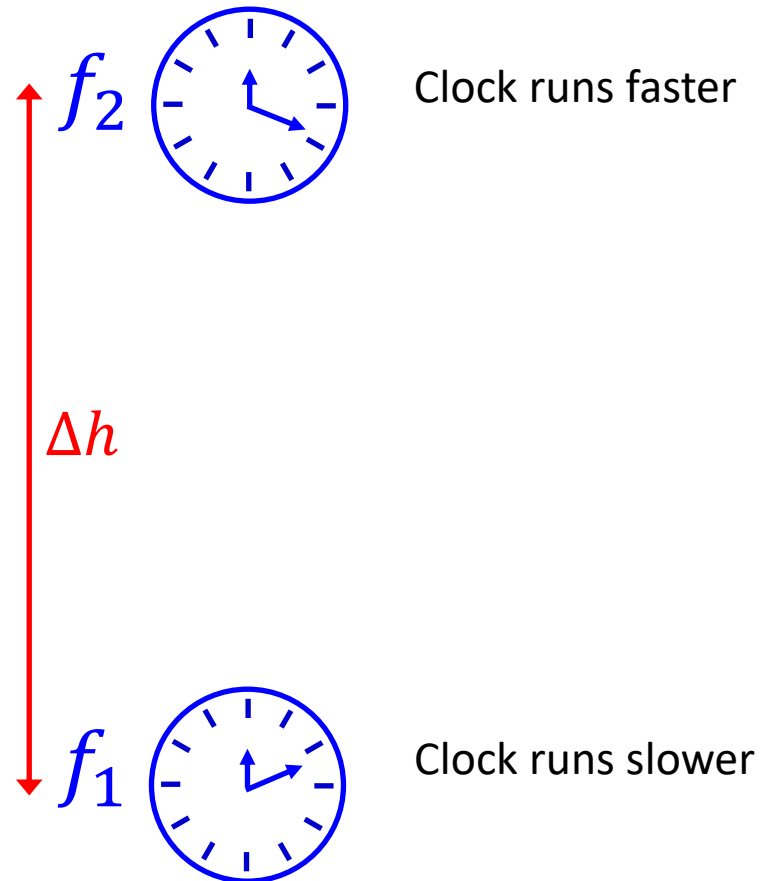
Clocks in a gravitational field run slower than clocks in free space.

For small changes in height  $\Delta h$ :

$$\frac{\Delta f}{f} = \frac{g\Delta h}{c^2}$$

$f$  = frequency of clock

$g$  = acceleration of gravity  
= 9.8 m/s<sup>2</sup> at Earth's surface



# Gravitational Time Dilation: large distances

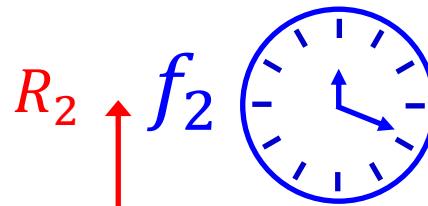
Clocks in a gravitational field run slower than clocks in free space.

$$\frac{f_2}{f_1} = \sqrt{\frac{1 - \frac{R_S}{R_2}}{1 - \frac{R_S}{R_1}}}$$

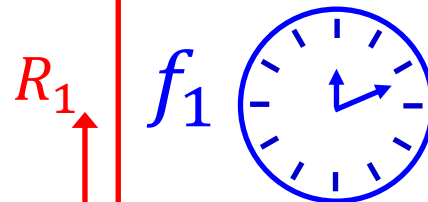
$f_{1,2}$  = frequencies at  $R_1$  and  $R_2$ .

$$R_S = \text{Schwarzschild radius} \\ = \frac{2GM}{c^2}$$

$M$  = mass of Earth, star, etc.



Clock runs faster  
“ticks faster”



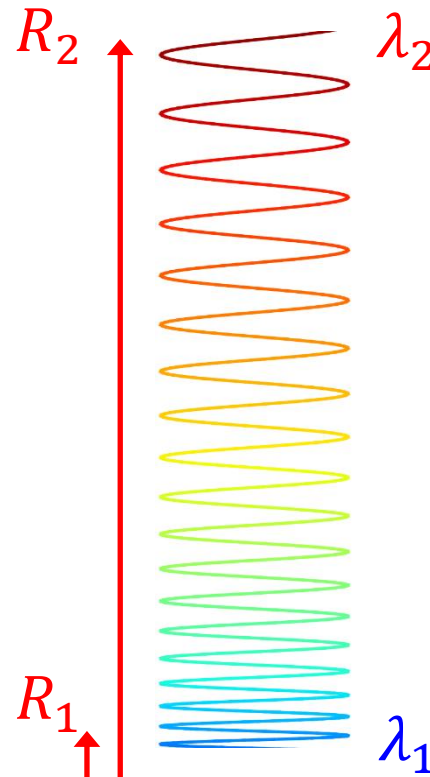
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Earth

# Gravitational Redshift:

Light shifts to the **red** when it escapes gravity

As light leaves the gravitational pull of Earth/star/blackhole, it loses “kinetic energy” and shifts to the red ( $E_{photon} = hf$ ).

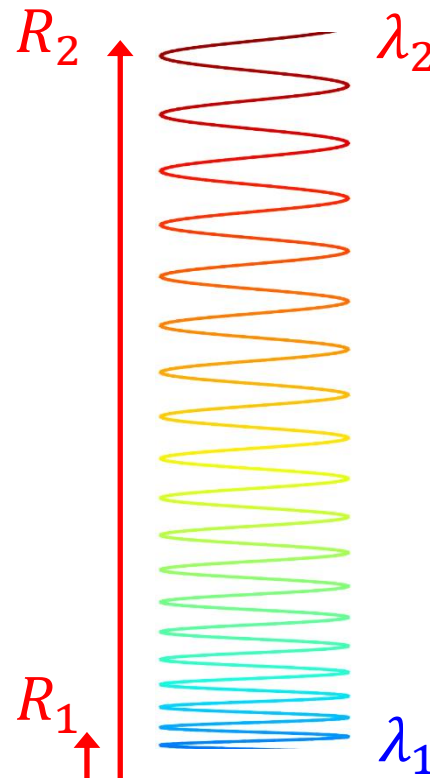


[<https://sites.google.com/site/salamcosmology/research/relativistic-effects-on-lss>]

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↑  
Planck's  
Constant  
 $h = 6.626 \times 10^{-34}$  J.S

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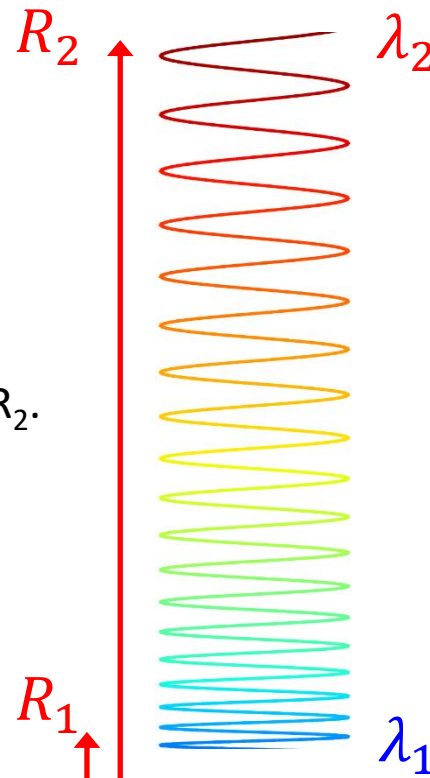
As light leaves the gravitational pull of Earth/star/blackhole, it loses “kinetic energy” and shifts to the red ( $E_{\text{photon}} = hf$ ).

$$\frac{\lambda_2}{\lambda_1} = \sqrt{\frac{1 - \frac{R_S}{R_2}}{1 - \frac{R_S}{R_1}}}$$

$\lambda_{1,2}$  = wavelengths at  $R_1$  and  $R_2$ .

$$\begin{aligned} R_S &= \text{Schwarzschild radius} \\ &= \frac{2GM}{c^2} \end{aligned}$$

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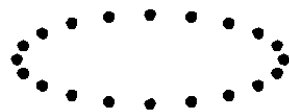
Earth

# Gravitational Waves

- Accelerating and **orbiting** masses will emit gravitational waves.
- Gravitational waves are a consequence of the **finite speed of gravity** (*speed of light*).
  - a change in gravity's strength propagates at the speed of light.  
(i.e. it's not instantaneous.)
- Only large masses emit significant gravitational waves.
  - Orbiting **black holes** and **neutron stars**.
  - Masses must be close together (i.e. fast moving) for significant emission.

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- A passing gravitational wave applies weak pulling & stretching forces along two perpendicular axes.



“+” polarization

or



“x” polarization

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“+” polarization

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“x” polarization

# Gravitational Wave “Telescope”

LIGO: Laser Interferometer Gravitational-Wave Observatory



# Black Holes

## Black hole

A celestial object whose gravity is so strong that even light cannot escape from it.

- Light emitted outside of the **event horizon** (i.e. **Schwarzschild radius**) can escape.
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- The **event horizon / Schwarzschild radius** defines the size and surface of a black hole.

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$$\text{Schwarzschild radius} = R_S = \frac{2GM}{c^2}$$

*The **event horizon** is about 2-3 times smaller than the black shadow.*

Supermassive black hole at center of M87 galaxy.



[Event Horizon Telescope, [www.eso.org](http://www.eso.org),  $\lambda=1.3$  mm]

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Computer simulation of accretion disc around a black hole.

[NASA's Goddard Space Flight Center/Jeremy Schnittman]

**PolleEv Quiz:** [PolleEv.com/sethaubin](http://PolleEv.com/sethaubin)

# 2020 Nobel Prize in Physics

## Black Hole Physics & Astronomy



**Roger Penrose**  
(U. of Oxford)



**Reinhard Genzel**  
(Max Planck Inst.)



**Andrea Ghez**  
(UC Los Angeles)

# 2020 Nobel Prize in Physics

## Black Hole Physics & Astronomy



[Source: Cirone-Musi, Festival della Scienza, CC BY-SA 2.0]

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Black hole  
physics & mathematics



[Source: Max Planck Institute for Extraterrestrial Physics]

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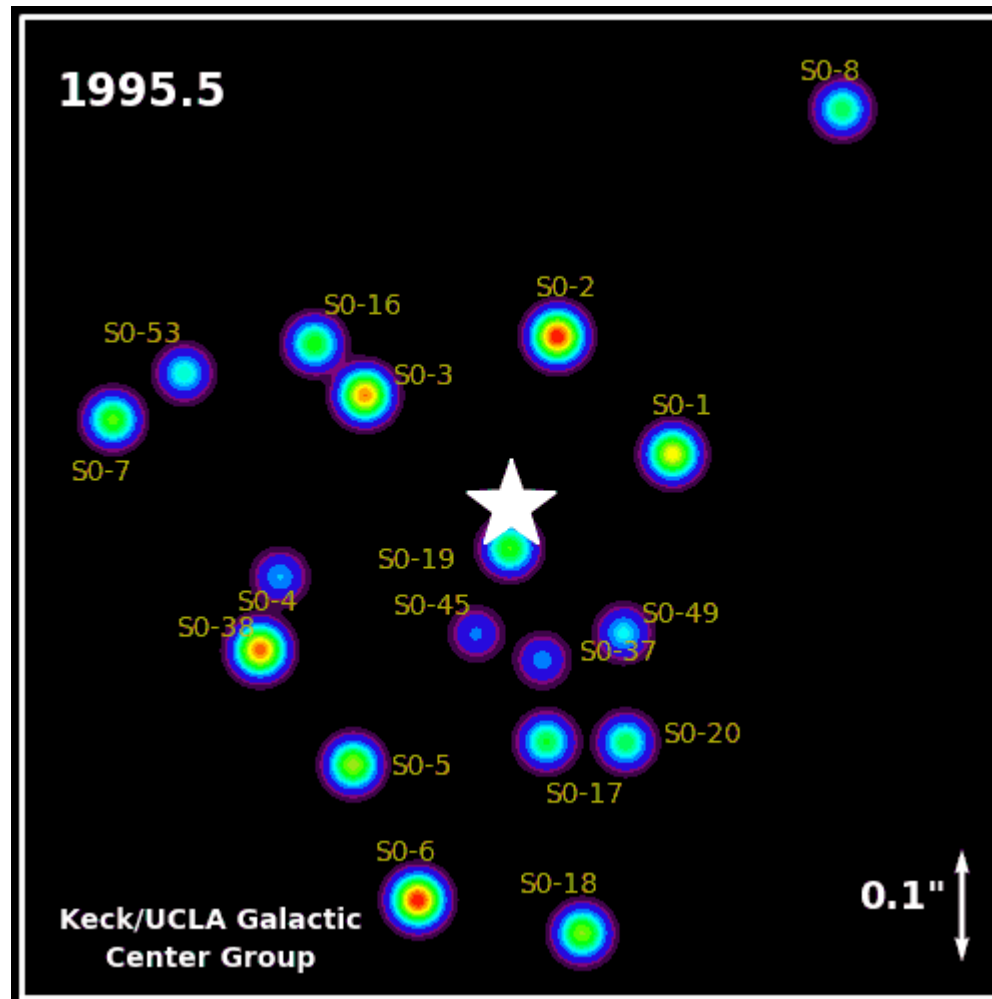
[Source: Christopher Dibble]

Andrea Ghez  
(UC Los Angeles)

Discovery of the black hole at the center  
of our Milky Way galaxy

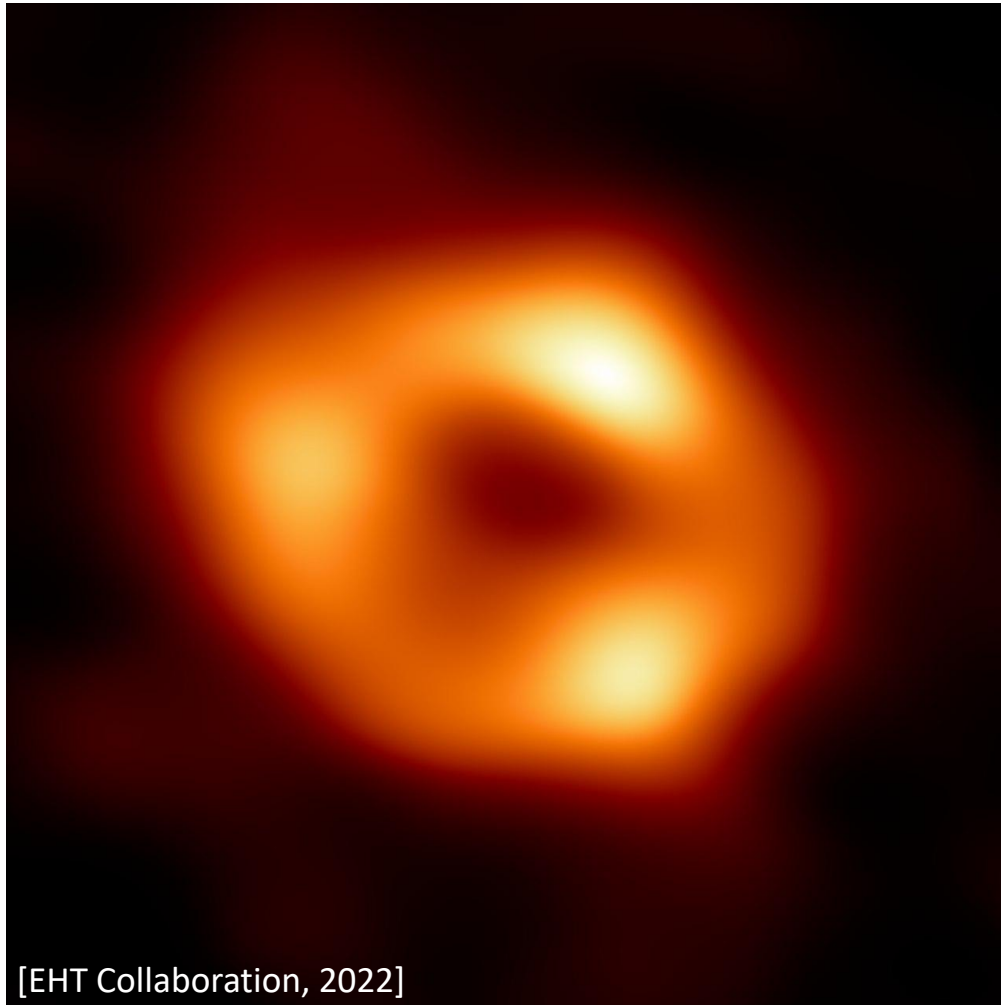
# Black Hole at center of Milky Way

The Sagittarius A\* supermassive black hole



# Black Hole at center of Milky Way

The Sagittarius A\* supermassive black hole



[EHT Collaboration, 2022]

Mass = 4 million  $M_{\text{Sun}}$

# What happens if you fall into a Black Hole?

## Stellar mass black hole

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- Any object falling towards the event horizon is **pulled apart** (spaghettified) by the strong **gravity gradient** (tidal force) of the black hole.

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**Gravitational time dilation:** The object appears to slow down as it gets closer and closer to the event horizon.

→ Very close to the event horizon, the object becomes too redshifted to be well seen and also appears to come to a standstill.

*(note: in frame of object, the object falls into black hole.)*