Today’s Topics

Wednesday, November 11, 2020 (Week 12, lecture 33) – Chapter 24.

A. Special Relativity review.

B. General Relativity.

C. Gravitational redshift.

D. Gravitational Waves.

E. Black holes.

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What happens when you travel close to the speed of light "c"

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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.

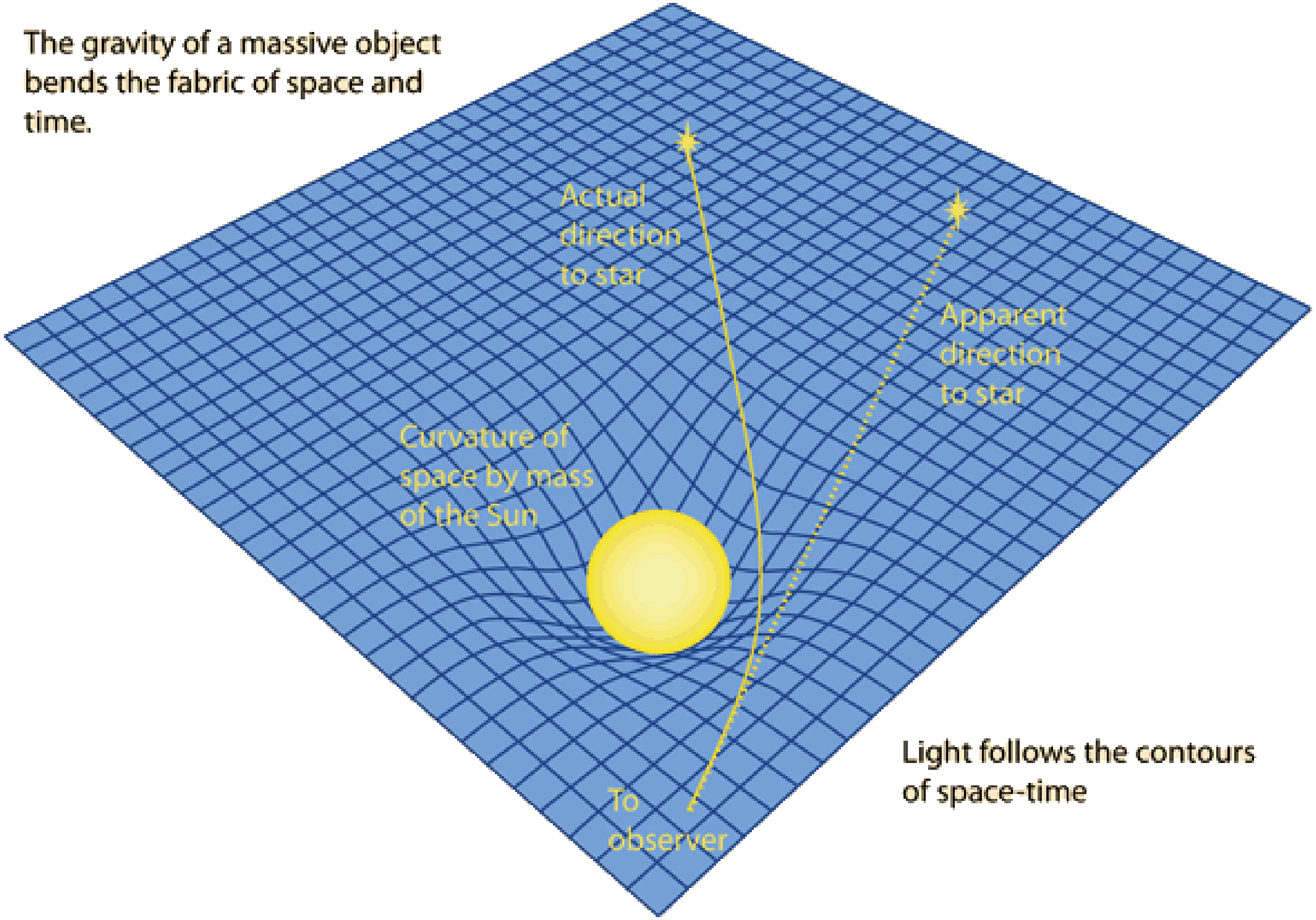
Corollary

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 in based on local measurements.

Equivalence Principle on ISS

[NASA]

Curved Space-Time: light rays in 2D



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

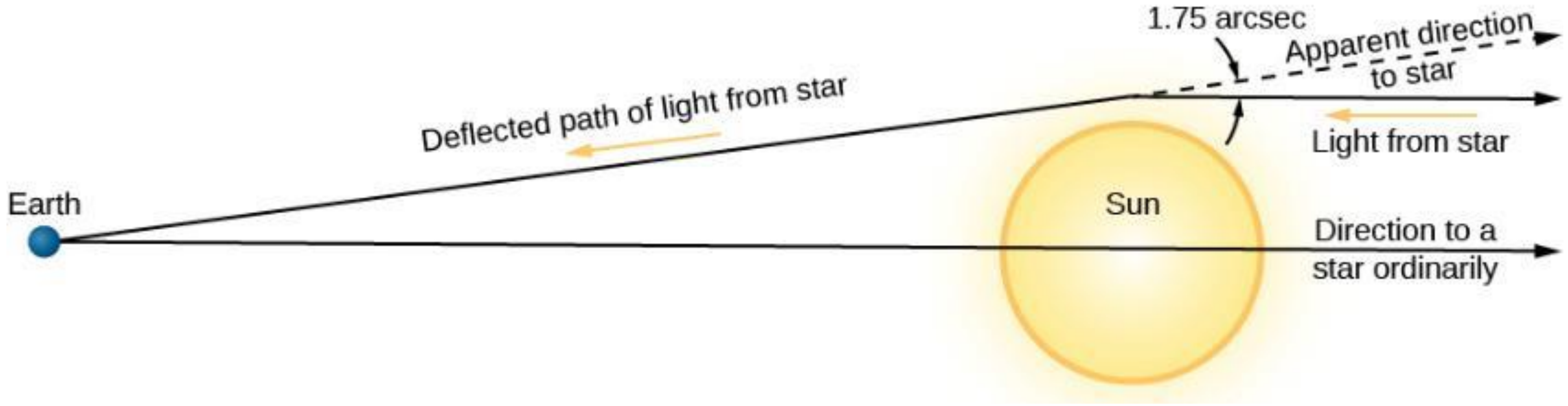
Light follows the contours of space-time

[http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/grel.html]

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.



[OpenStax: Astronomy]

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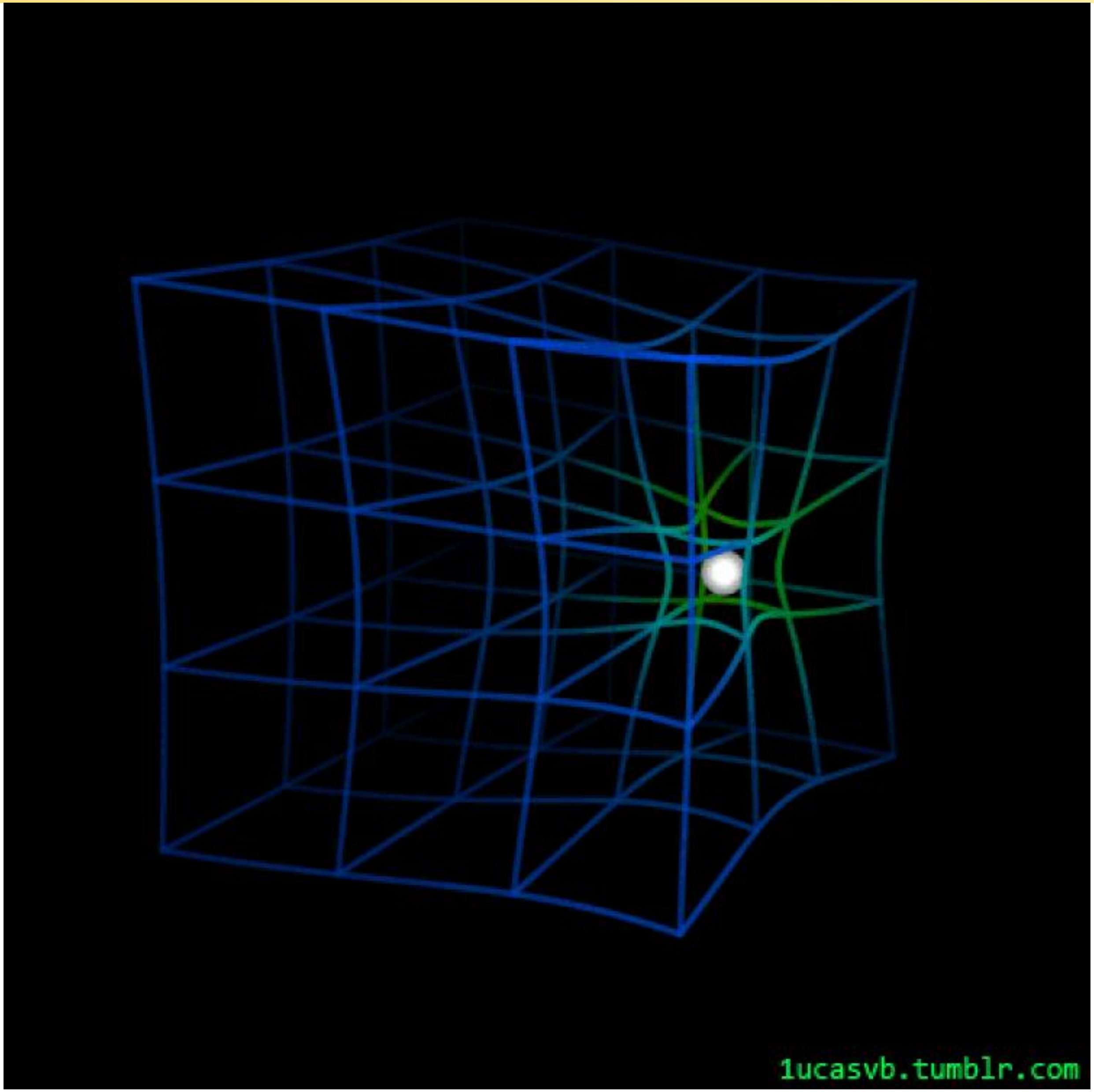

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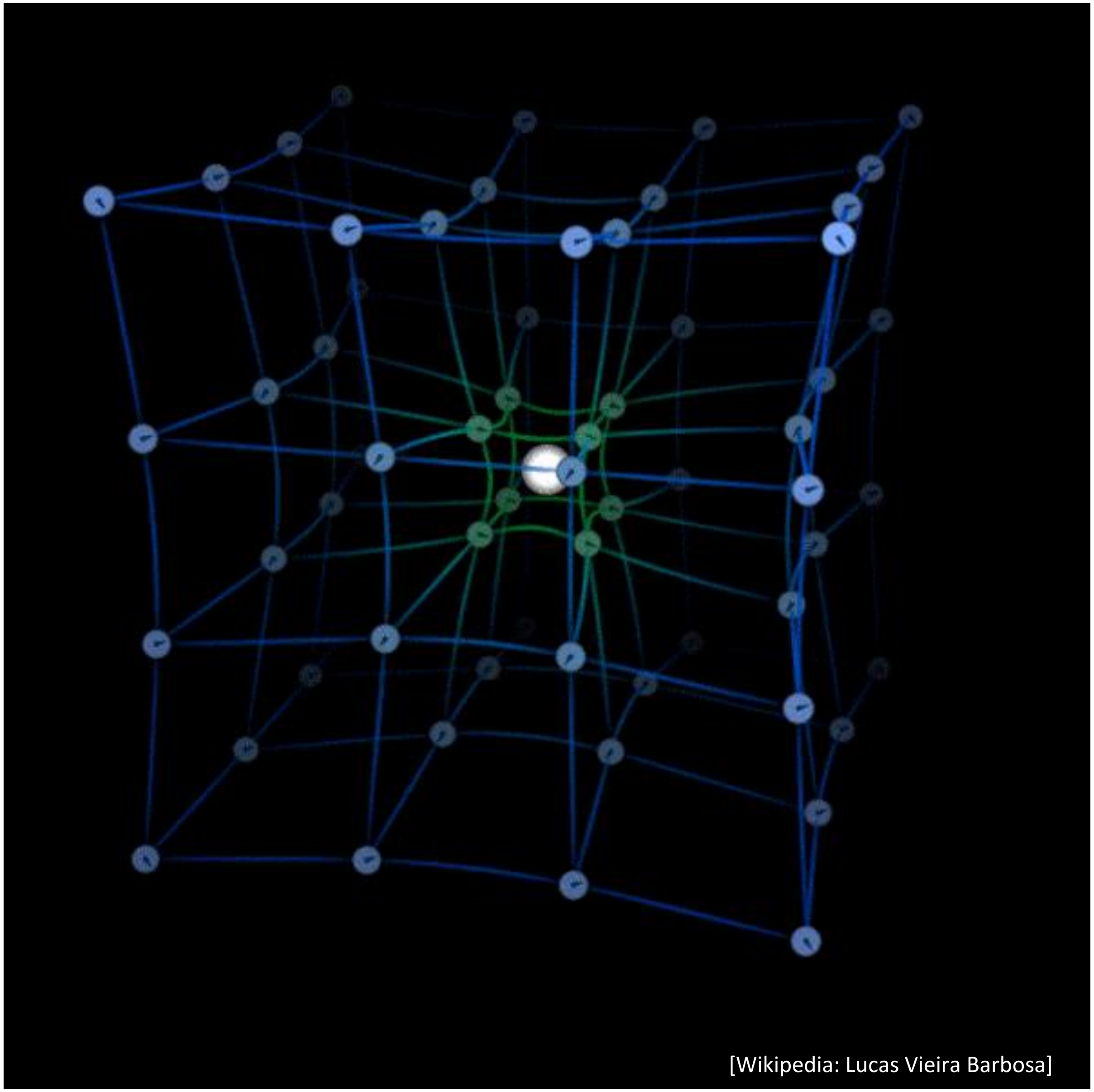


[Wikipedia: Lucas Vieira Barbosa]

Gravitational Time Dilation: small heights

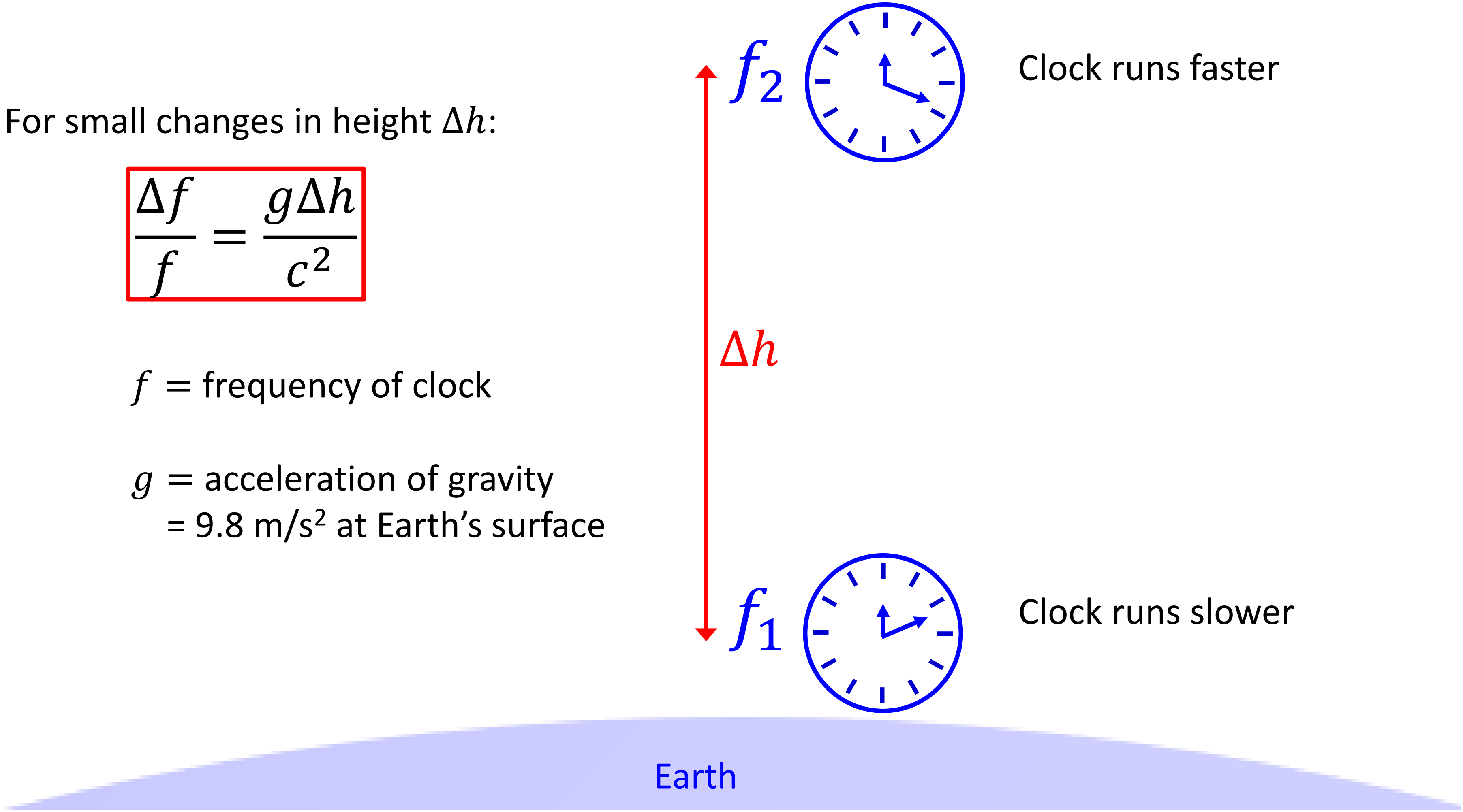
Clocks in a gravitational field run slower than clocks in free space.

For small changes in height Δh:

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

f = frequency of clock

g = acceleration of gravity
= $9.8\ \mathrm{m/s^2}$ at Earth's surface



Gravitational Time Dilation: large distances

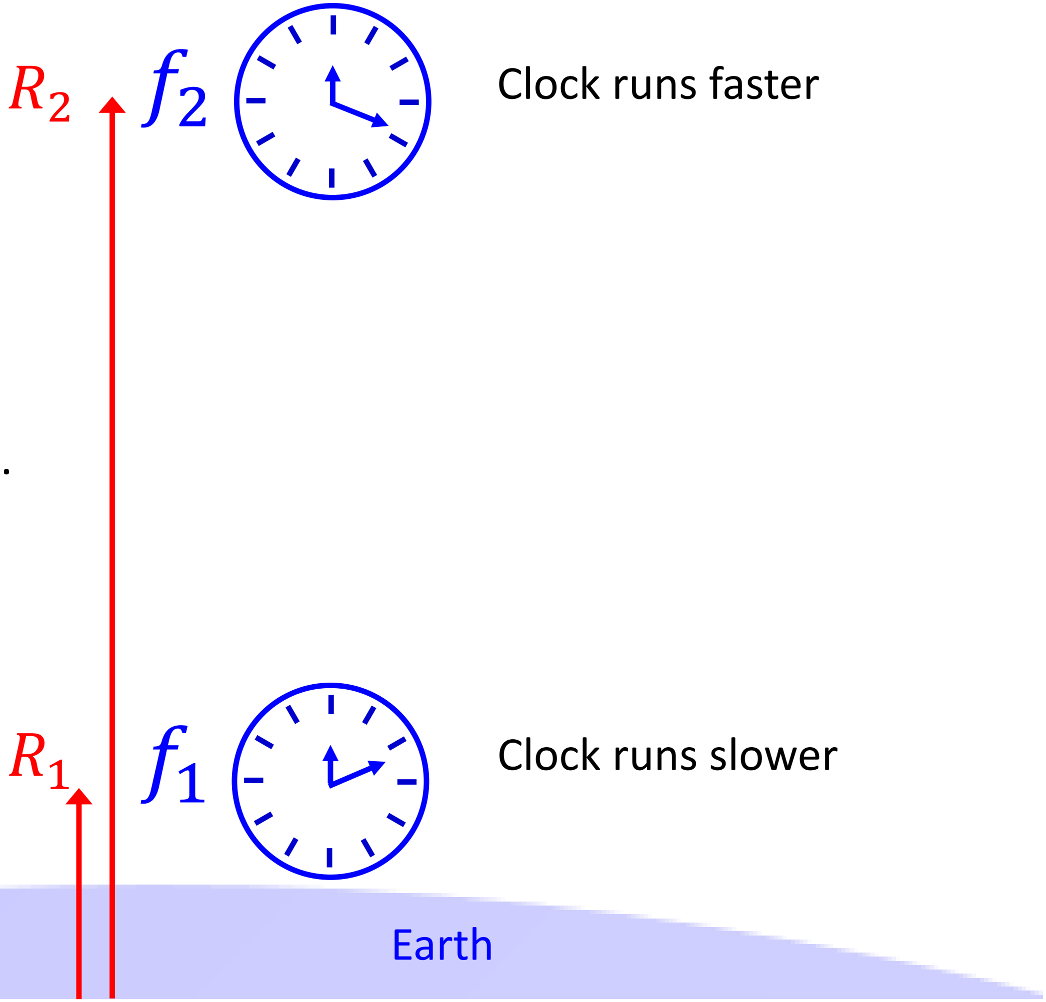
Clocks in a gravitational field run slower than clocks in free space.

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

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

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

M = mass of Earth, star, etc.



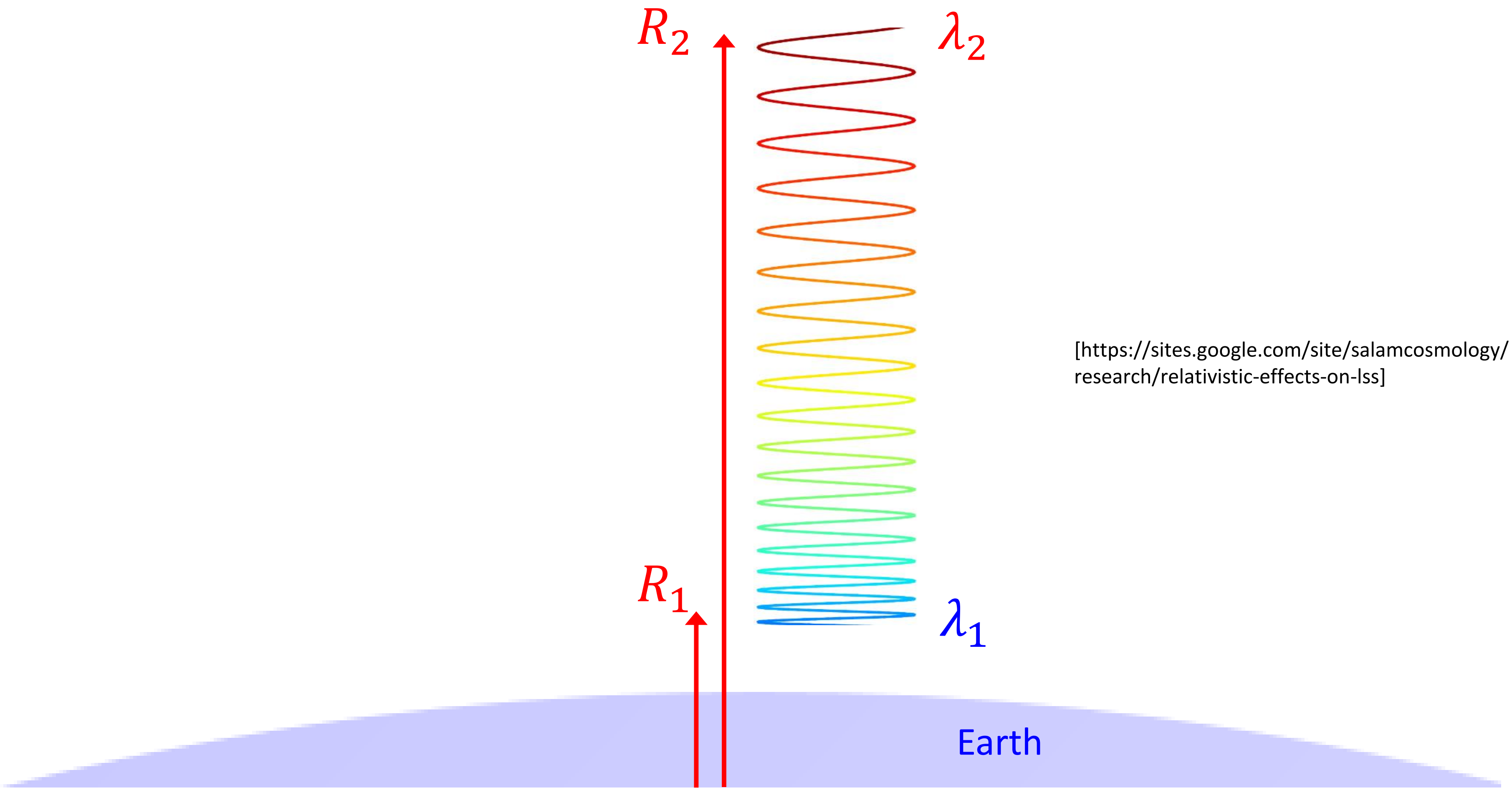
Clock runs faster

Clock runs slower

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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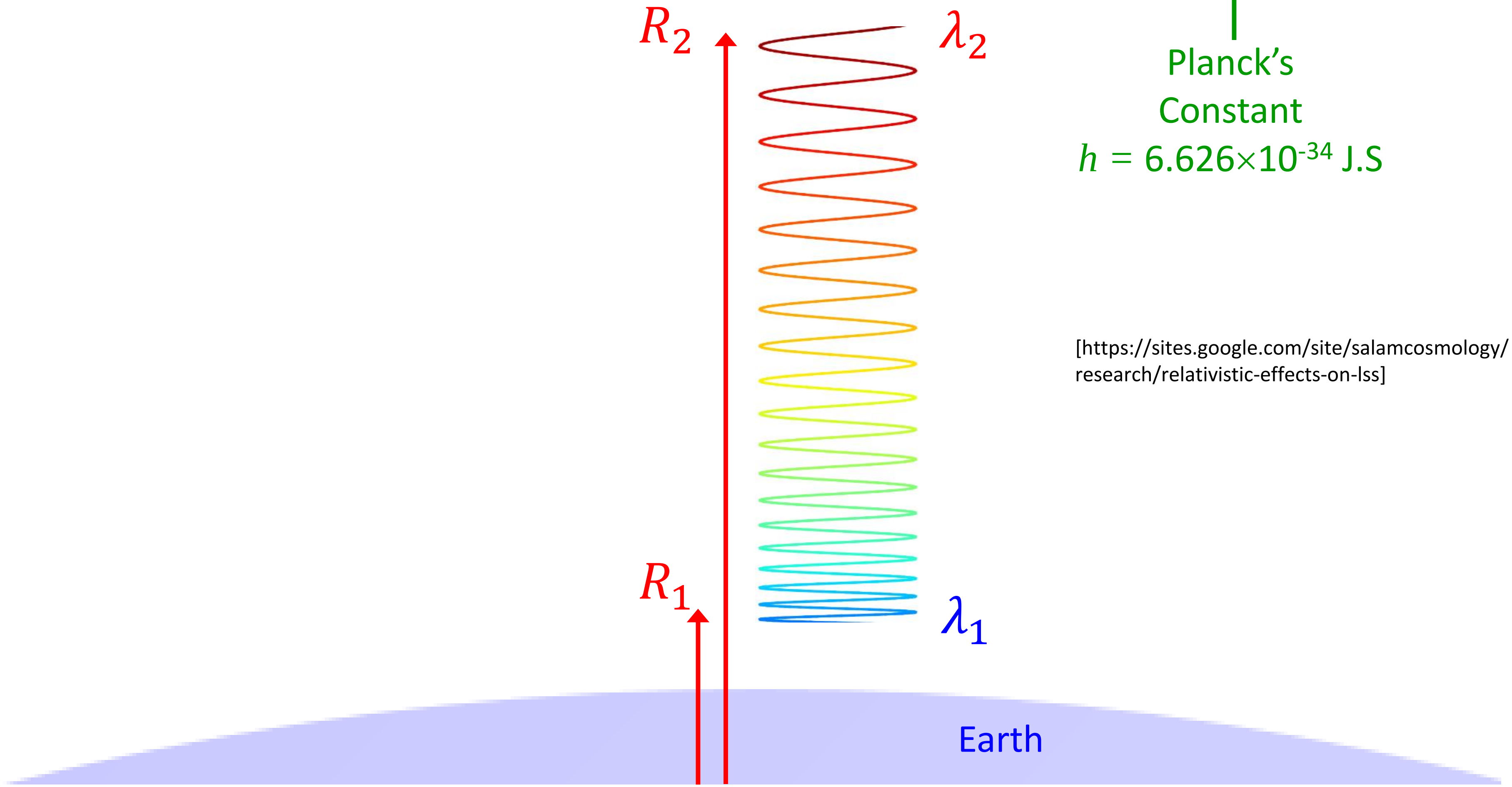

Planck’s Constant

h = 6.626×10^{-34} J.S

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$\lambda_{1,2}$ = wavelengths at R$_1$ and R$_2$.

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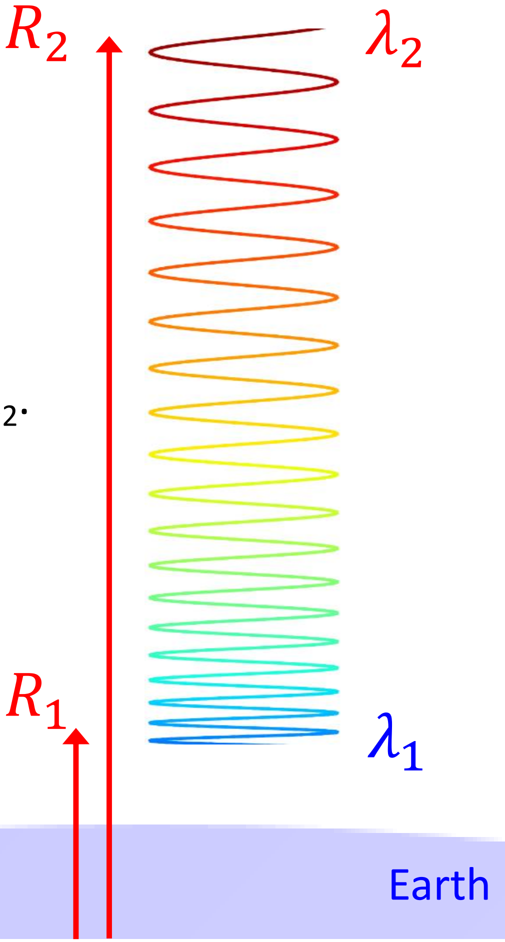

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Gravitational Waves

- 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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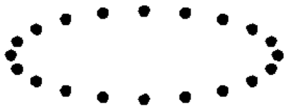
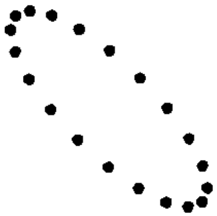


"+" polarization

or



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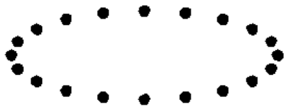

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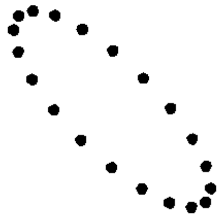

"×" polarization

Gravitational Wave “Telescope”

LIGO: Laser Interferometer Gravitational-Wave Observatory

[http://ligo.caltech.edu: LIGO Livingston, LA]

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. **Schwarzchild radius**) can escape.

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→ The **event horizon** / **Schwarzchild radius** defines the size and surface of a black hole.

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*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, λ=1.3 mm]

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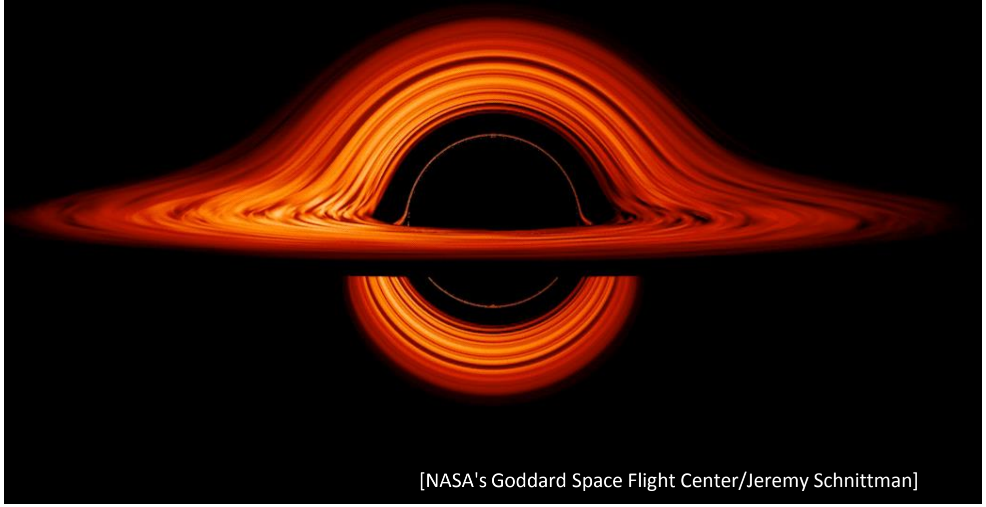
Computer simulation of accretion disc around a black hole.



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

2020 Nobel Prize in Physics
Black Hole Physics & Astronomy

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

Roger Penrose
(U. of Oxford)

[Source: Max Planck Institute for Extraterrestrial Physics]

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[Source: Christopher Dibble]

Andrea Ghez
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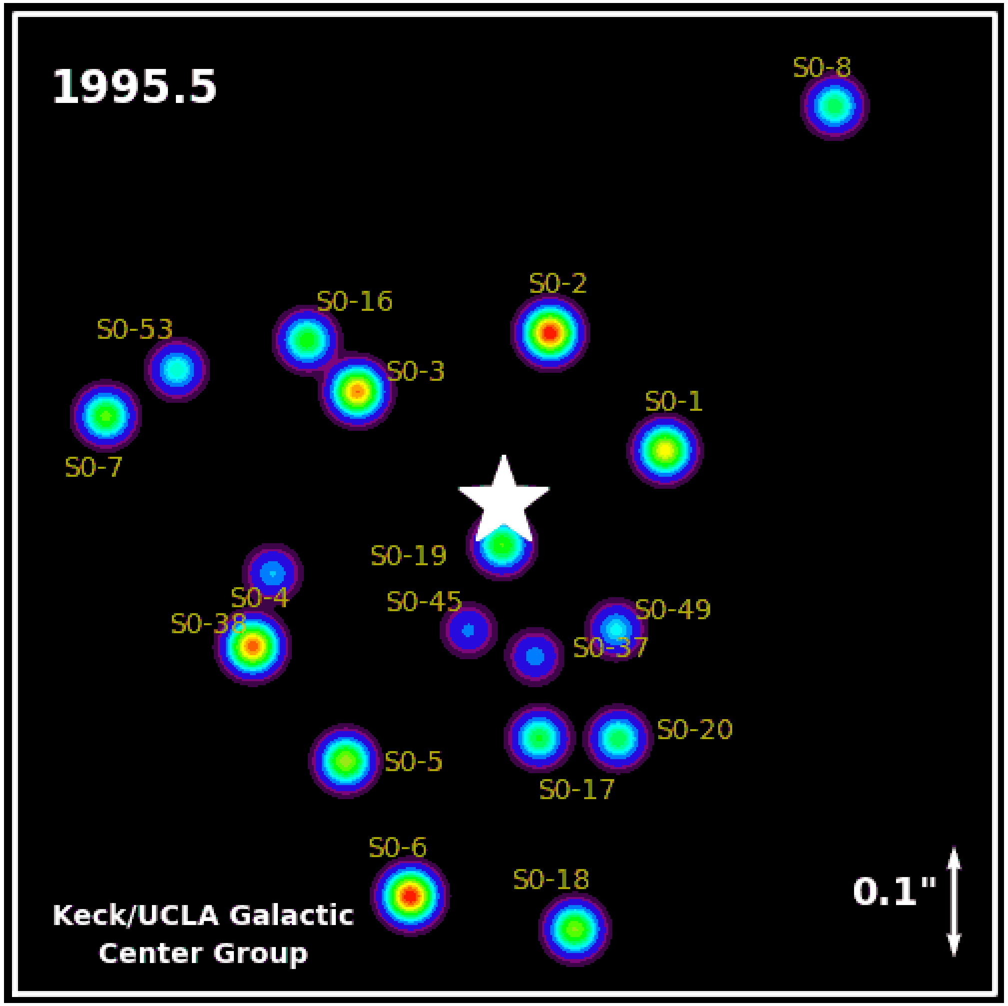
Black hole
physics & mathematics

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



What happens if you fall into a Black Hole?

Stellar mass black hole

- The **Roche limit** is well outside of the event horizon.
- 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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→ 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.)