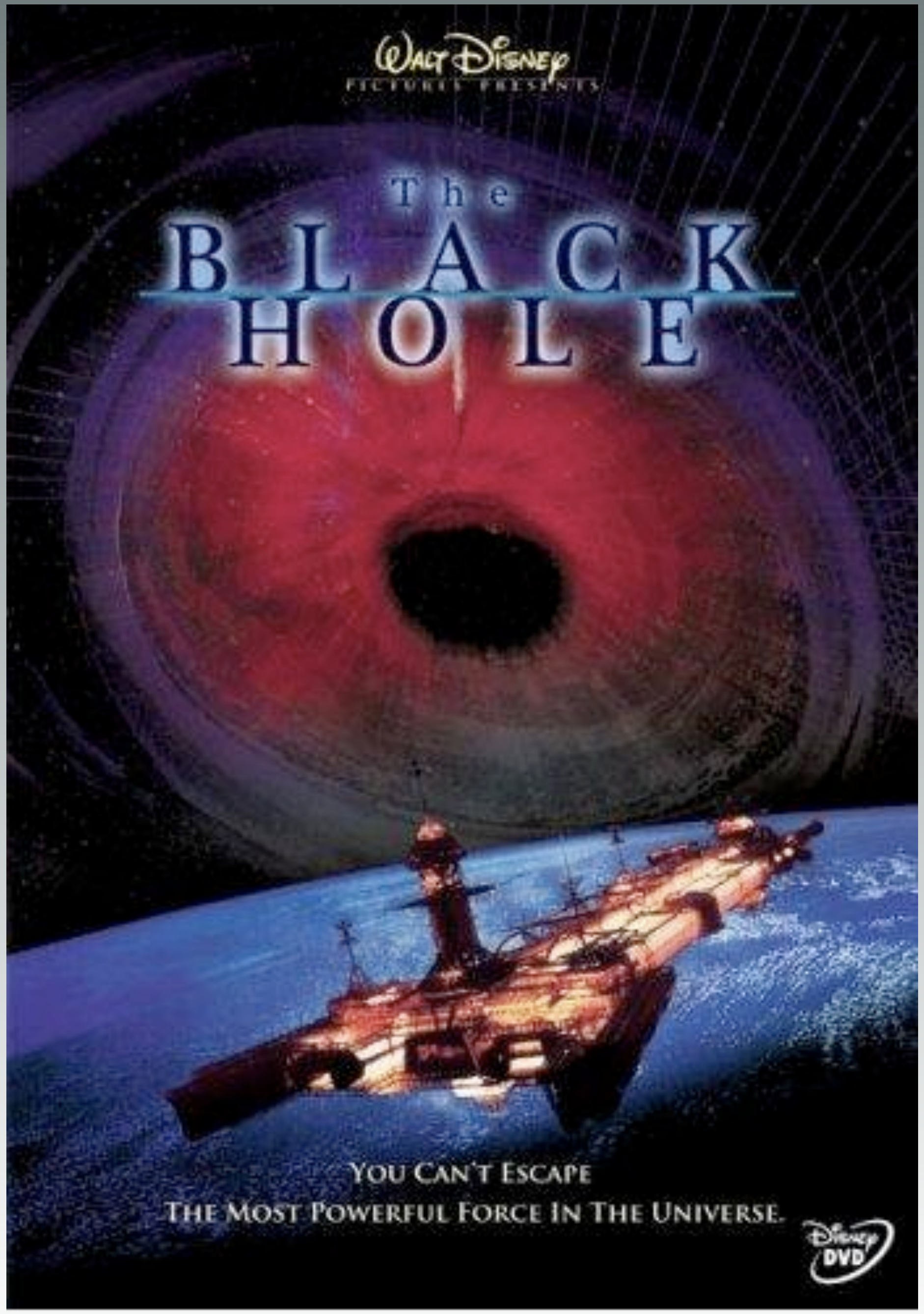
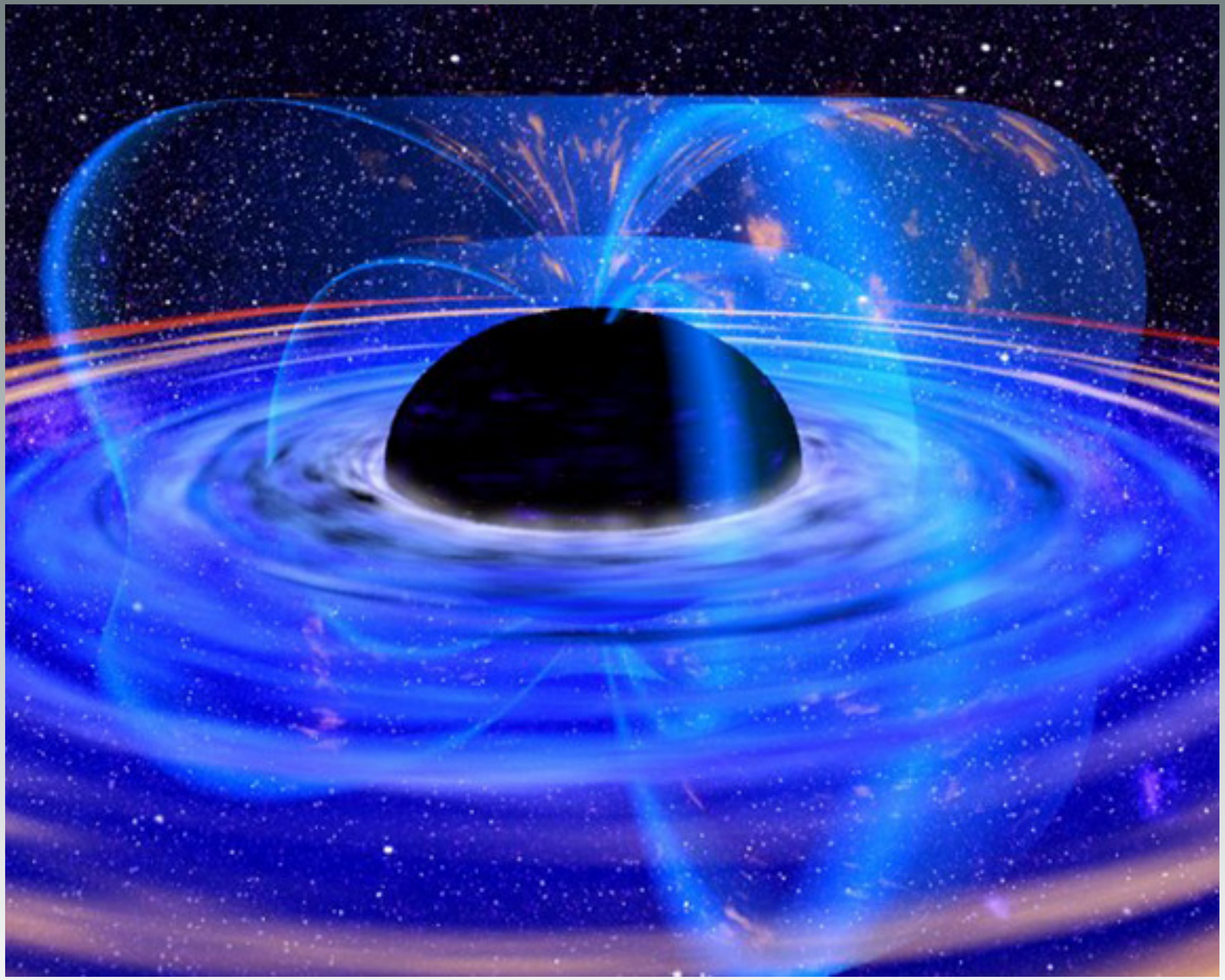
Black Holes & The Theory of Relativity



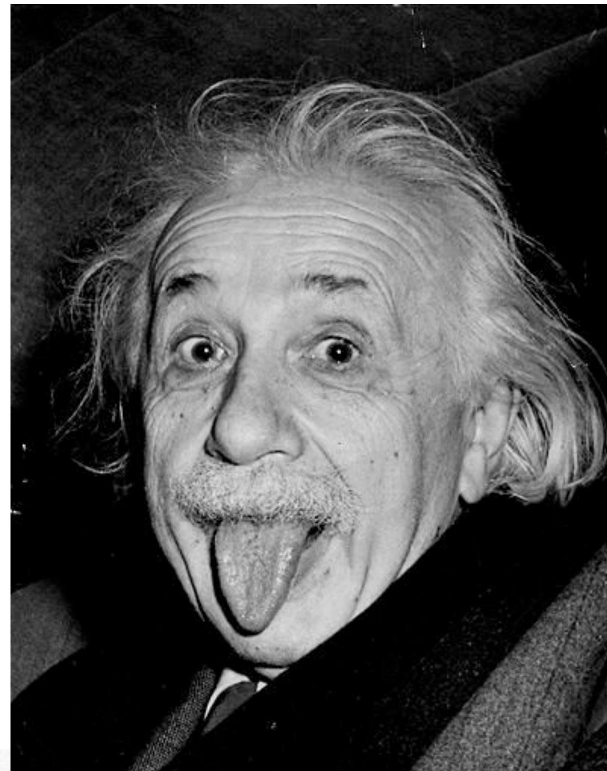


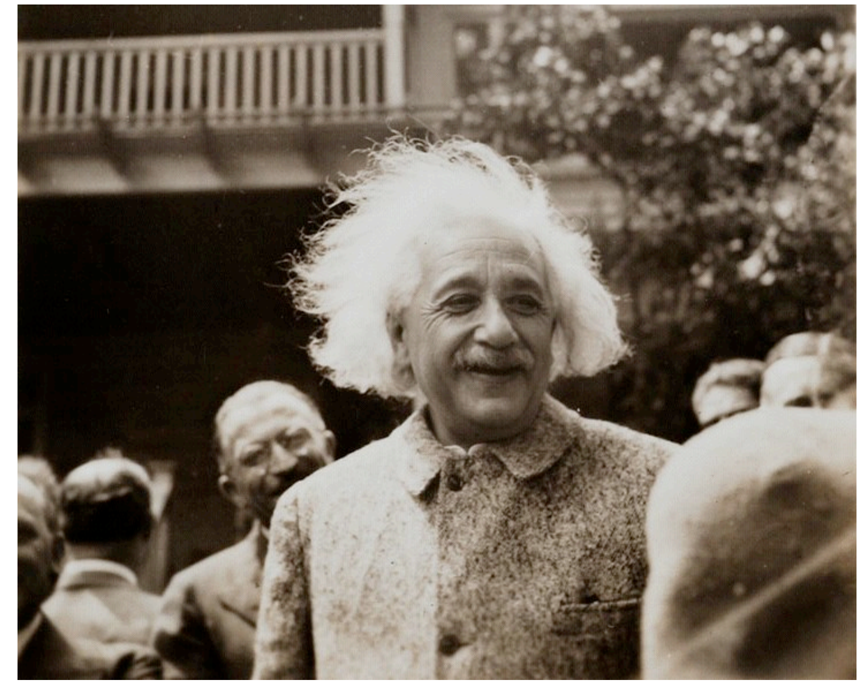
A.Einstein 1879-1955

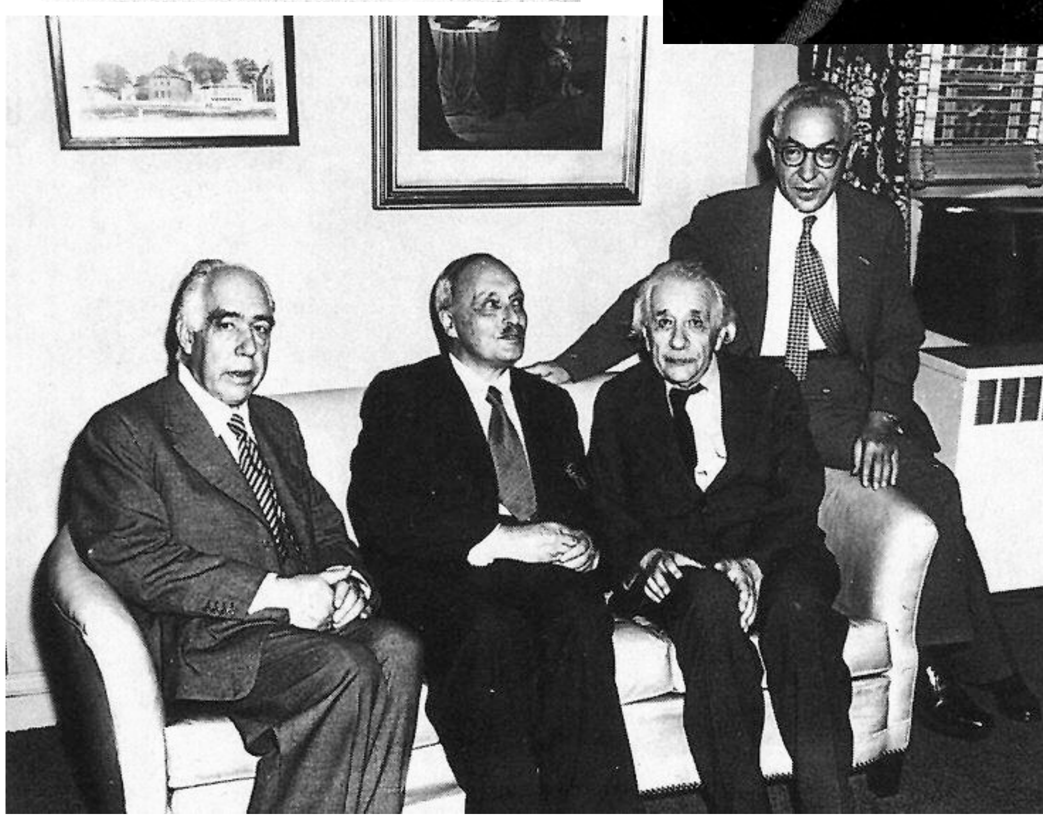
Born in Ulm, Württemberg, Germany in 1879, Albert Einstein developed the special and general theories of relativity. In 1921, he won the Nobel Prize for physics for his explanation of the photoelectric effect. Einstein is generally considered the most influential physicist of the 20th century. He died on April 18, 1955, in Princeton, New Jersey

At age 23 Einstein found employment as a technical expert at a Swiss patent office

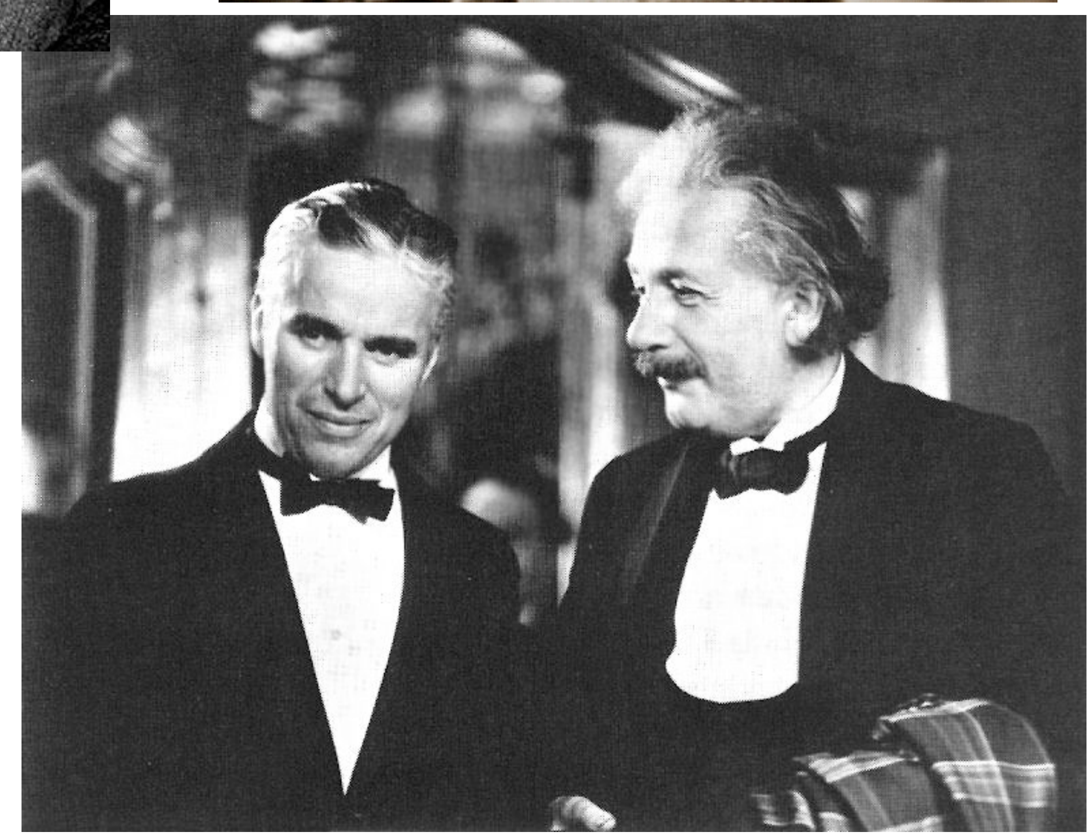
A. Einstein





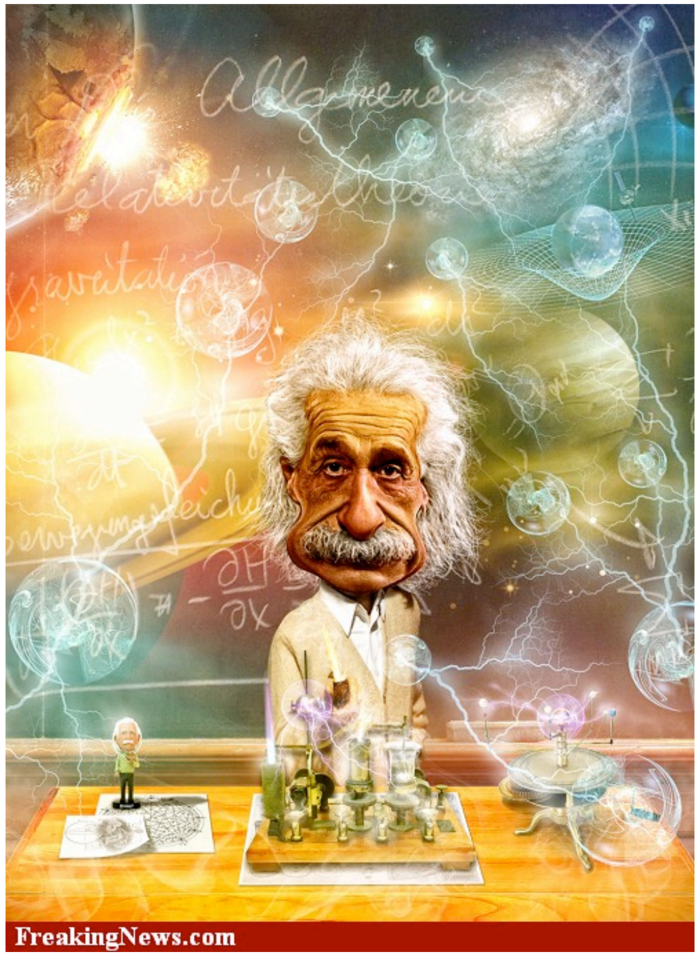


Borh, Frank, Einstein Rabi



Charlie Chaplin and A. Einstein

A. Einstein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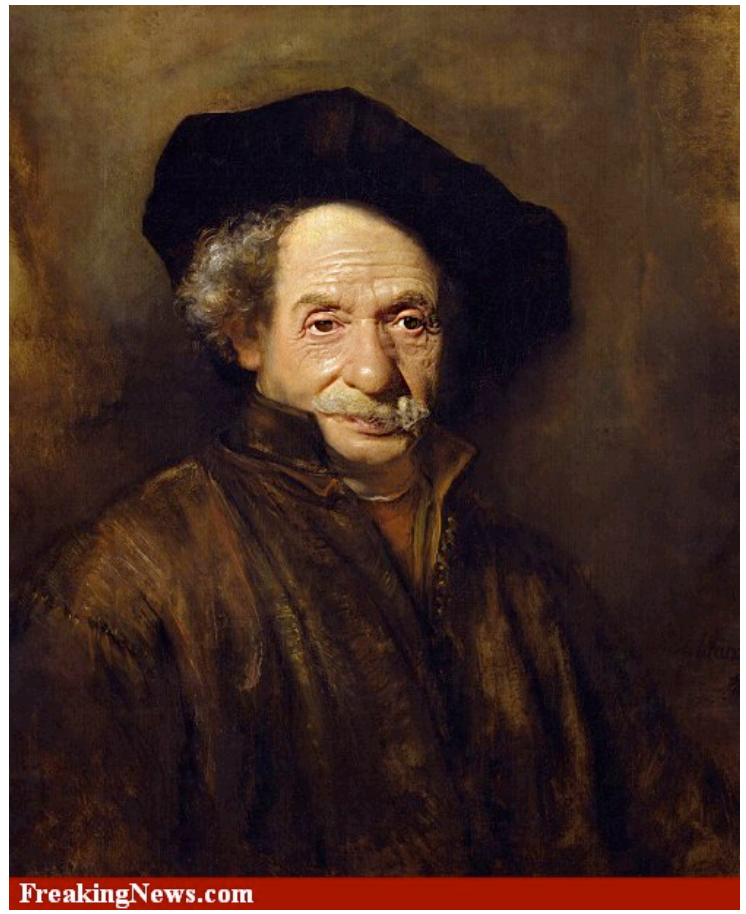
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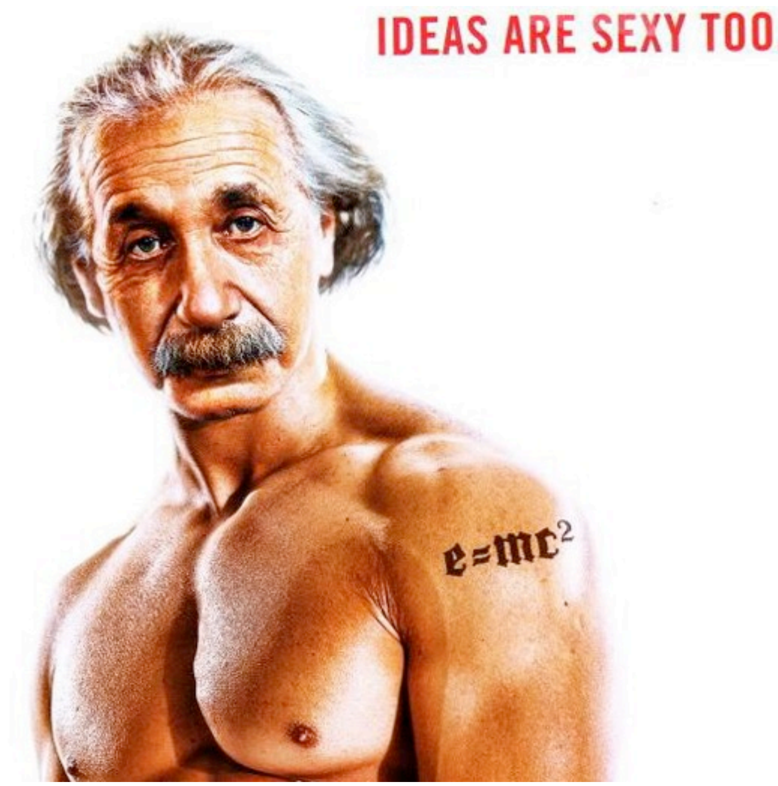
IDEAS ARE SEXY TOO.
$e=mc^2$


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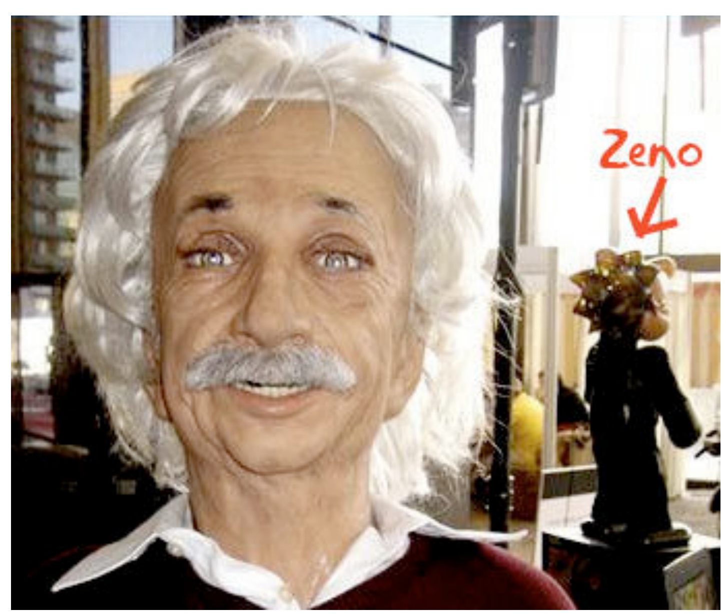

Zeno

Overview of Relativity

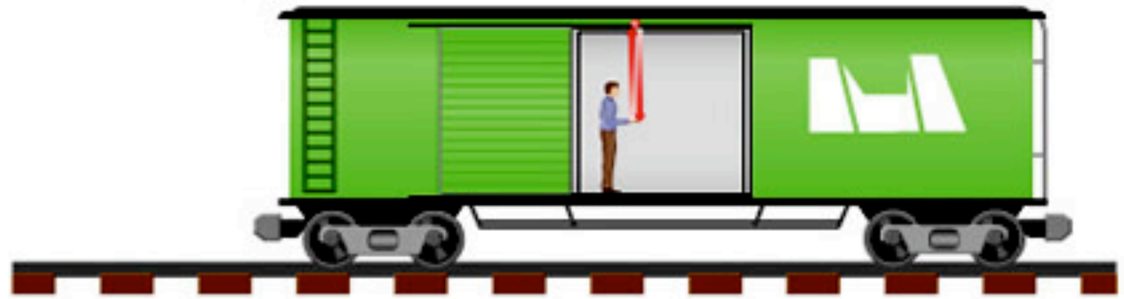
1. By the beginning of the 20th century, it became clear that Newton's Laws of Motion & Gravity were not completely general. In particular, Newton's Laws do not correctly describe motions of objects that are traveling ***near the speed of light or that are in a very strong gravitational field***.

2. Einstein developed several important postulates about motion:
   - There is no absolute rest frame in the Universe. The best that one can do is measure *relative* motions.
   - The speed of light, **c**, is **constant** with respect to all observers, independent of velocity. This makes light a very different phenomenon from objects with mass that have different apparent velocities depending on the motion of the observer. This result gives rise to different *relative* measures of time and length as determined by two observers in motion.

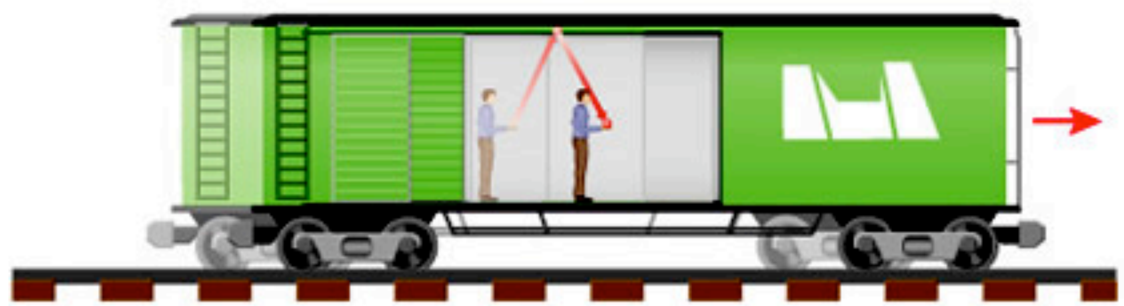
3. The above postulates gave rise to Einstein's famous law relating the equivalence of mass of energy.

4. Although Einstein's Theory of Relativity produced different results from Newton for velocities near light and for strong gravity, ***it completely agrees with Newton for lower velocities and gravity*** fields like that on Earth.

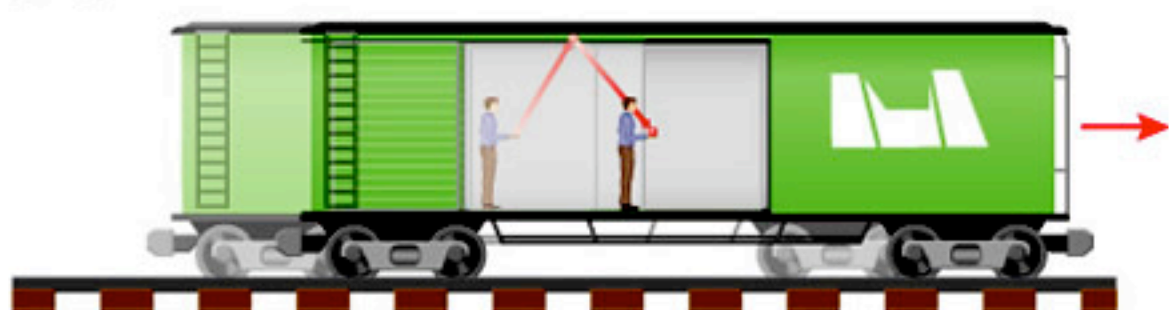
Inside the train, the ball
goes up and down.

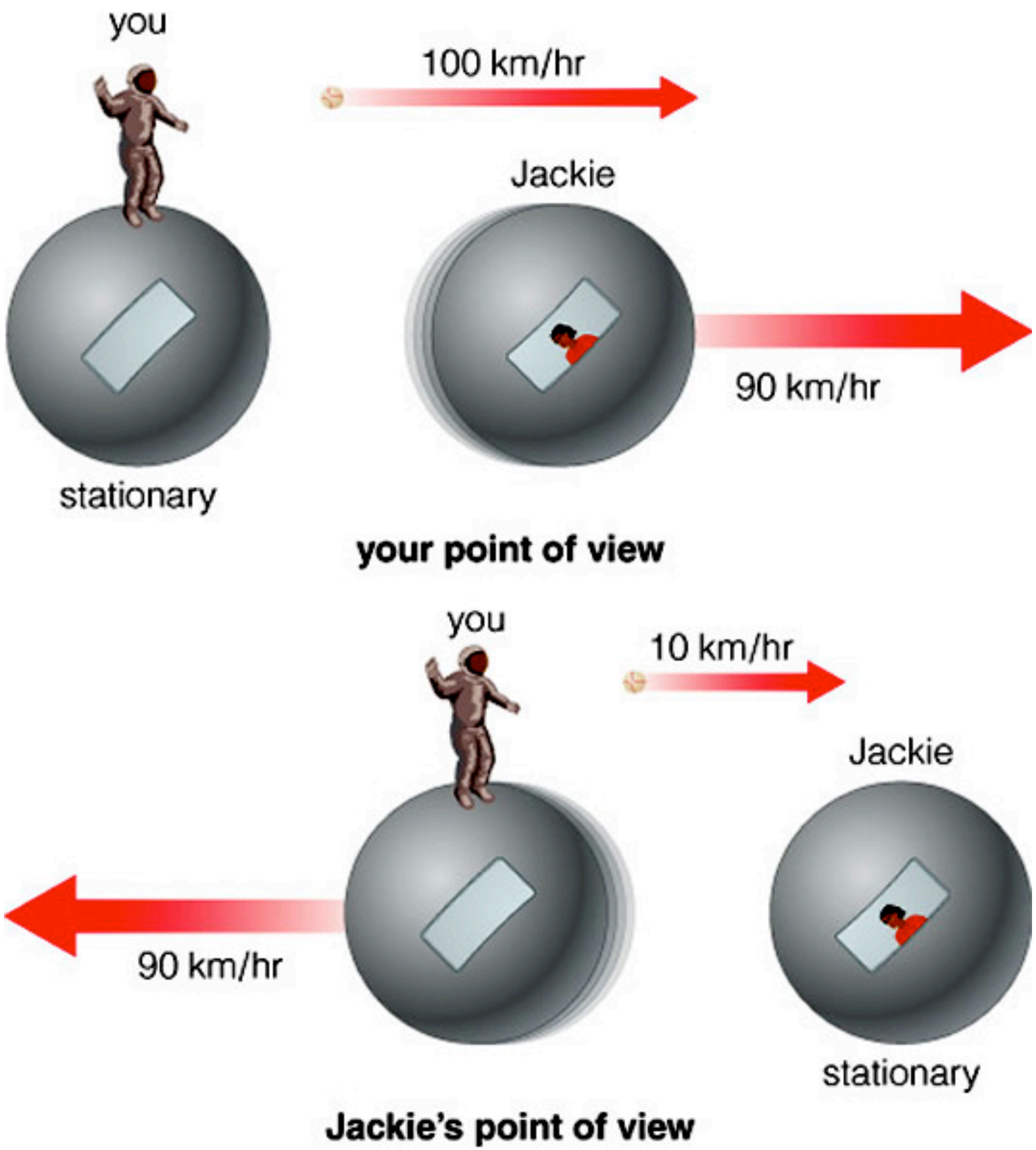


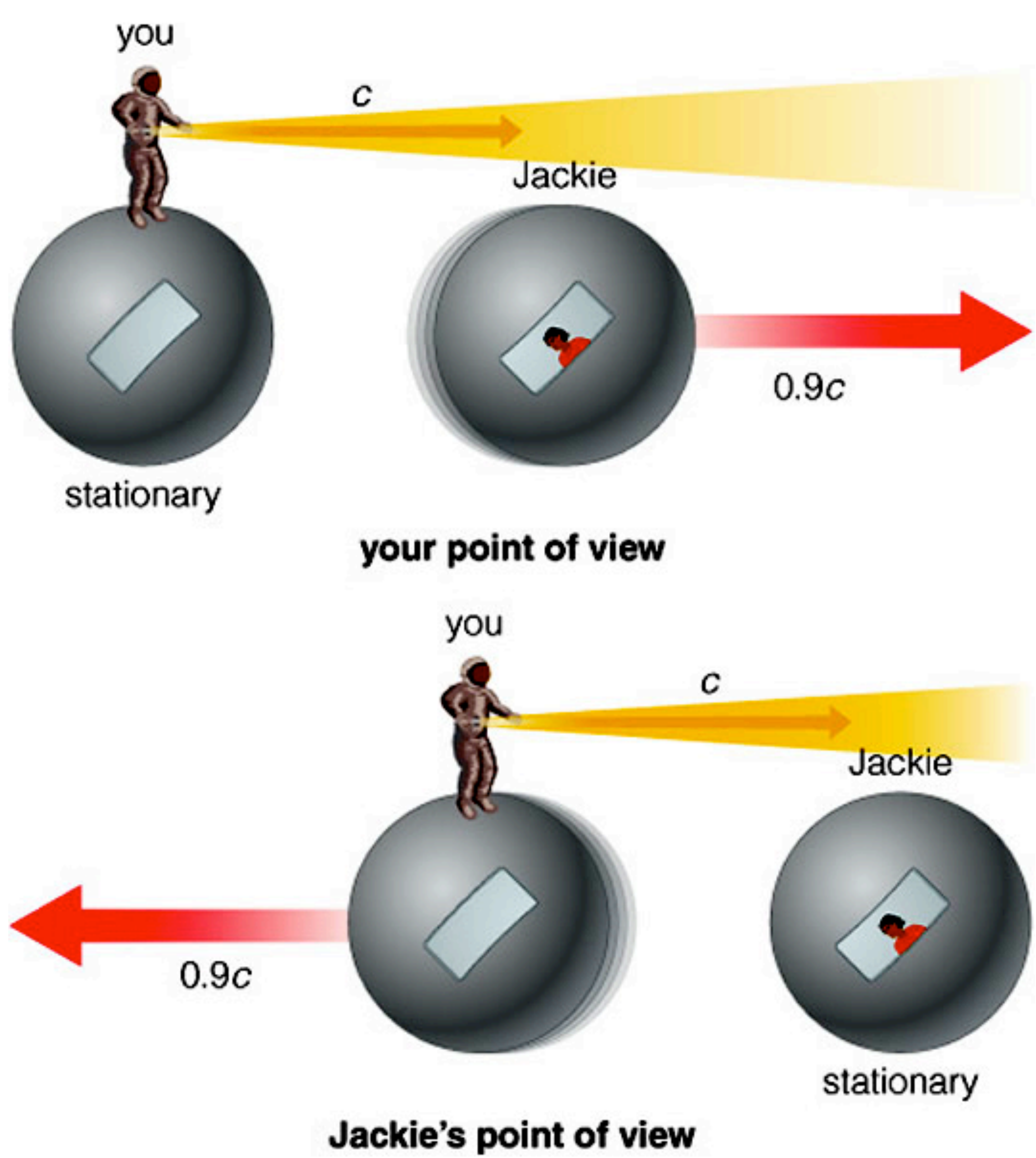
Outside the train, the ball appears
to be going faster: It has the same
up-and-down speed, plus the
forward speed of the train.



The faster the train is moving,
the faster the ball appears to be
going to the outside observer.




you
100 km/hr
Jackie
90 km/hr
stationary
your point of view
you
10 km/hr
Jackie
90 km/hr
stationary
Jackie's point of view


you
c
Jackie
0.9c
stationary
your point of view
you
c
Jackie
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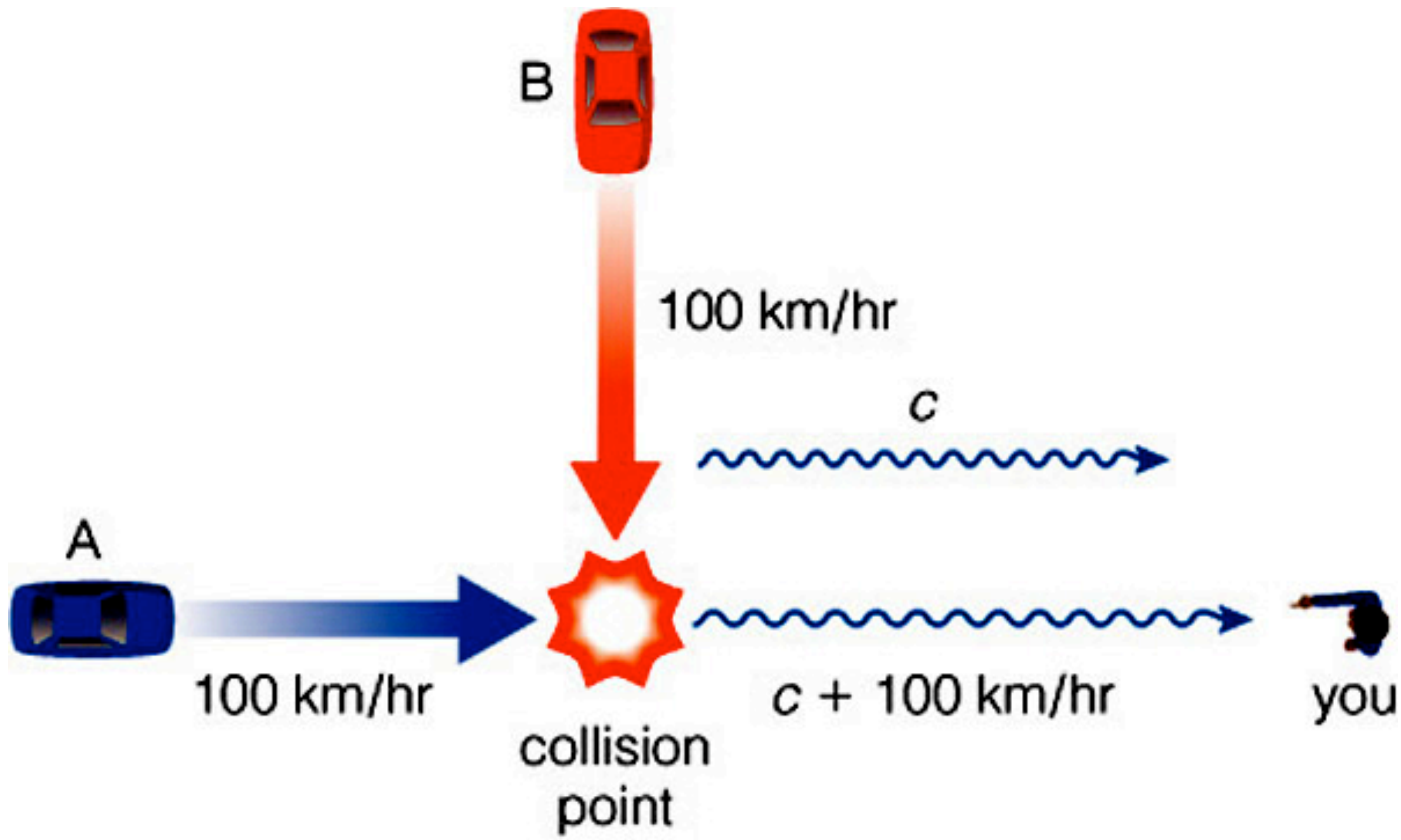
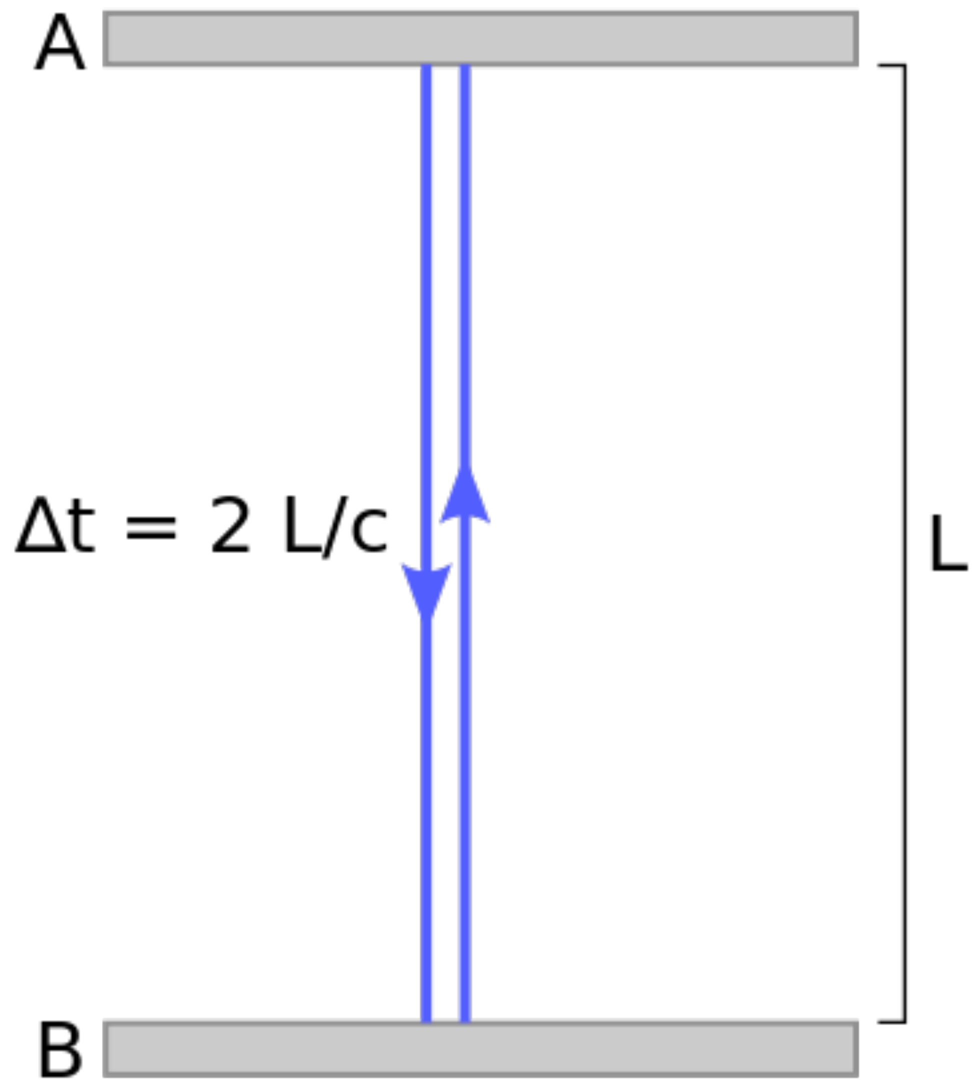
stationary
Jackie's point of view

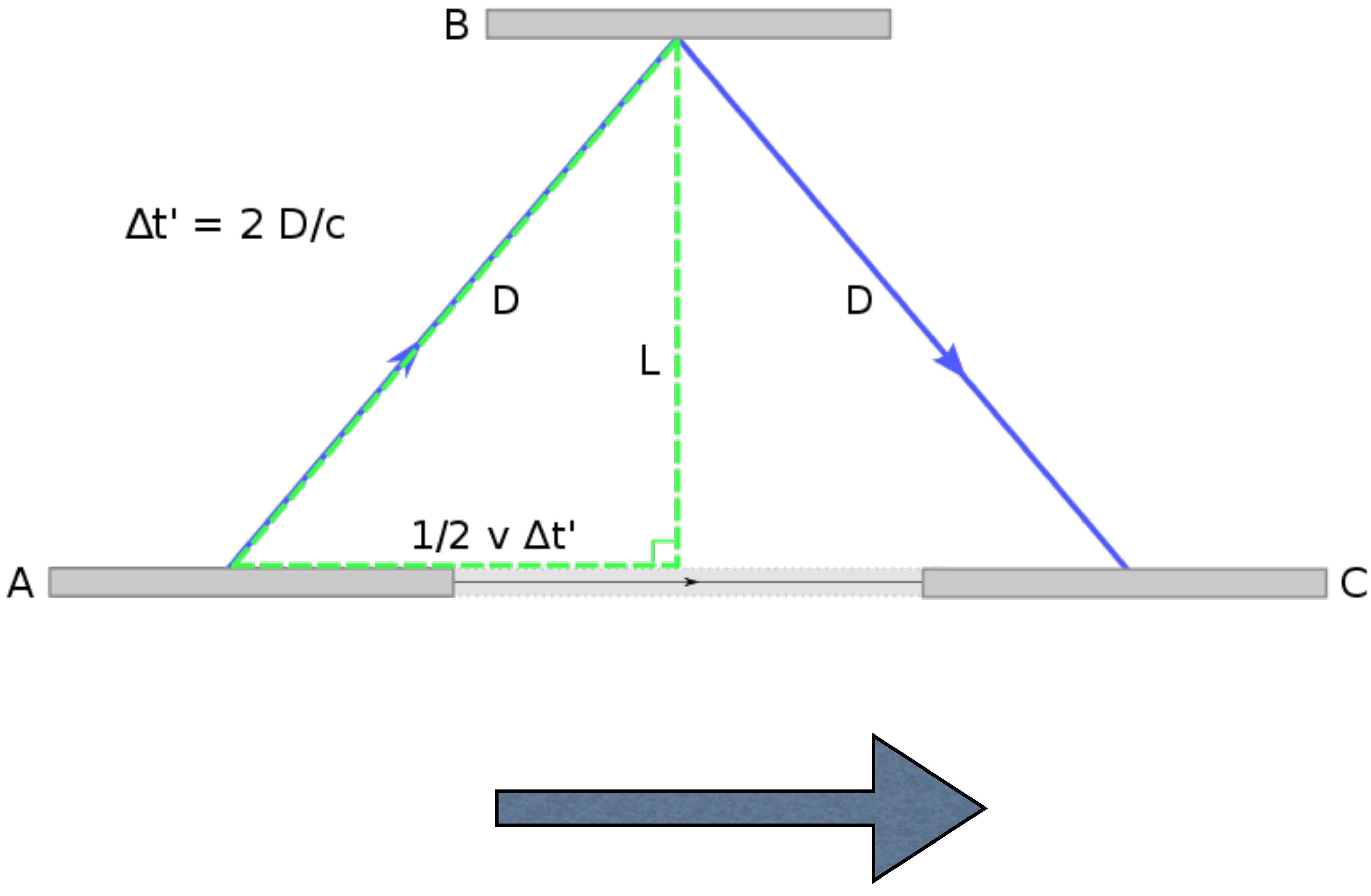


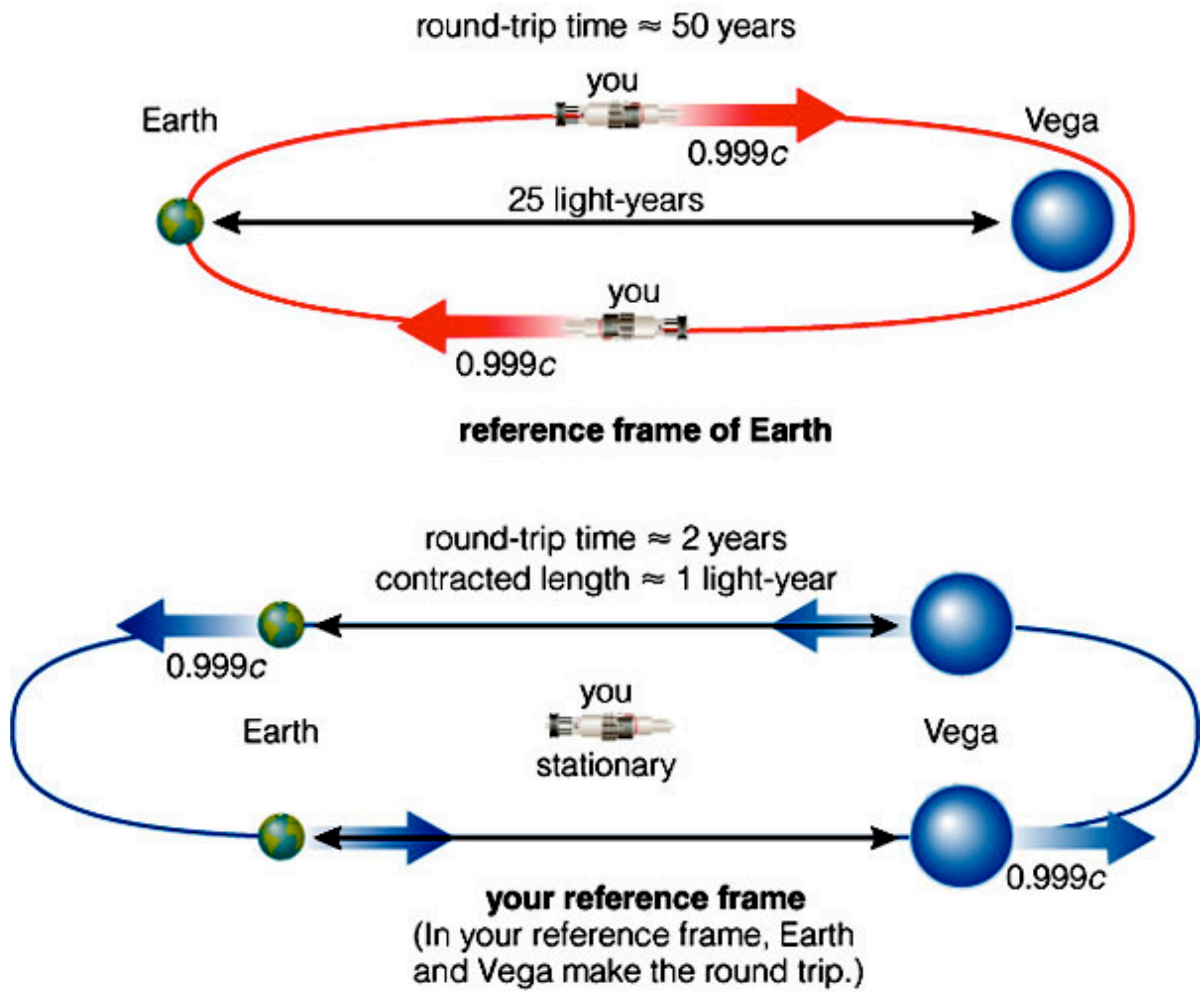
If *c* were not absolute, you would see car A reach the collision point before car B.

Time depends how object moves



Time slows down when object moves fast




round-trip time ≈ 50 years
you
Earth
Vega
0.999c
25 light-years
you
0.999c
reference frame of Earth
round-trip time ≈ 2 years
contracted length ≈ 1 light-year
0.999c
you
Earth
stationary
Vega
0.999c
your reference frame
(In your reference frame, Earth
and Vega make the round trip.)

The Curvature of Space-time

- Einstein's recognition that time was measured differently for different relative observers led him to treat ***time as a fourth coordinate in describing an event - one needs to have 4 dimensions*** to specify an event including & where is time. For example, we see the Sun as it was 8 minutes ago. Einstein unified the concepts of space & time together as *space-time*.

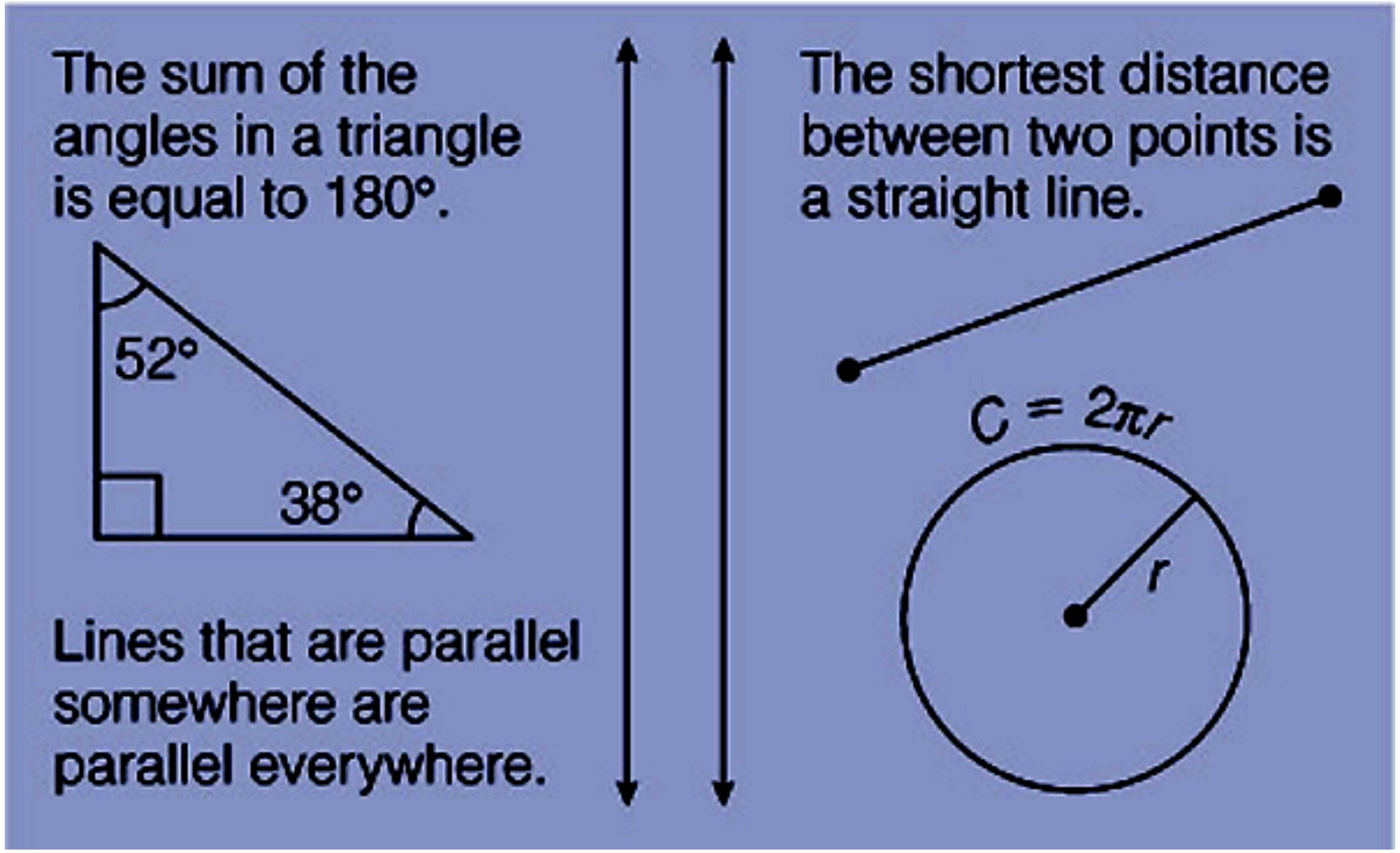
- Einstein did not use the concept of force to understand motions in a gravitational field. Instead, his theory of ***gravity is a theory that involves the geometry of space-time***.

- When no masses are present, the geometry of space-time is flat. A 2-dimensional analog is a flat, frictionless table top. Start a ball moving at a given velocity across the table. It will continue to move in a straight line at that velocity following the simple flat geometry of the table. The same is true for 4 dimensional space-time.

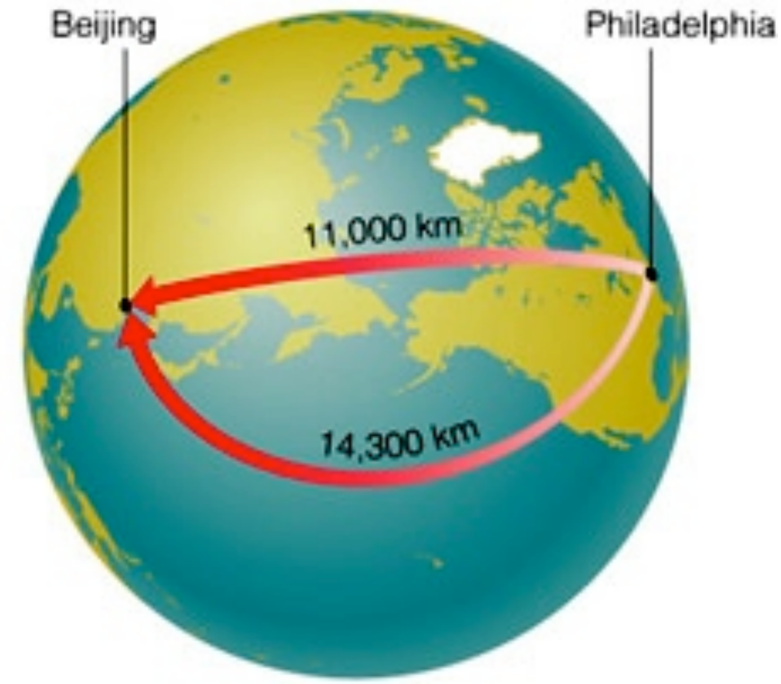
- Now, when a mass is present, this ***mass produces a curvature of space-time***. The 2-dimensional analog would be a stretched piece of thin rubber with an indentation at the center where the mass is located. Let a ball go near the edge of the indentation & it will accelerate toward the bottom. If you give the ball a little velocity in a tangential direction, it will ``orbit'' the indentation. Thus, the basic observed features of motion in a gravitational field can be understood through this theory of curved space-time.

- Keep in mind that ***time, also, will flow differently depending upon the location of the observer on this curved, 4-dimensional space-time.***

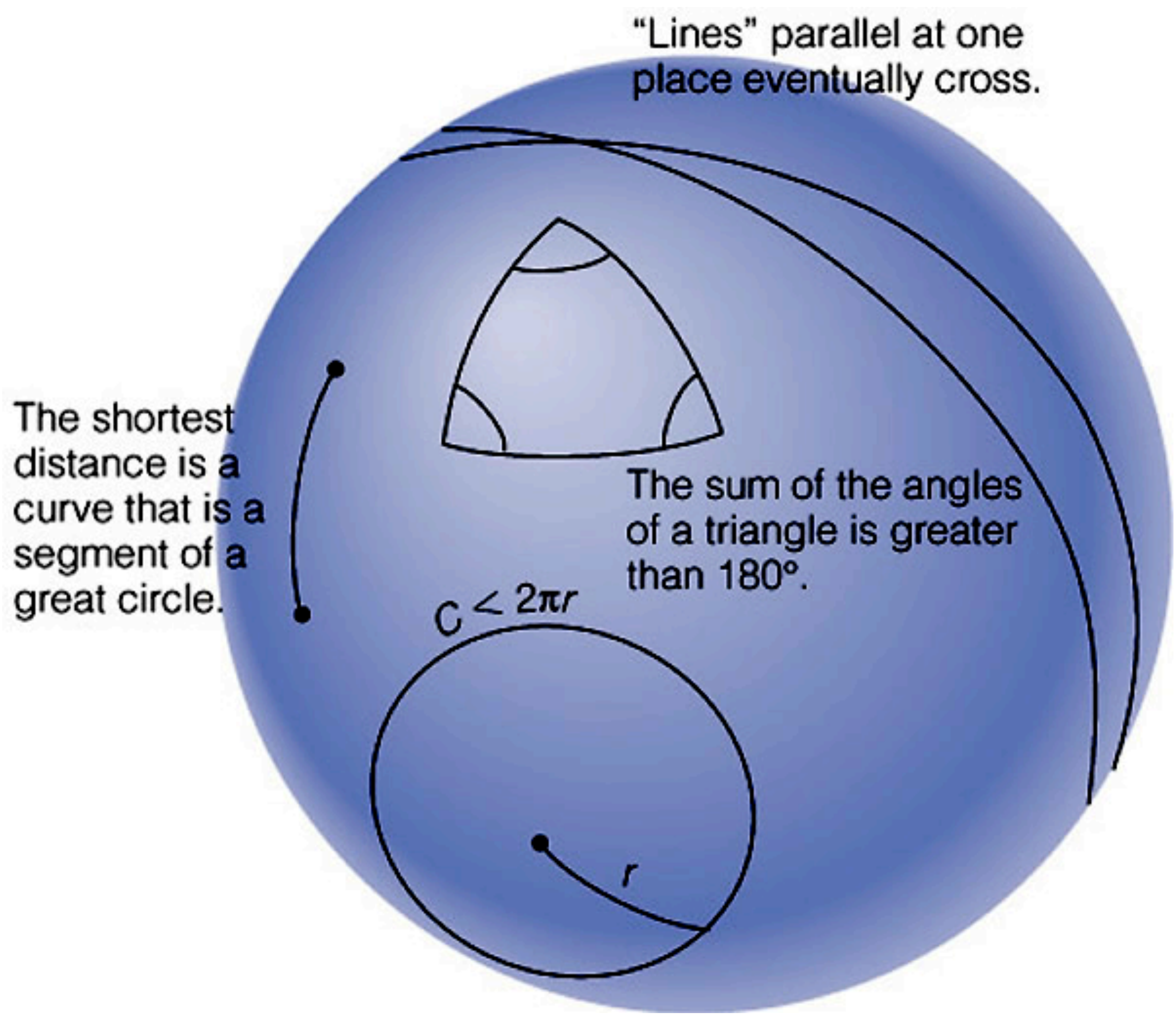
Geometry of flat space



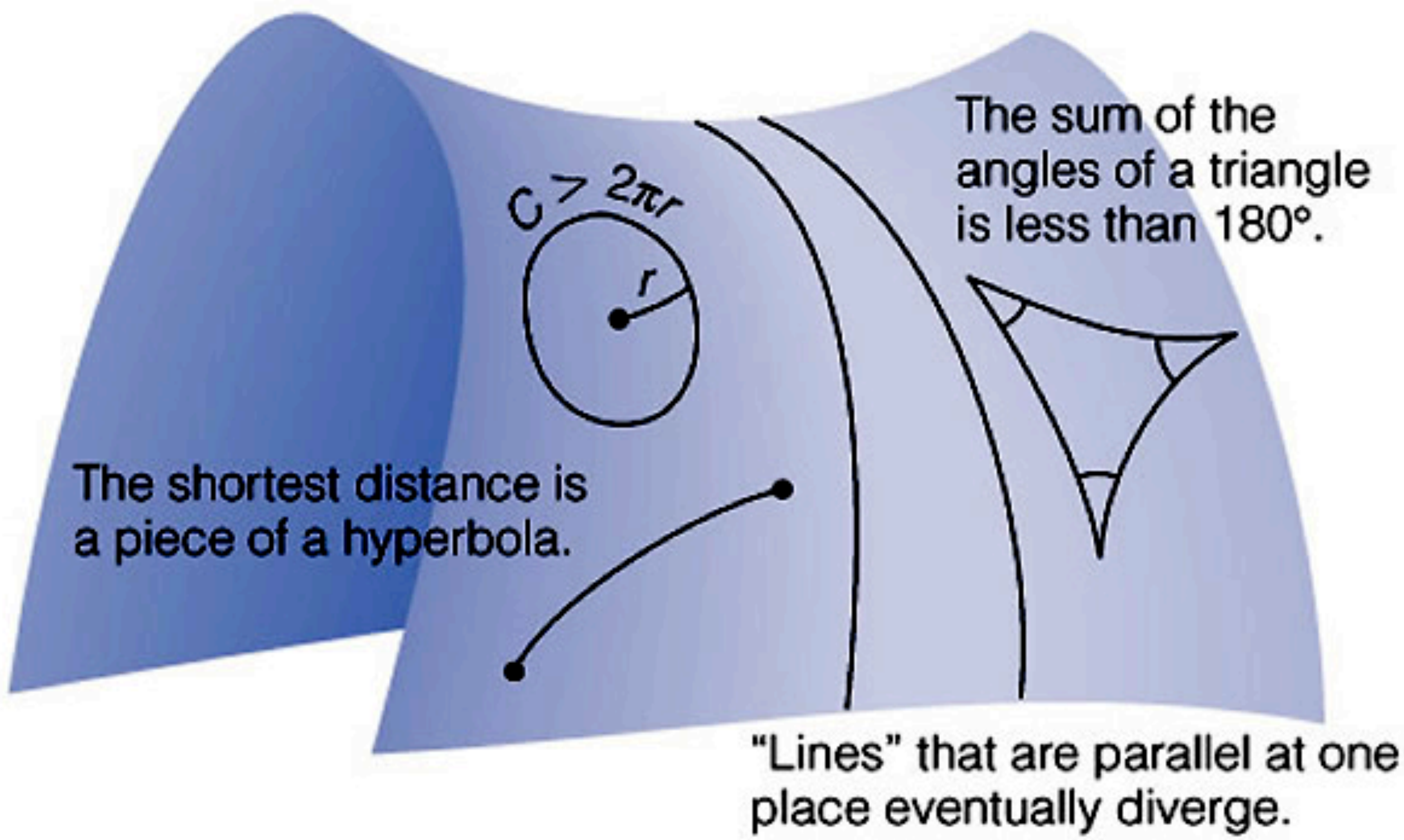

11,000 km
14,300 km
Beijing
Philadelphia


Beijing
Philadelphia
11,000 km
14,300 km

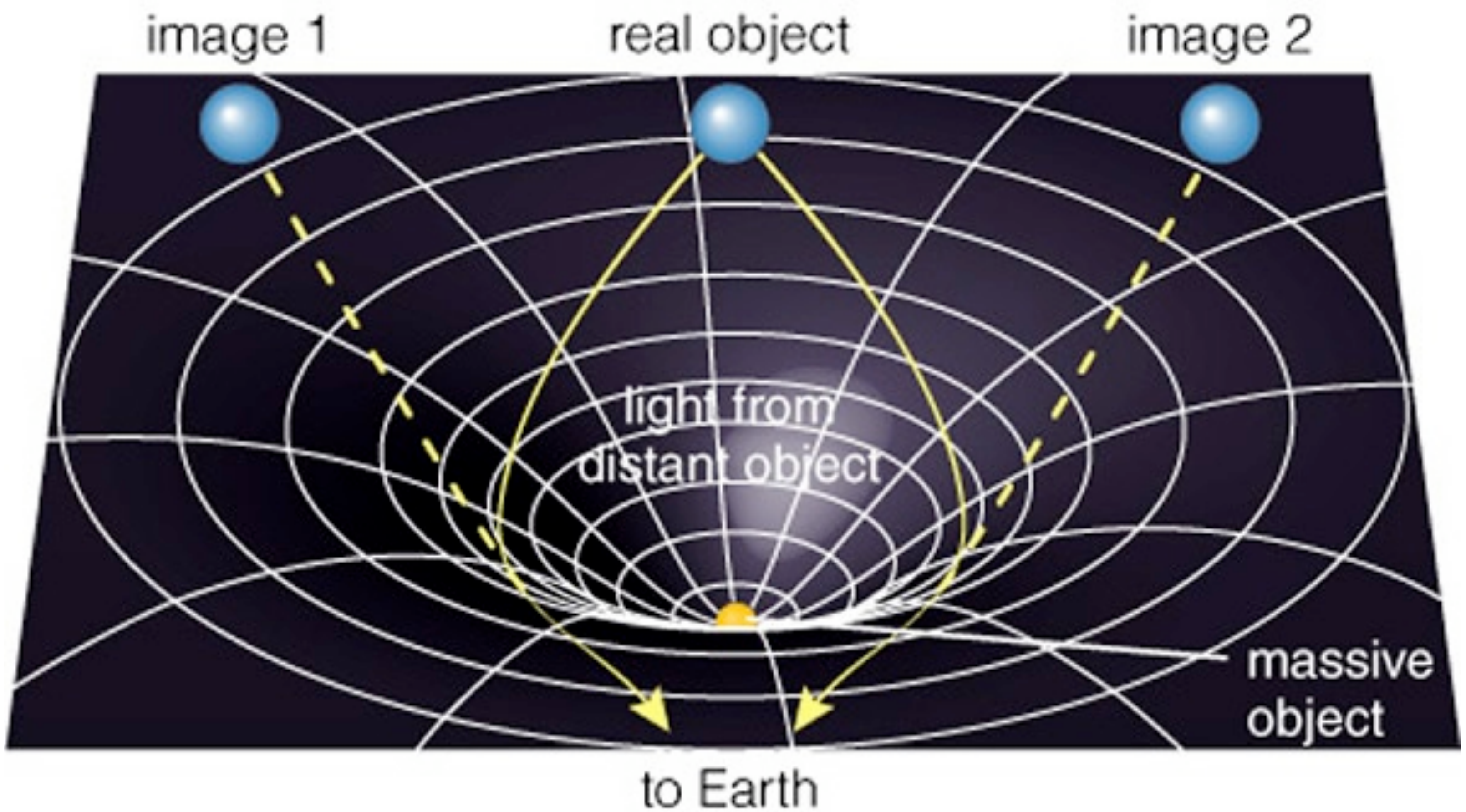
Geometry of positively curved space

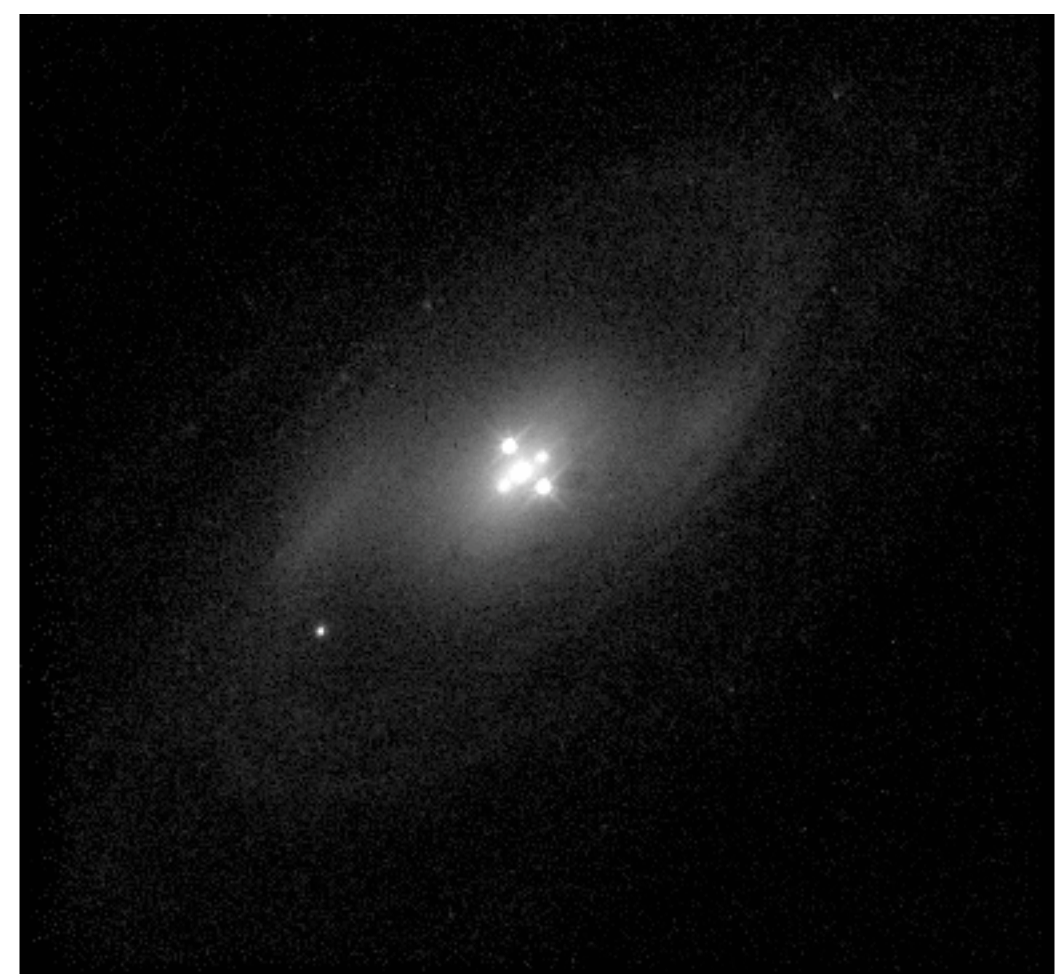


Geometry of negatively curved space

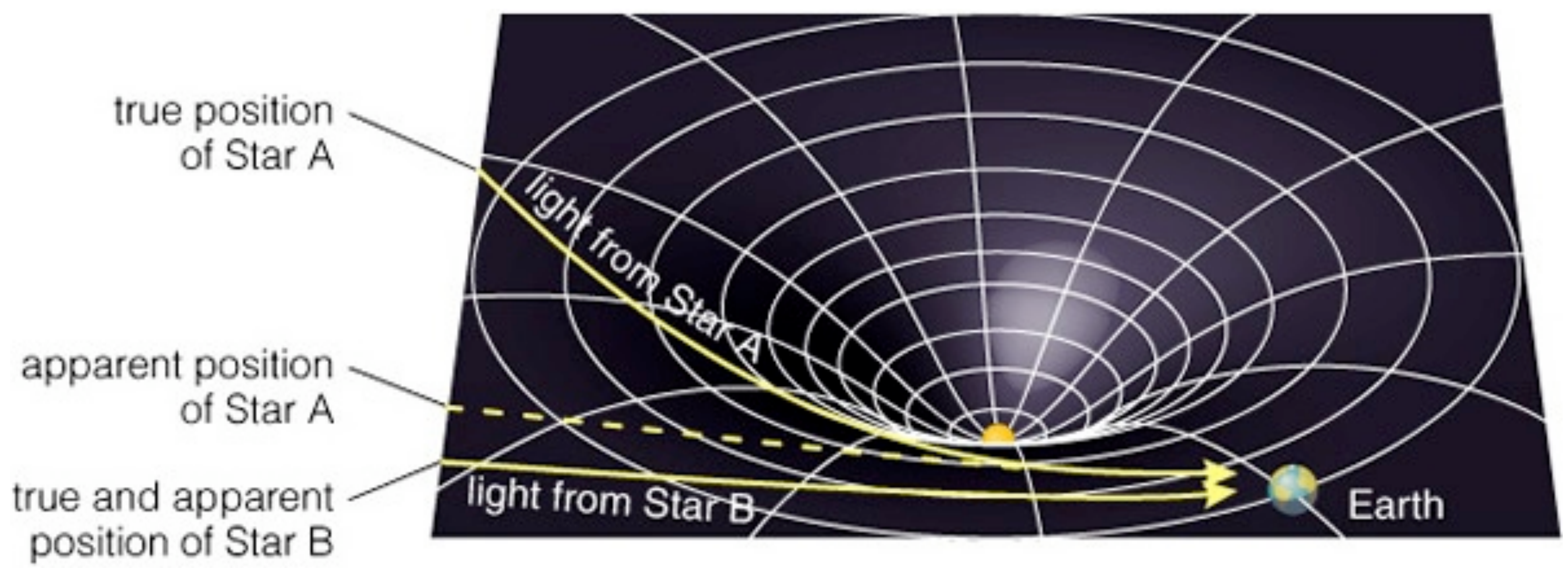


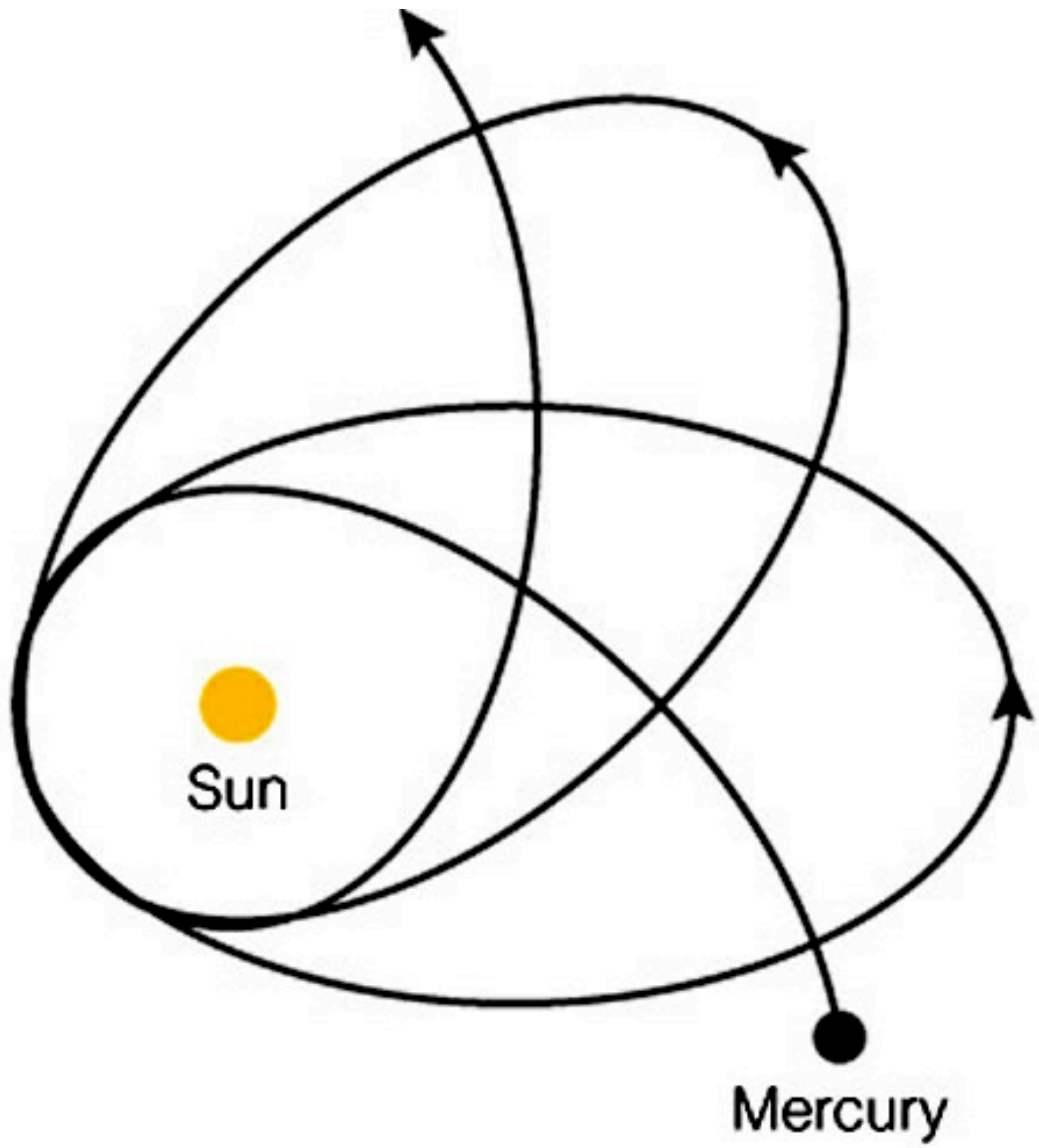
Gravitational lenses





Einstein's Cross: Bright quasar is seen 5 times

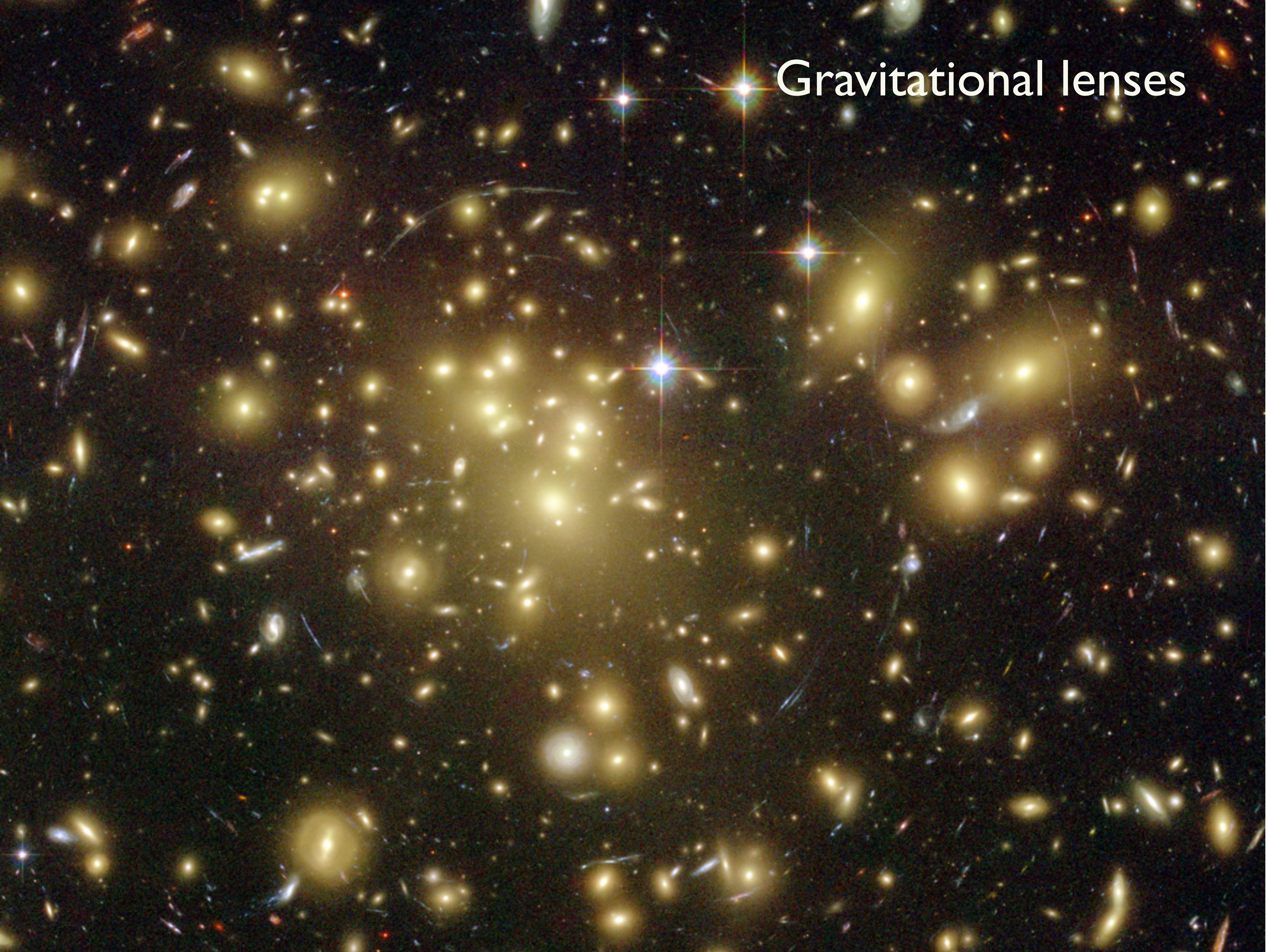

true position
of Star A
light from Star A
apparent position
of Star A
true and apparent
position of Star B
light from Star B
Earth



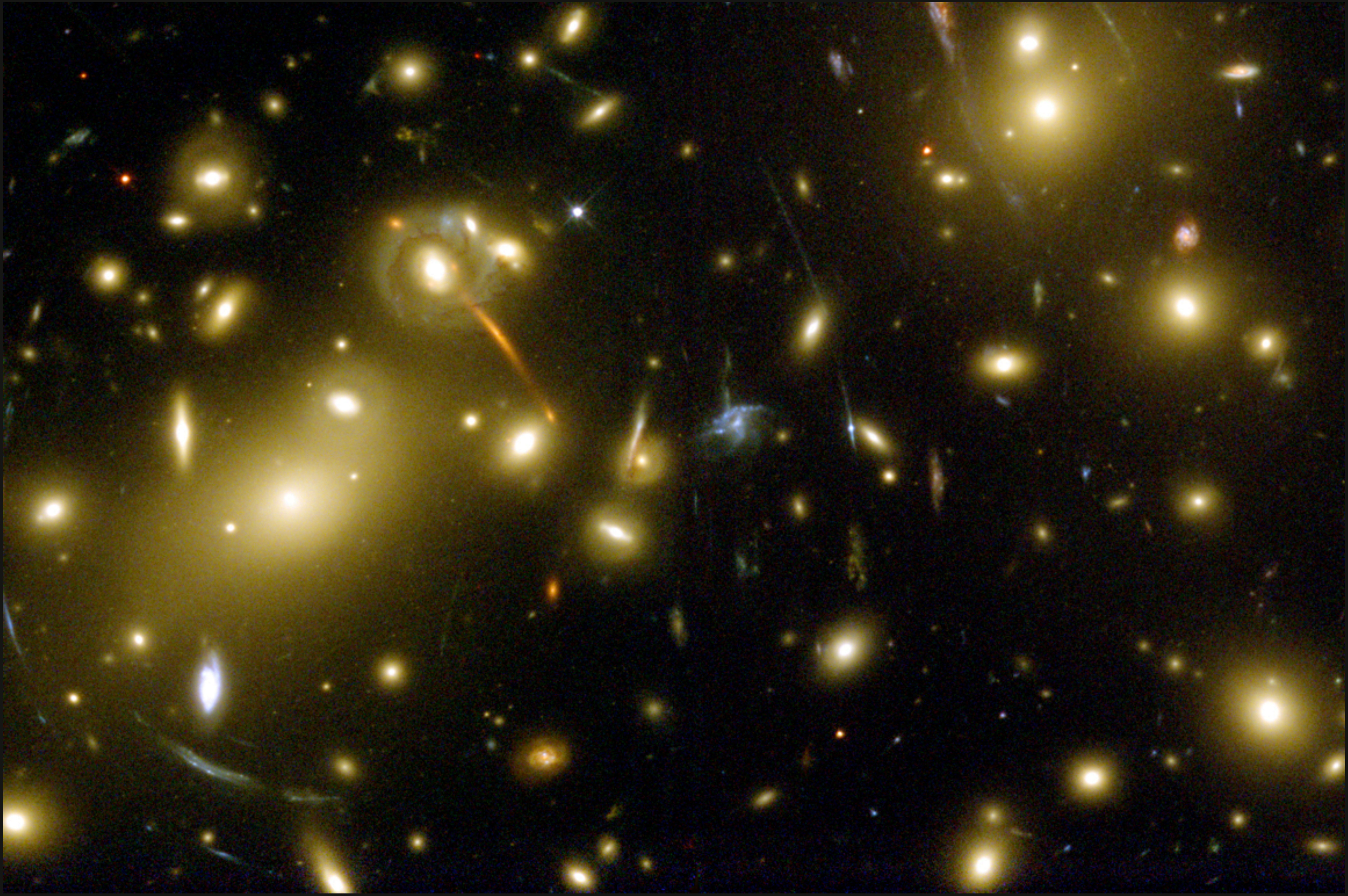
Note: The amount of precession with each orbit is highly exaggerated in this picture.

Gravitational lenses

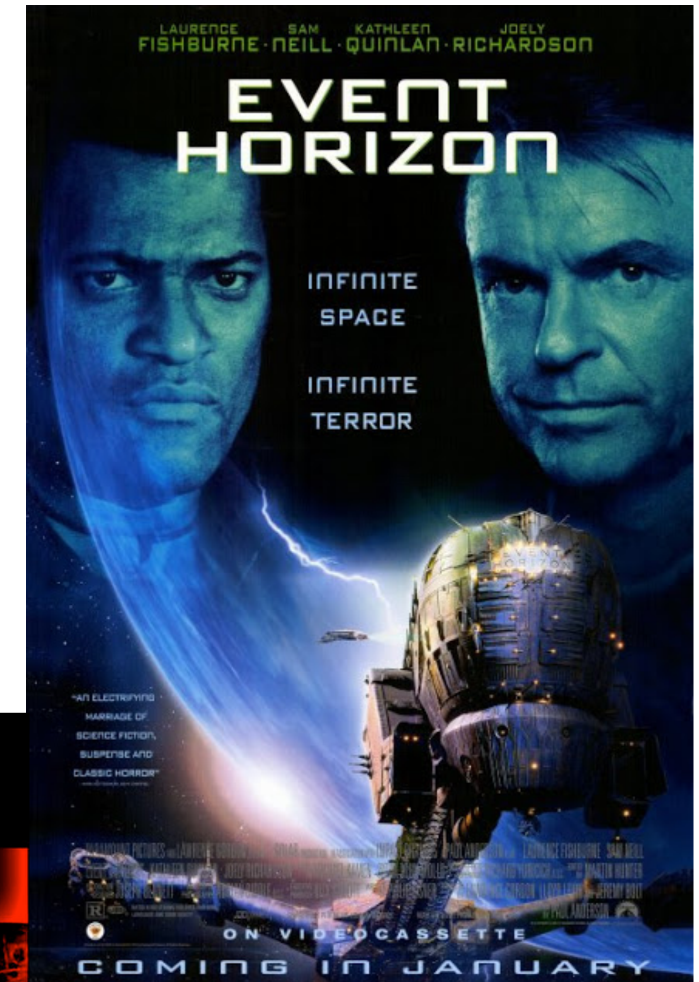
Gravitational lenses

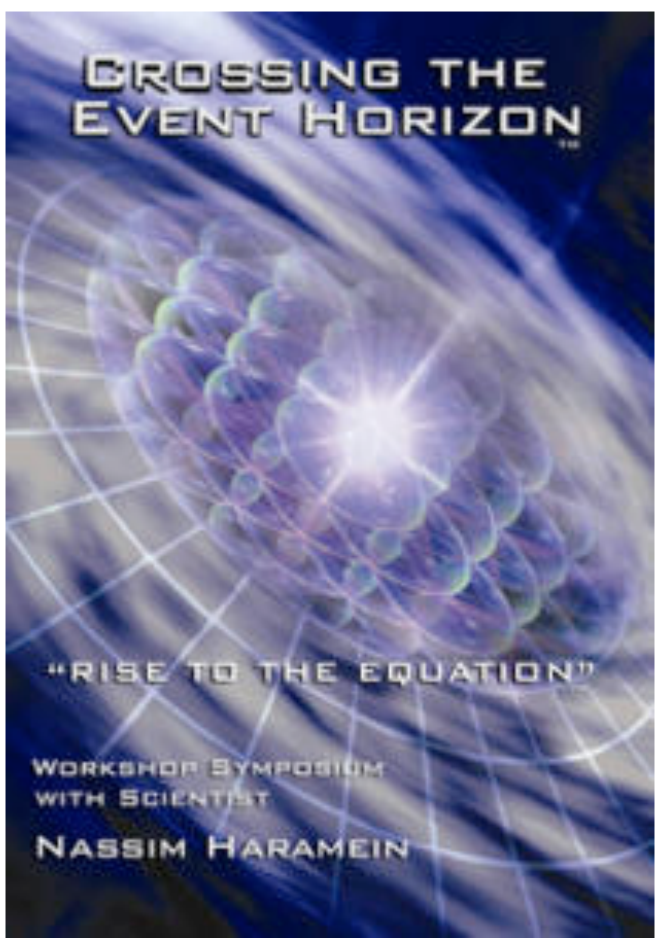


Gravitational lenses

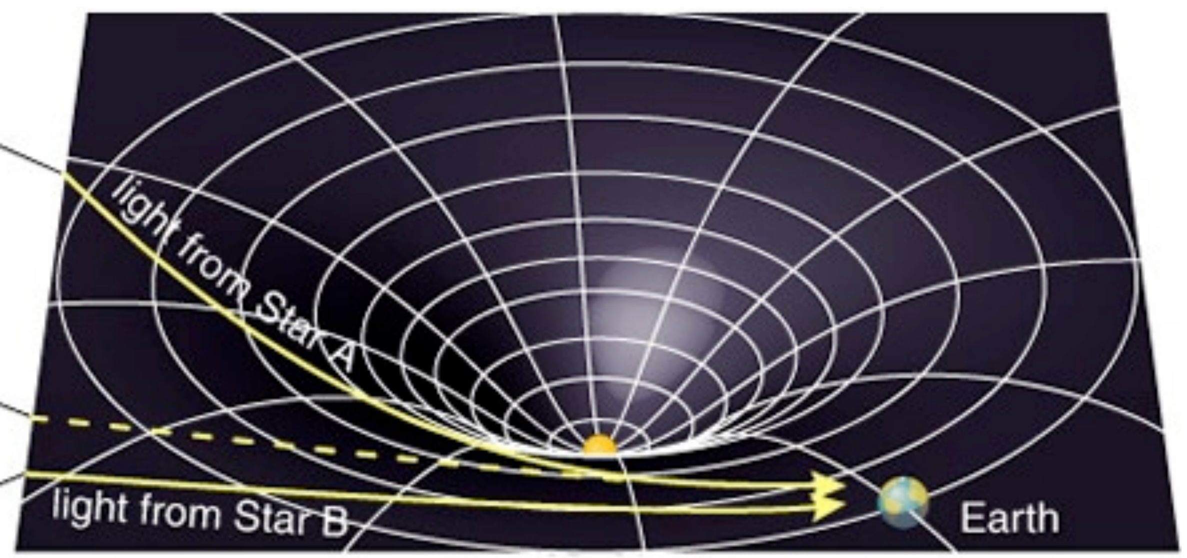


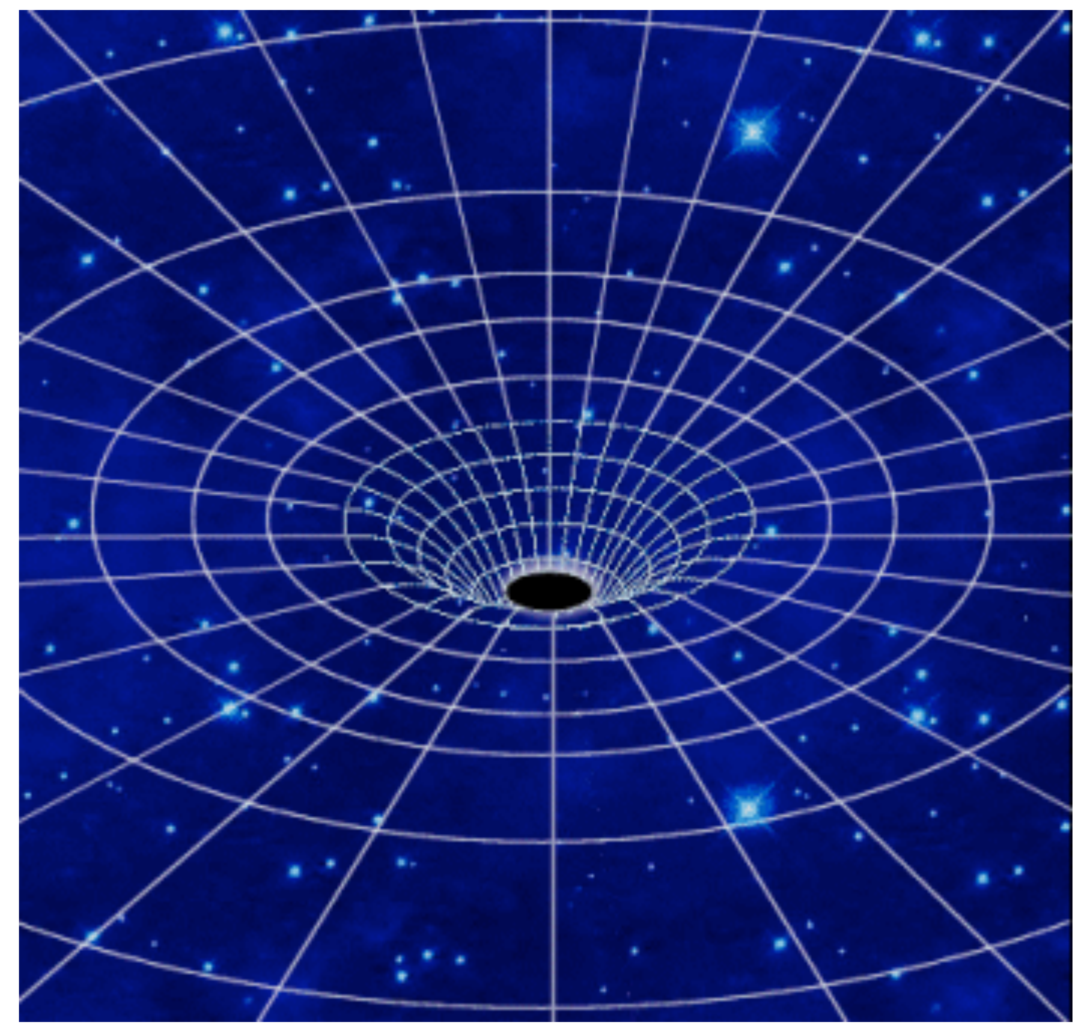
Black Holes and Event Horizon



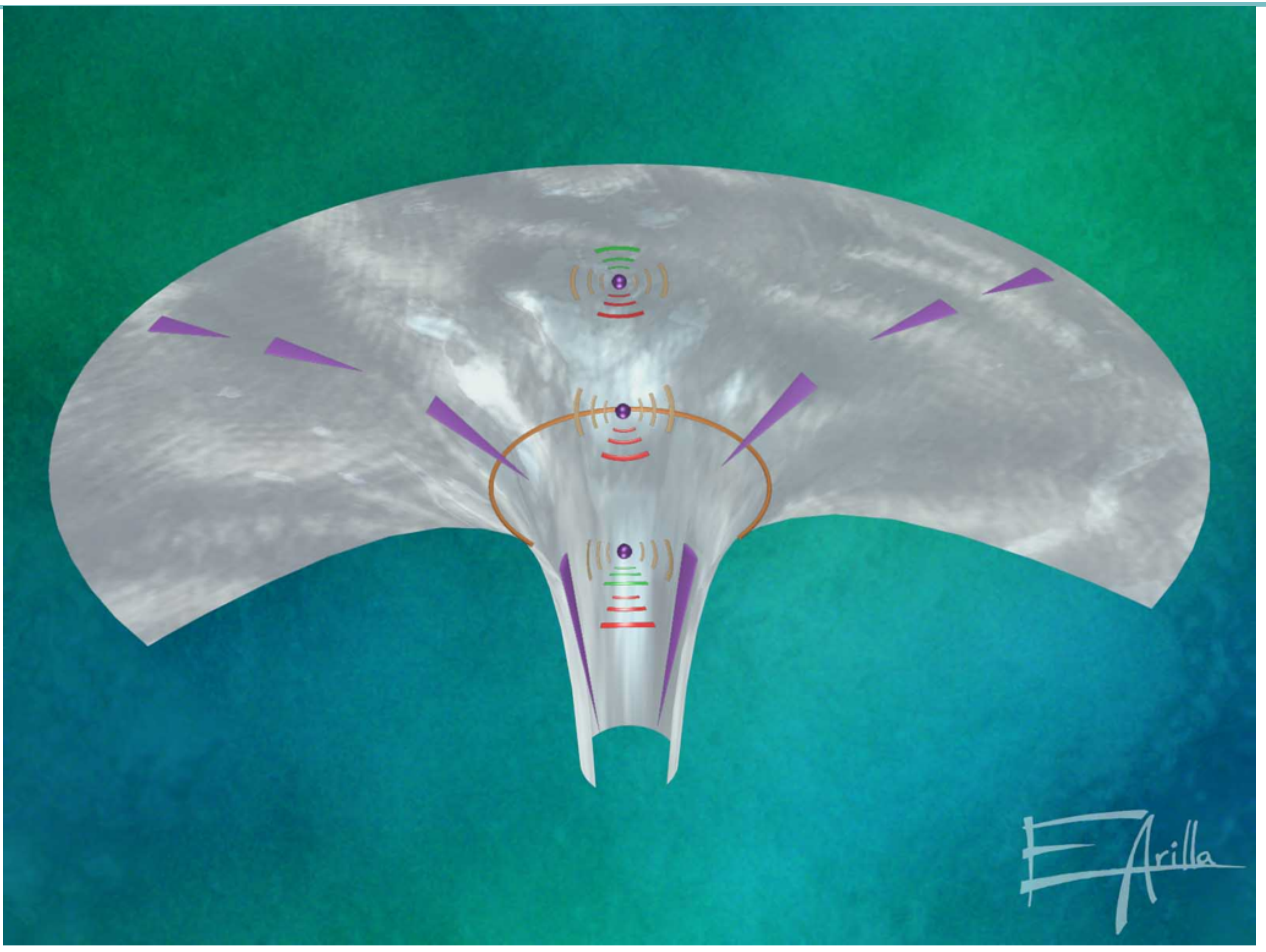


Black Holes and Event Horizon





At the ``event horizon'' or *Schwarzschild* ***radius of a black hole, the escape velocity is equal to the speed of light.*** For an object with the mass of the Sun, this radius is only 1.5 km; for an object with 10Msun, this radius is 15 km.



- Einstein's Relativity Theory predicts that the larger the mass, the greater the curvature (or indentation) of space-time. A black hole is the extreme example in which the indentation is infinitely deep.

- Consequences include:

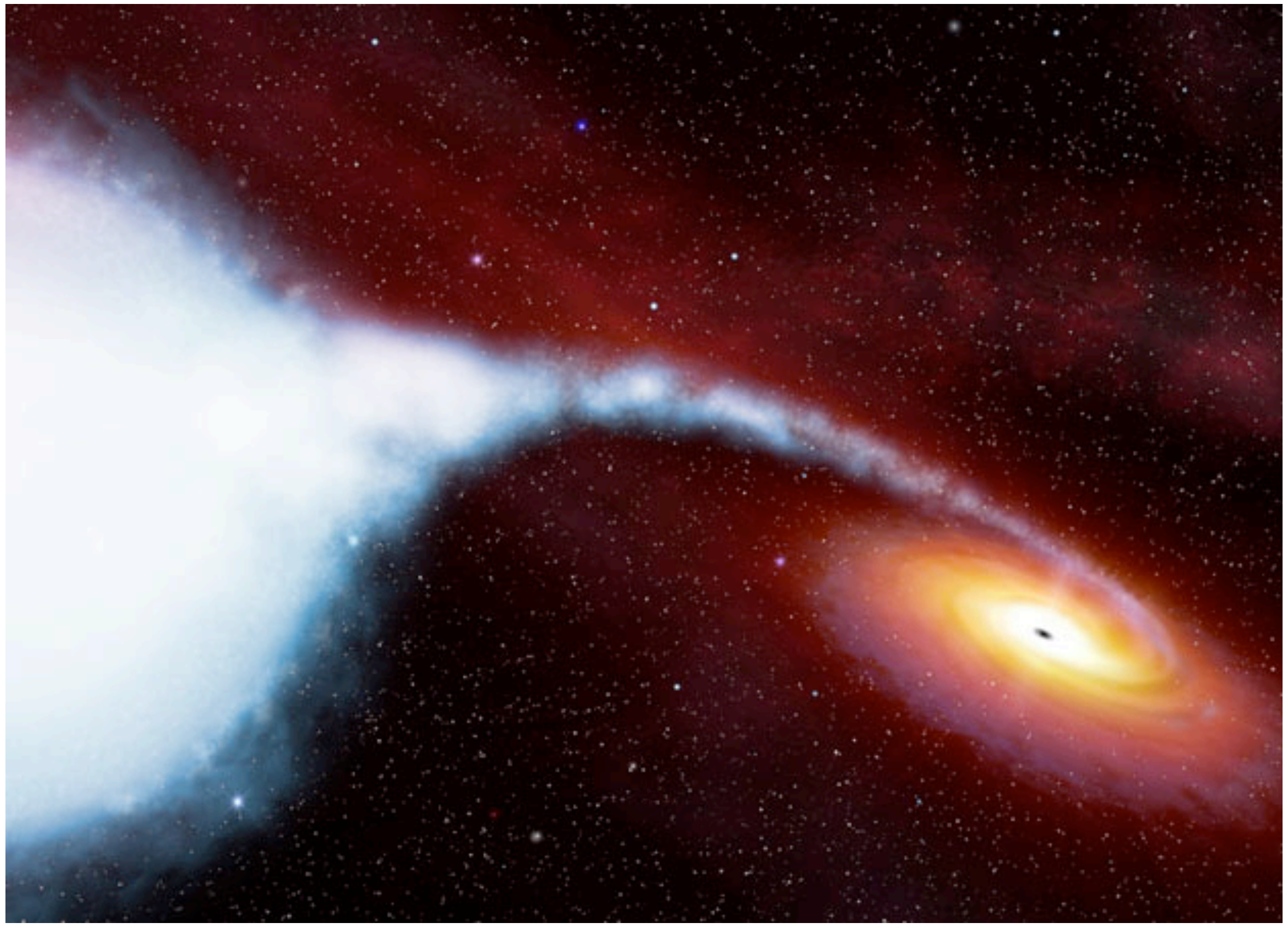
    - At the ``**event horizon**'' or *Schwarzschild* ***radius of a black hole, the escape velocity is equal to the speed of light.*** For an object with the mass of the Sun, this radius is only 1.5 km; for an object with 10Msun, this radius is 15 km.

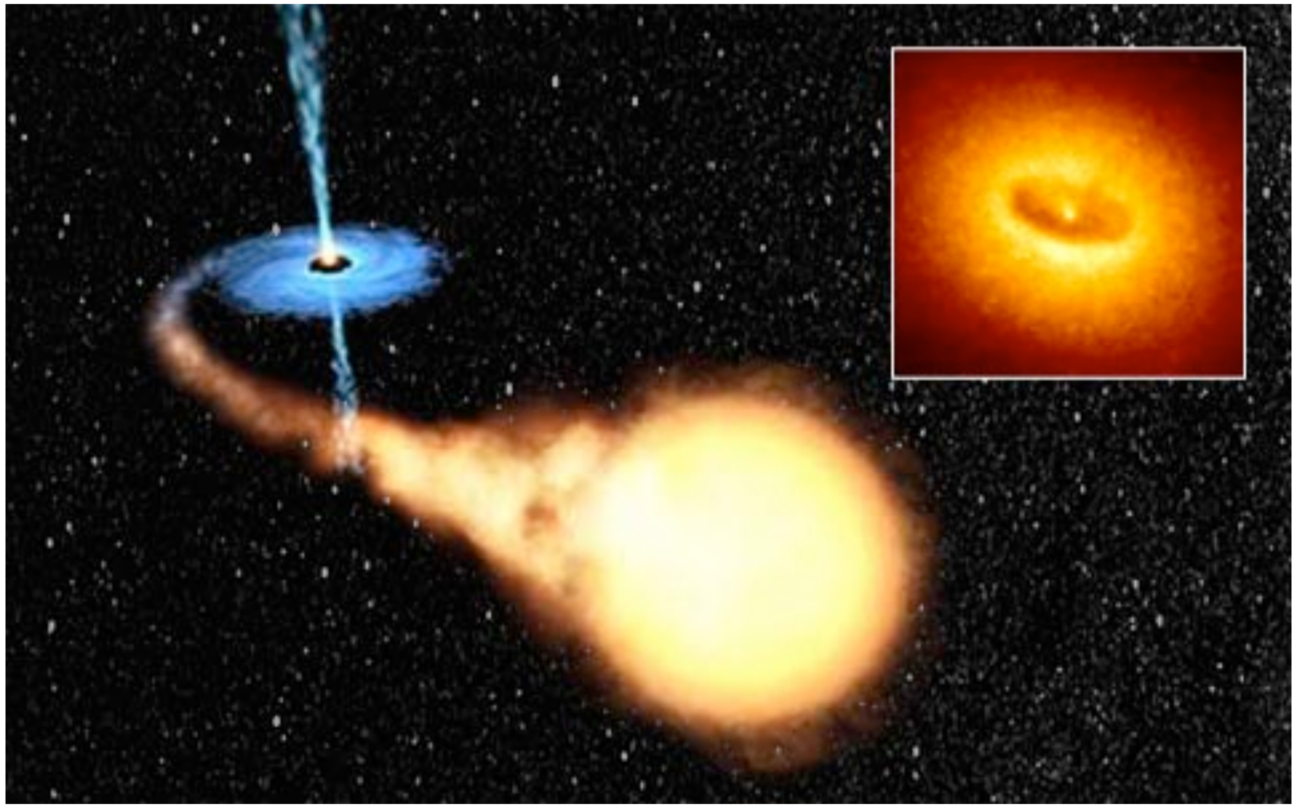
    - Once an ***object falls inside the event horizon, it can never come back out***. It is lost forever to us. This includes light which is the reason we call this object a ``black hole''.

    - Although time would appear to run normally for an astronaut approaching a black hole, an outside observer would judge that the astronaut's clock is running slowly. In fact, that outside observer would see that it would appear to take an ***infinitely long time for the astronaut to fall into the black hole*** at the event horizon. This is due to the extreme curvature of space-time near the black hole.

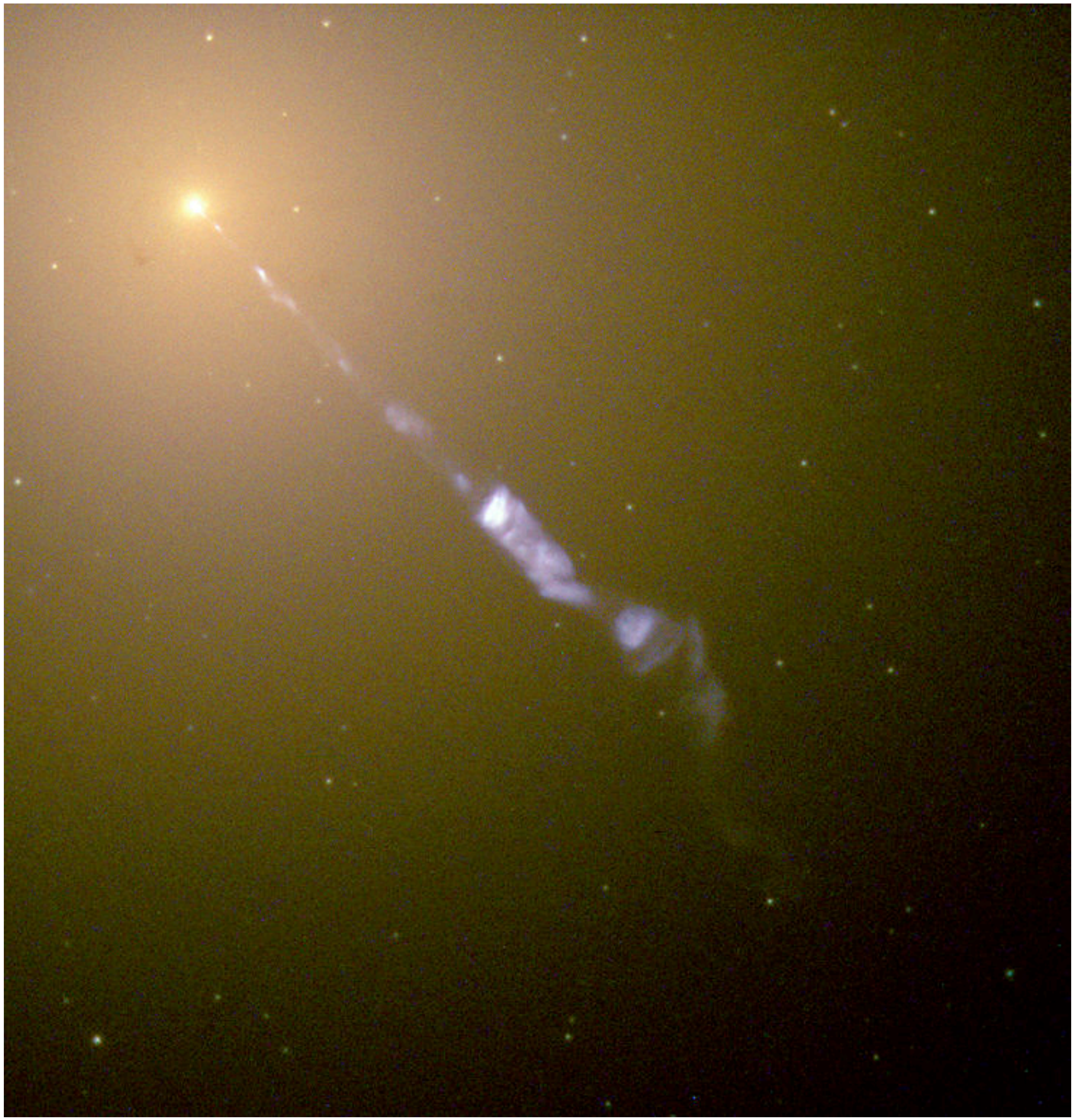
- How does a black hole form? For stars at the end of their lives (after Red Giant & supernova stages) which are 5Msun , there is no barrier to total gravitational collapse. The gravity is strong enough to overcome the degenerate gas pressure which halts the collapse of lower mass white dwarfs & neutron stars. The volume becomes very small and the density is infinitely large. The resulting curvature of space-time is infinitely deep & the object becomes a black hole.

- Have we ever seen a black hole? Since the black hole Schwarzschild radius is small & the hole is black, we cannot hope to directly observe the hole. However, we can possibly see it through the strong gravitational effects it has on nearby objects. A black hole in a binary star system with a Red Giant companion will accrete gas from the companion; the resulting accretion disk will heat & produce X-rays. The Cygnus X-1 star system is a good candidate for a black hole; it has a visible Red Giant star and an invisible companion with an inferred mass of using Kepler's 3rd Law.





M87 giant elliptical galaxy has a powerful jet, which is coming from the a disk around 10^9Msun black hole



Merging galaxy Cen A has a jet and a black hole