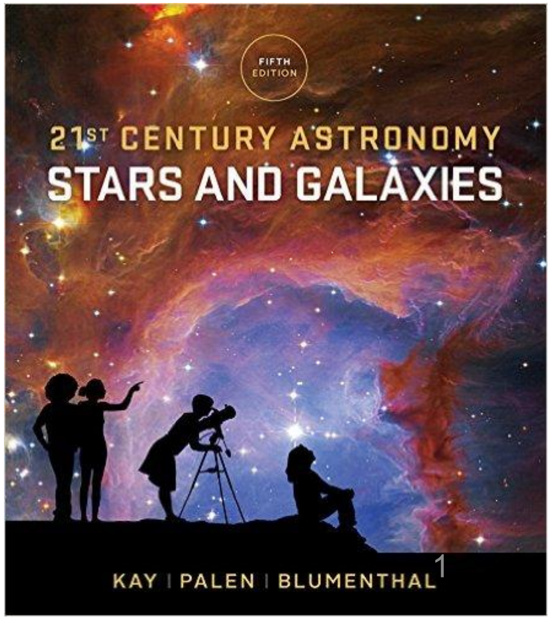
PHYS 104N
Introductory Astronomy of Galaxies and Cosmology

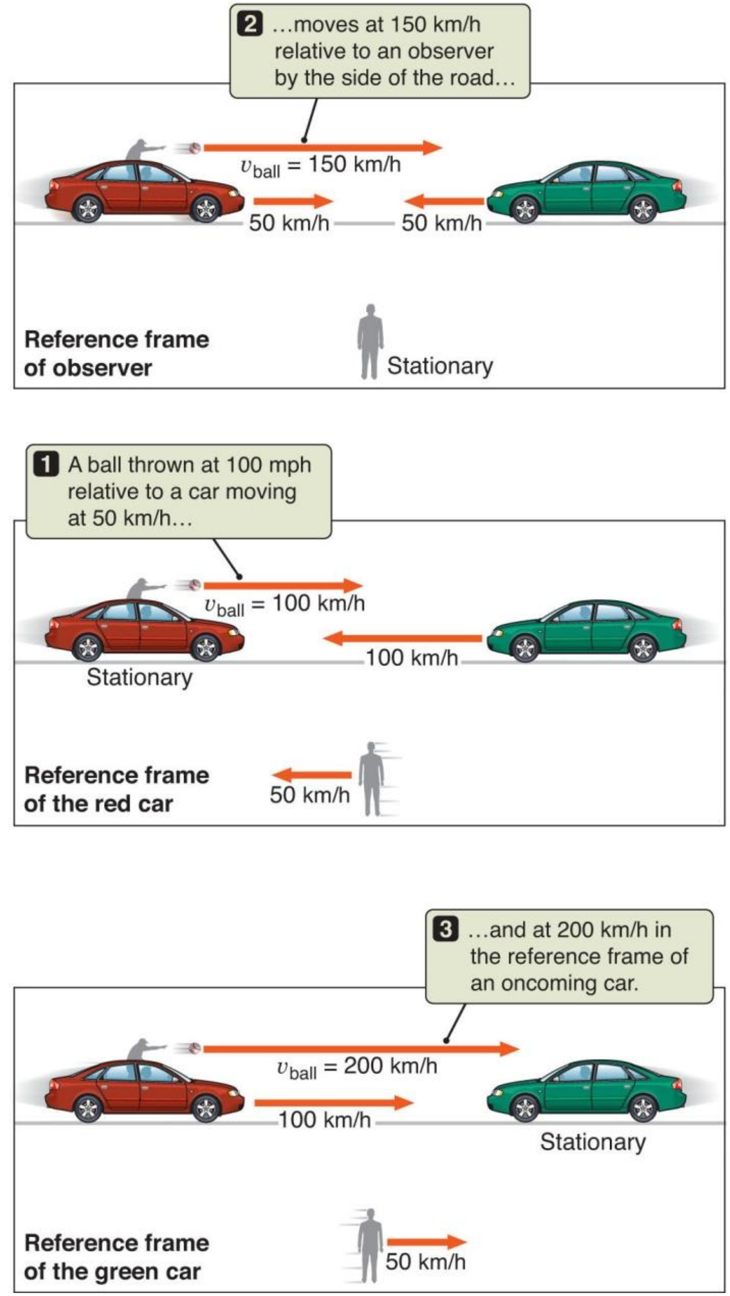
Chapter 18
Relativity and Black Holes



Reference for Illustrations:
Kay, Palen, Blumenthal,
21st Century Astronomy: Stars and Galaxies
5th edition, W.W. Norton 2016

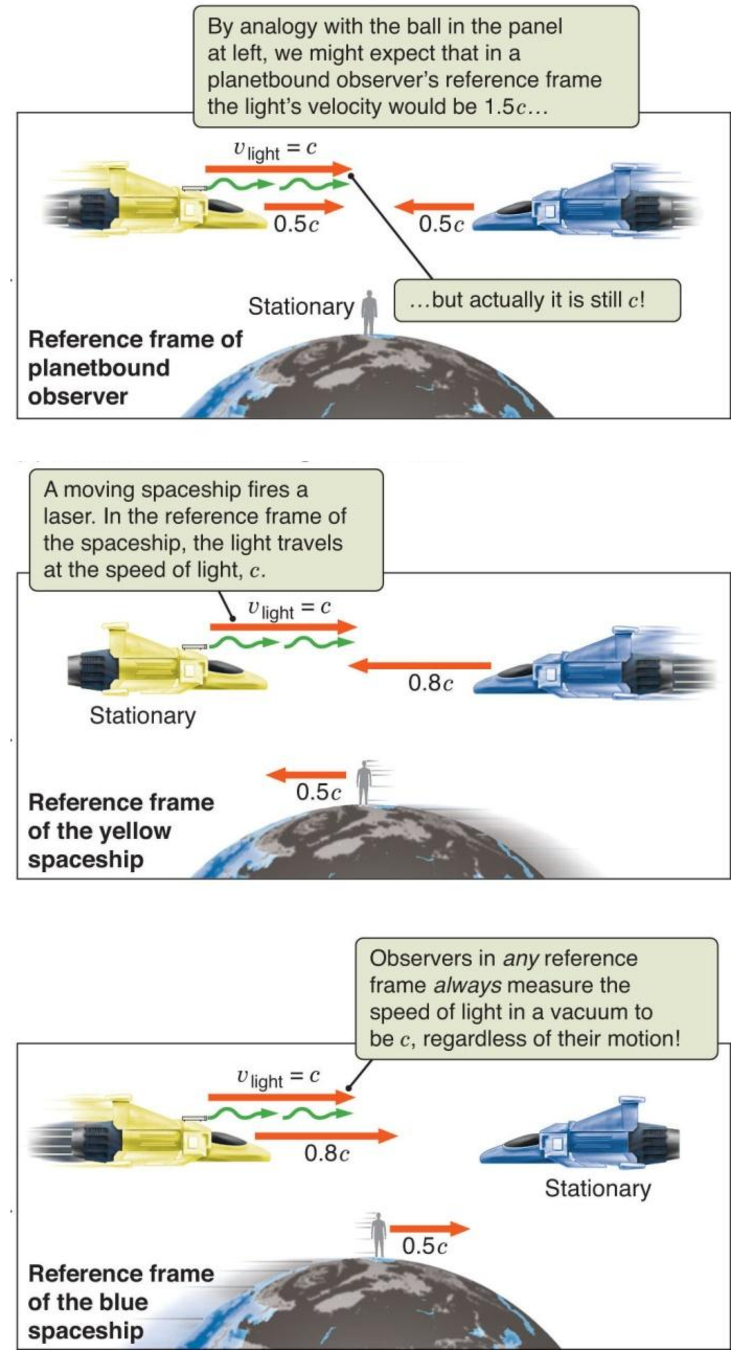
Special Relativity

- The (Newton’s) laws of physics apply in any
  inertial reference frame
  - any frame that is not accelerating
- Velocities add up
- Every vantage point can be related to a different vantage point



Special Relativity

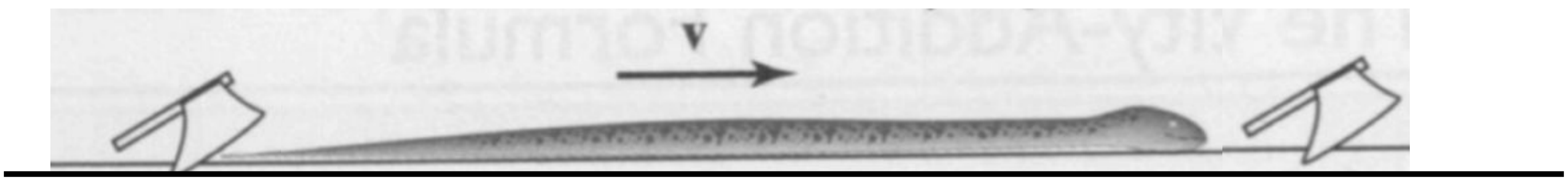
- At high speeds, close to the speed of light, all observers measure that light travels with c
- Speeds do not simply add up
- Einstein's theory of special relativity needs to be applied
- Special relativity relates events in space and time
  4-dimensional spacetime
- Newton's laws of physics are an extreme low speed case of special relativity



Relativistic Snake

A 1m long snake slithers across a table at 0.6 c.

A cruel boy plays a game with the snake and drops two axes simultaneously 1 meter apart (trying to pinch the snake)

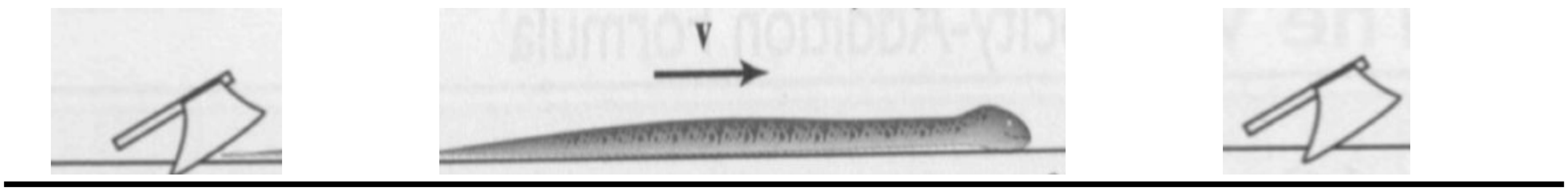


Both the snake and boy measure the speed of light to be c.

What are the consequences?

Relativistic Snake

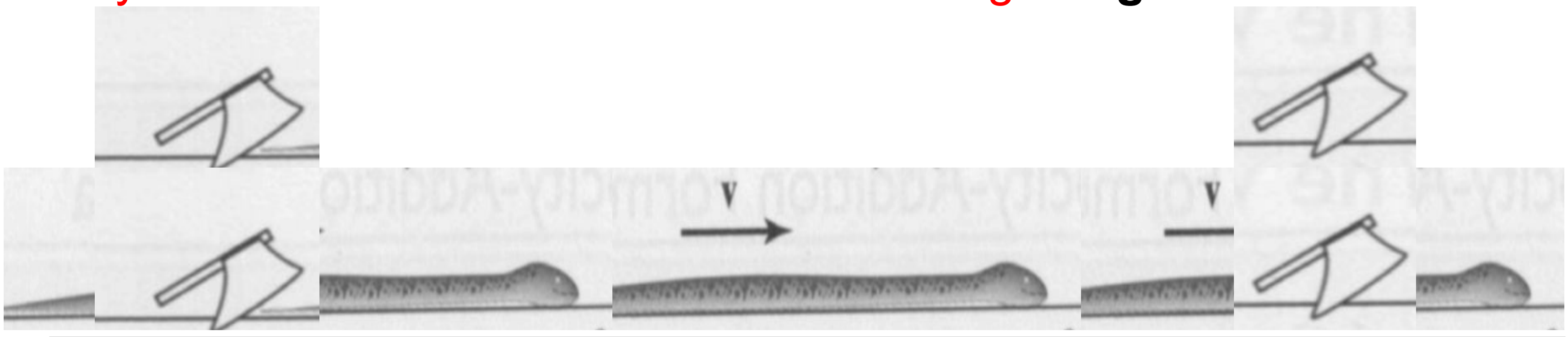
Boy sees snake to be less than a meter long **Length Contraction**



Snake sees the axes less than a meter apart

Relativistic Snake

Boy sees snake to be less than a meter long **Length Contraction**

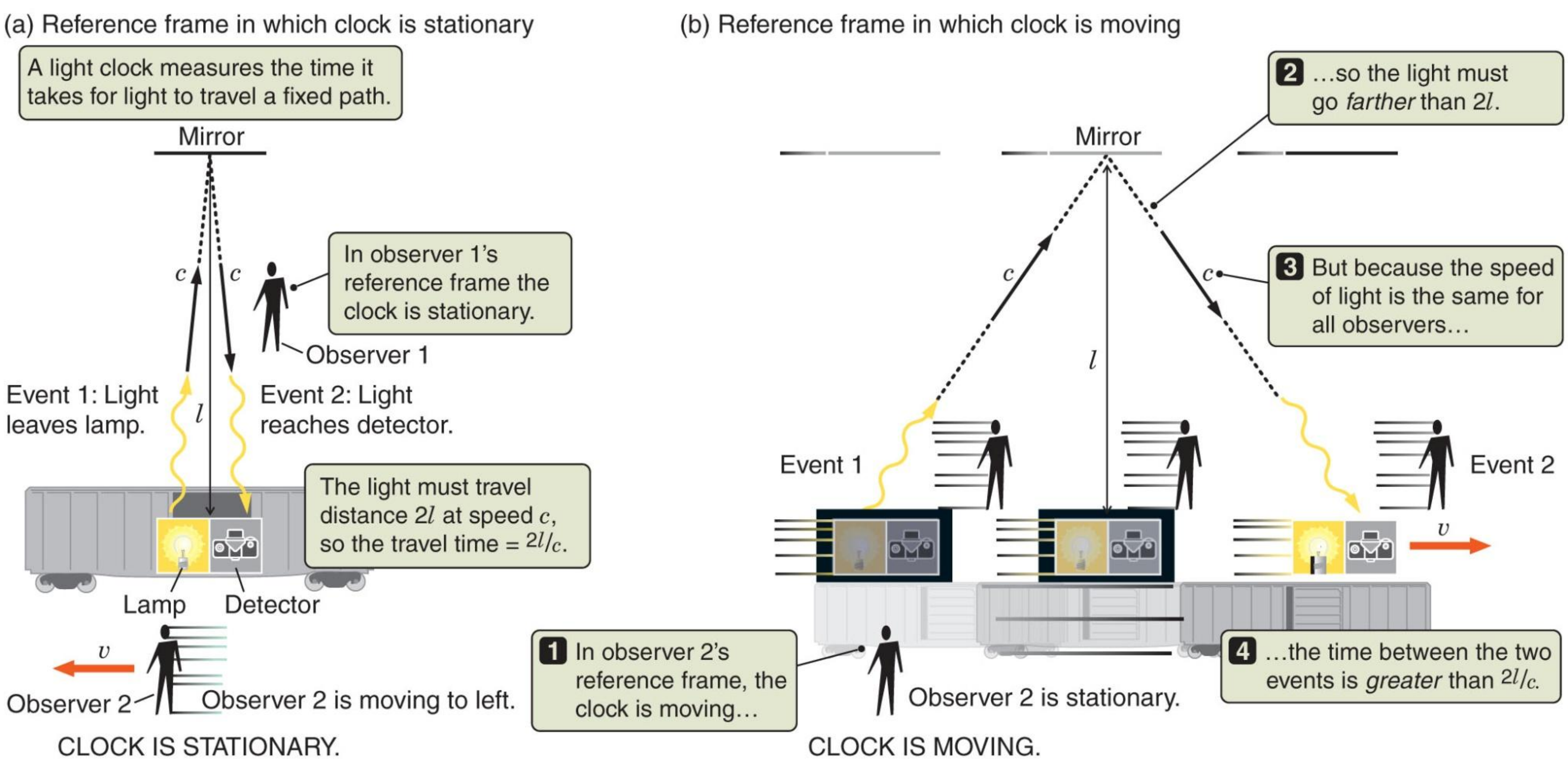


Snake sees the axes less than a meter apart

Time Dilation

Special Relativity

- Time between events depends on reference frame
- Results in time dilation

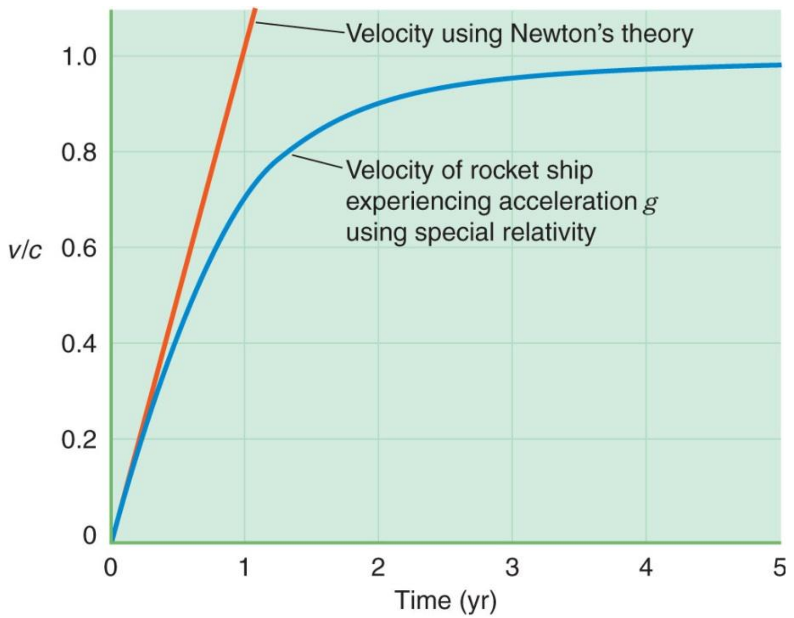


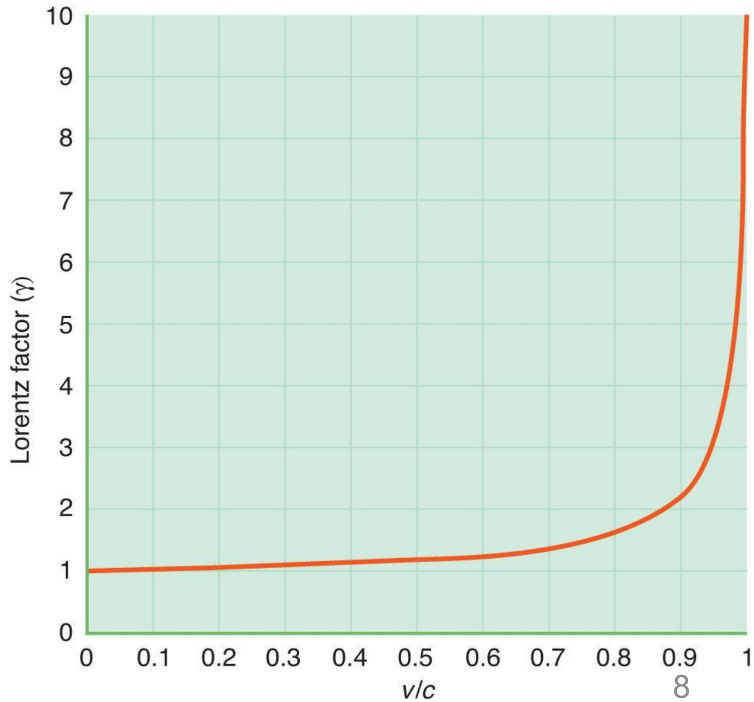
Implications of Special Relativity

- Speed of light c is ultimate speed
- Time is relative and depends on reference frame
- Lorentz factor γ is a measure of relativistic effects

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

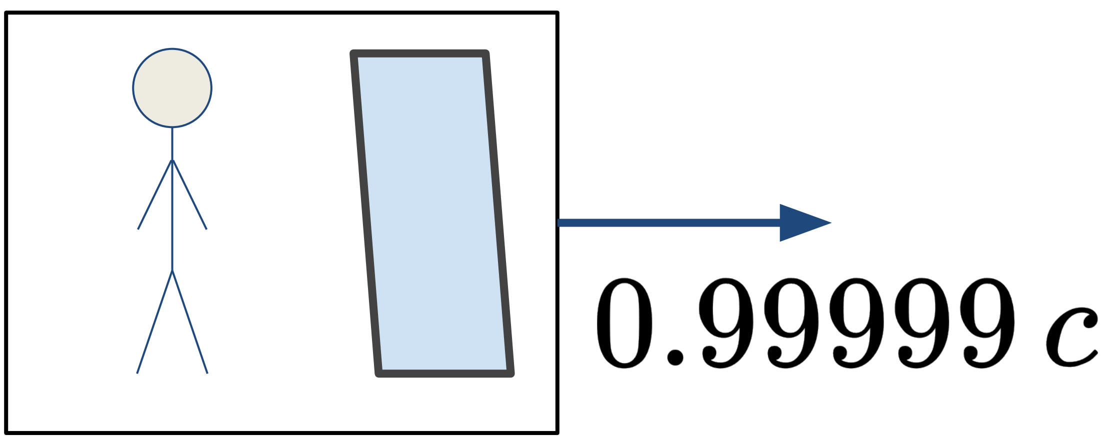
- Time dilation and length contraction





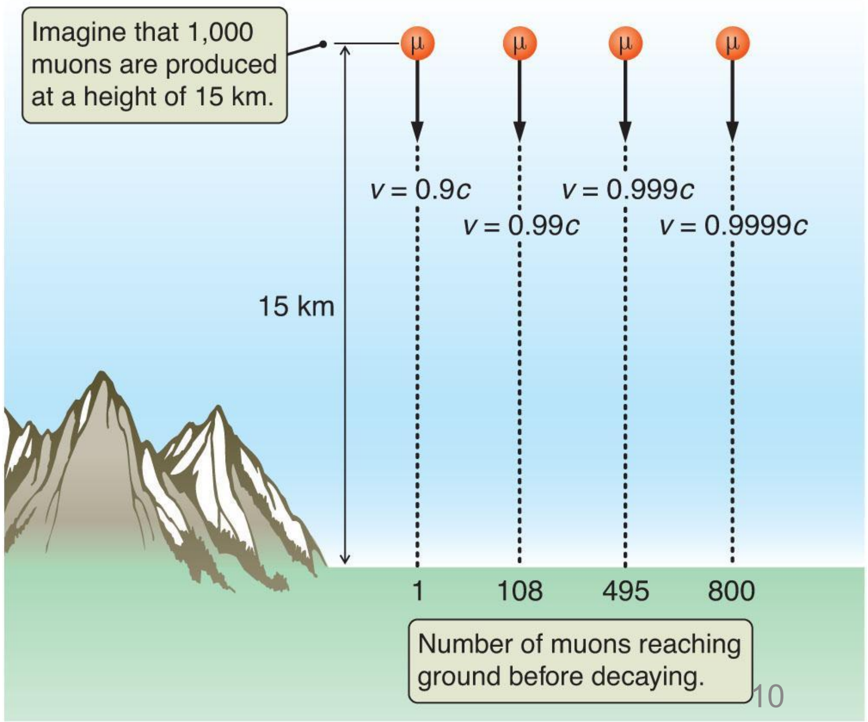
Suppose you are in a rocket ship going 99.999% the speed of light and you look at a mirror. At this moment what do you see in the mirror?

A. Nothing, the photons have yet to reach the mirror
B. Yourself from a few seconds ago
C. Yourself, perfectly normal
D. Yourself contracted



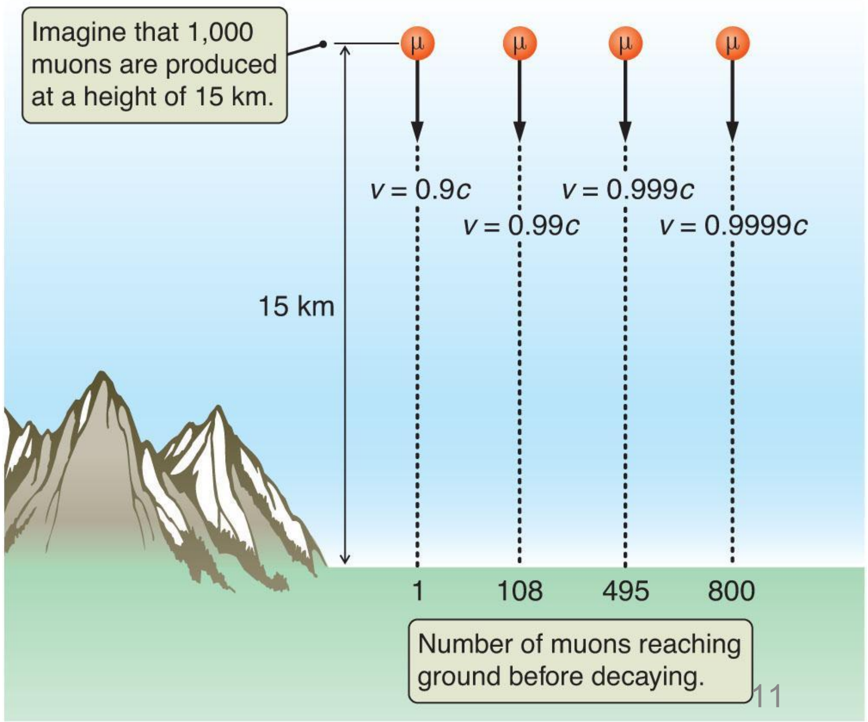
Time Dilation and Length Contraction

- We saw that moving clocks go slower than clocks at rest
- Cosmic muons are created in the upper atmosphere
- Muons are unstable and have a mean life time of 2.2 μsec
  - Muons traveling at the speed of light should cover an average distance of 660 m before decaying
  - Muons created at 15 km altitude should not be able to reach the ground at sea level
- Traveling at near speed of light, the clock of an outside observer runs faster than the internal clock of the muons

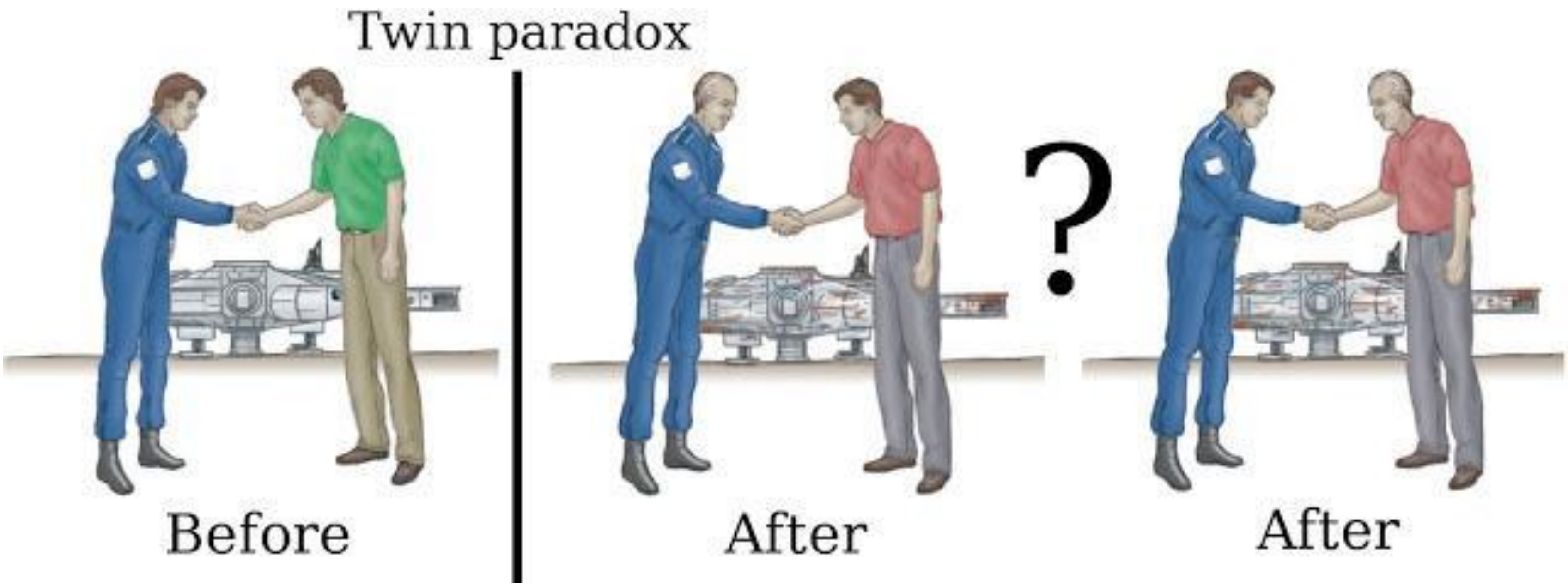


Time Dilation and Length Contraction

- Time between two events in the rest frame is given by Δt
- Time between two events in the moving frame is given by $\Delta t' = \gamma \, \Delta t$ (time dilation)
- The same phenomenon can also be explained by length contraction
- Distance in the rest frame is given by L
- Distance in the moving frame is given by $L' = L / \gamma$ (length contraction)



Twin Paradox



Which twin should have aged less?

Not a true paradox since special relativity can resolve this.
Need to account for rocket ship's acceleration when turning around to come back to Eartn

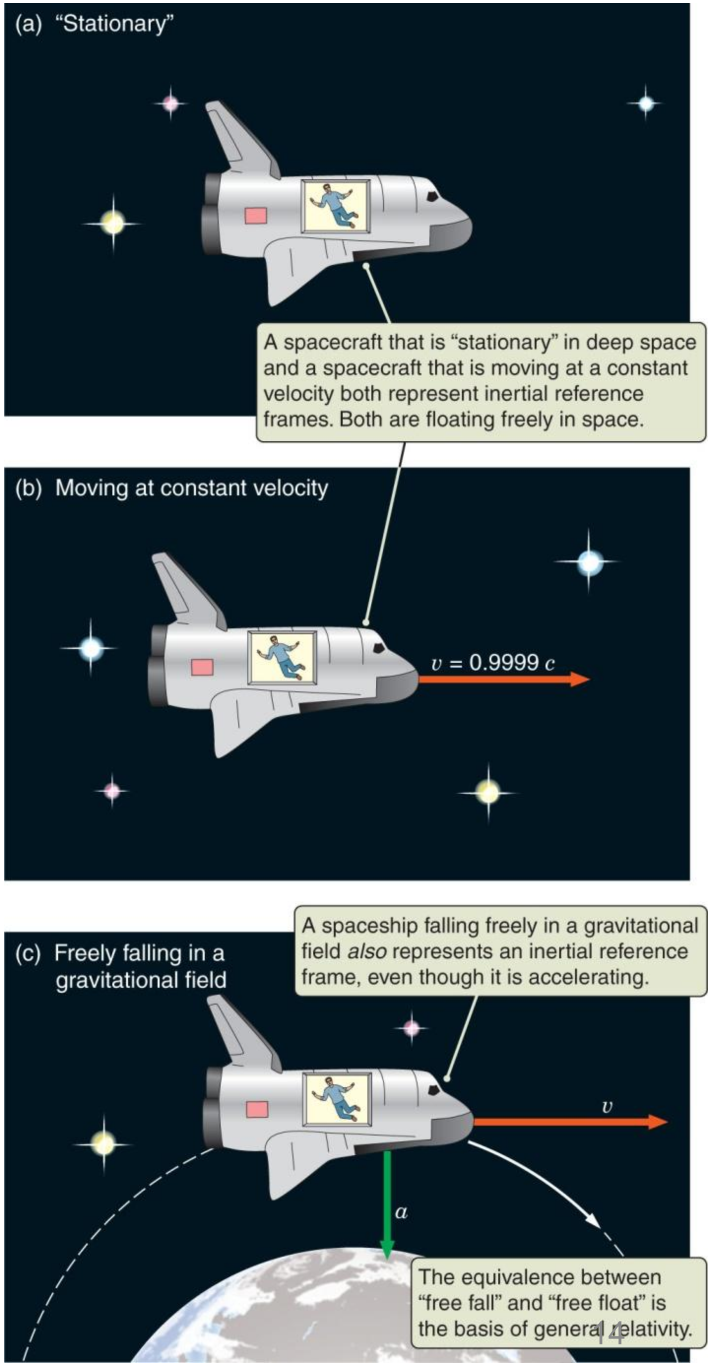
Speaking of Twins

- No Scott Kelly's DNA did not change by 7%. He would be dead if that had happen
- Different gene were found to be more active during his time in space
- His ground based brother and samples taken before trip in space provided unique biological data to study

Identical twins Mark and Scott Kelly. Scott spent 340 consecutive days in space.

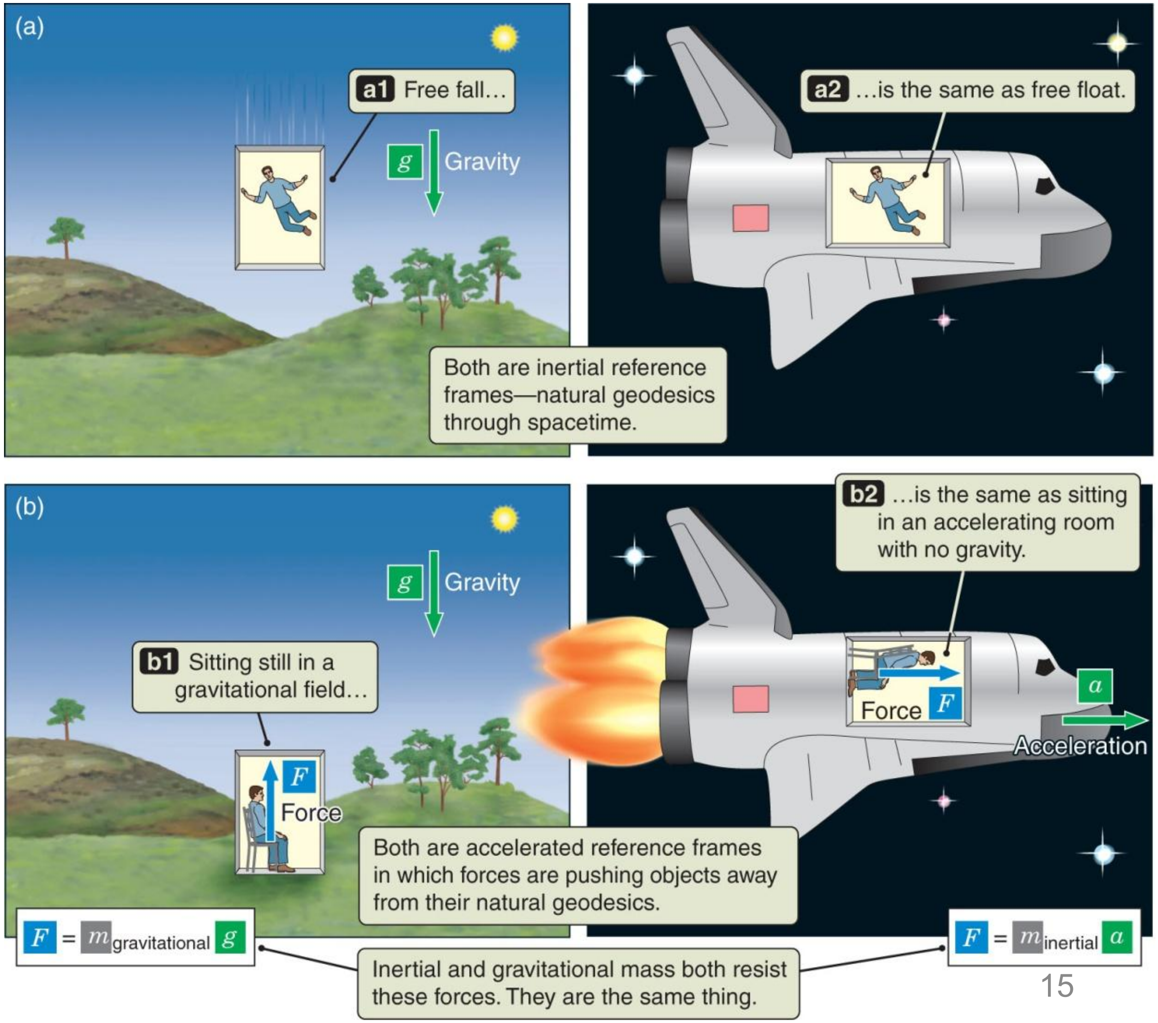
Special Relativity

- In special relativity all these frames of reference are valid
  - Stationary
  - Moving at constant velocity
  - Free falling in a gravitational field



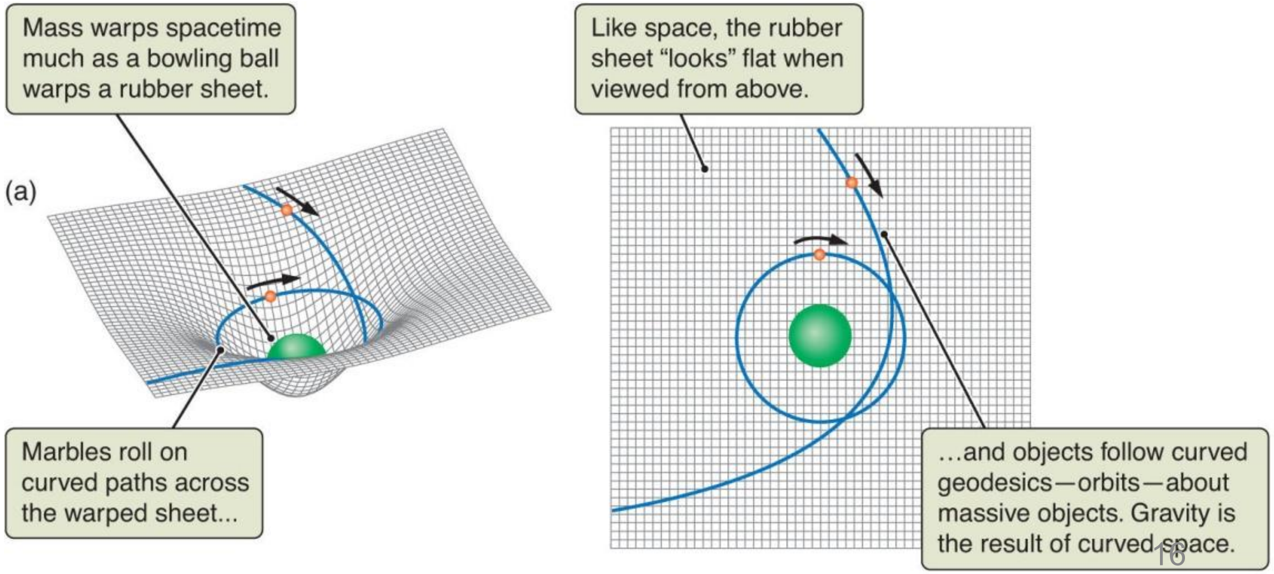
General Relativity

- In general relativity gravitational mass and inertial mass are identical
- Equivalence Principle:
  - You cannot tell the difference between mass in a gravitational field or mass in an accelerating frame
  - Both are accelerating reference frames



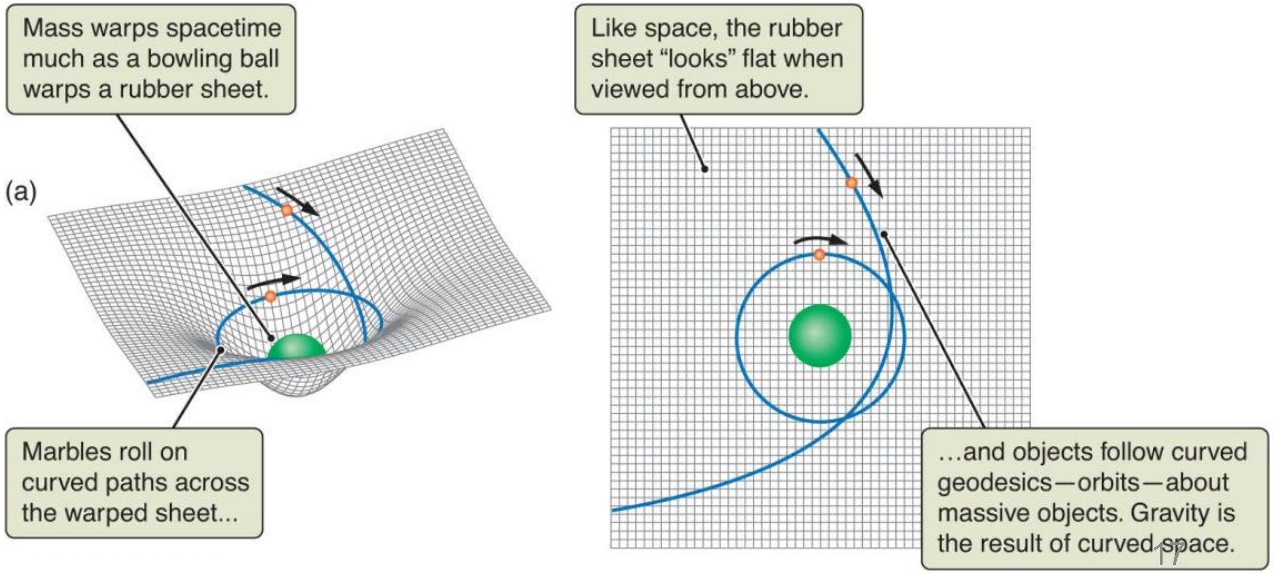
General Relativity

- The theory of general relativity describes how objects move in spacetime in the presence of mass
- Rather than using the concept of force, Einstein uses the concept of a distorted geometry of spacetime
- If no mass is present, an object's path would be a straight line in spacetime
- The presence of mass changes the shape of spacetime



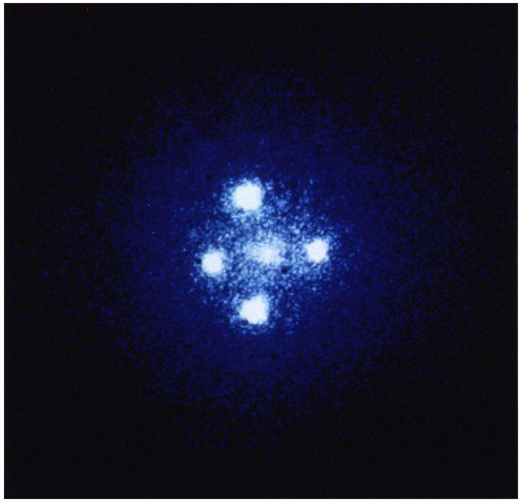
General Relativity

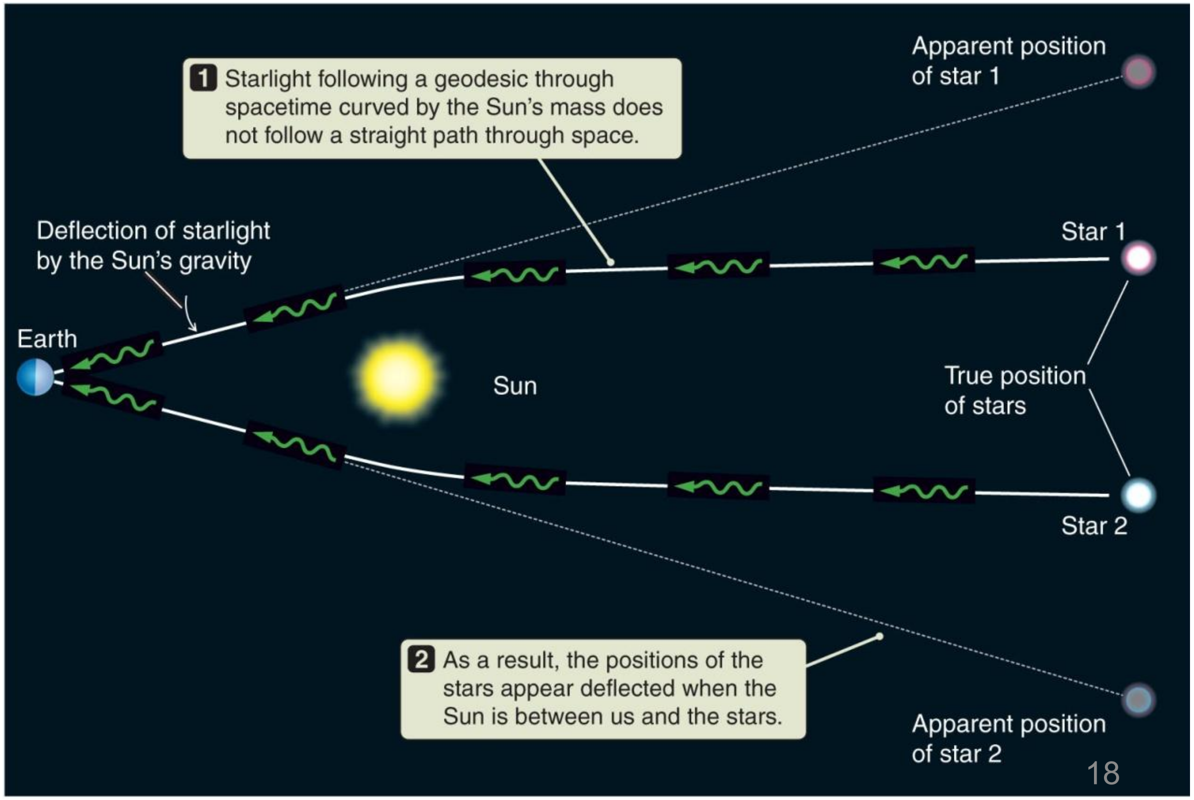
- Larger masses distort spacetime more
- A moving object follows the geometry of spacetime on the shortest possible path (geodesic)
- In the presence of mass, the objects geodesic will be curved



Gravitational Lensing

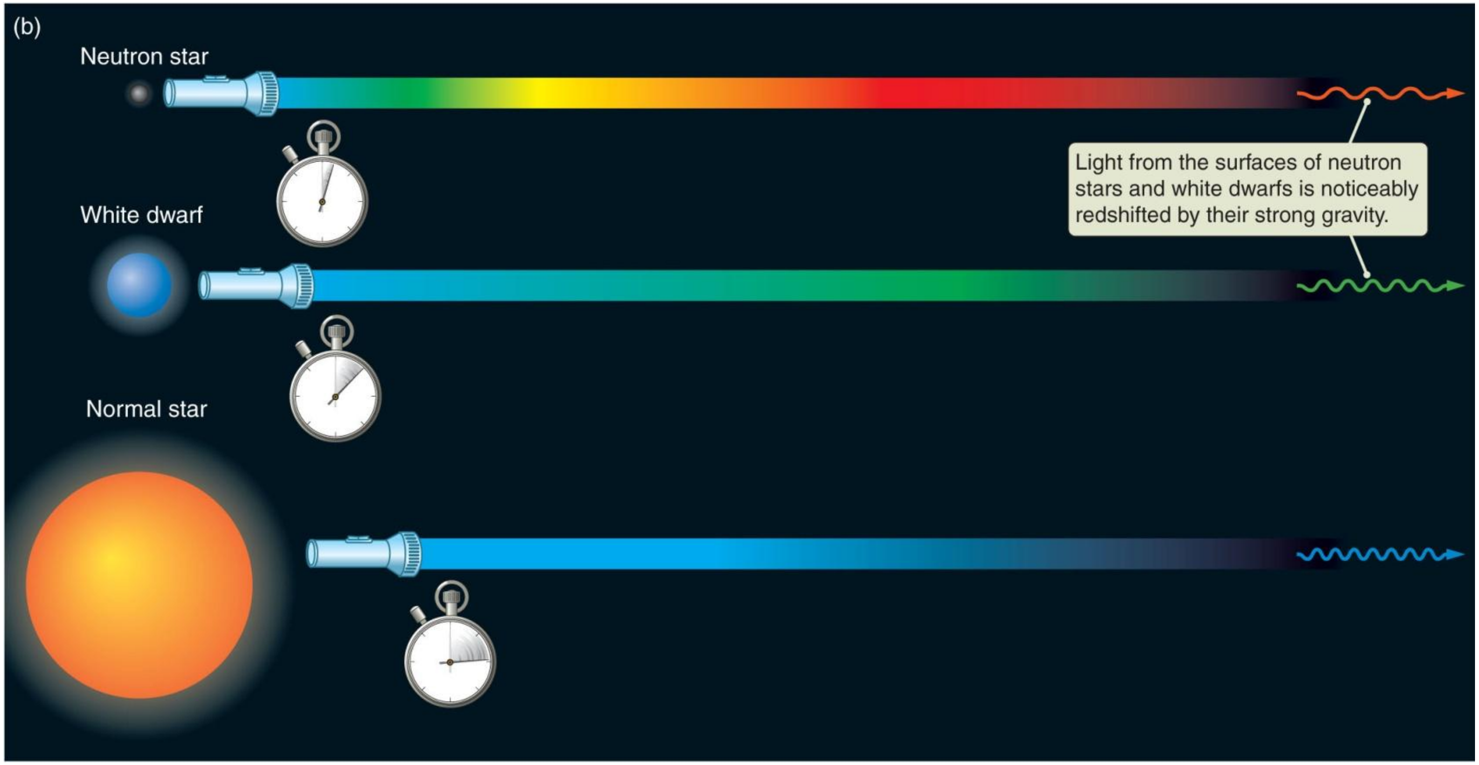
- Light also follows the curvature of space
  - Lights geodesic will be bent by massive object
  - Can be used to detect the presence of very massive objects by observing distorted or displaced images of stars and galaxies
- Einstein Cross of quasar *Q2237+030* around galaxy





Gravitational Redshift

- Time runs slower near massive objects
  - General Relativistic time dilation
- Light emitted from neutron stars and other massive objects shows a redshift independent of recessional velocity



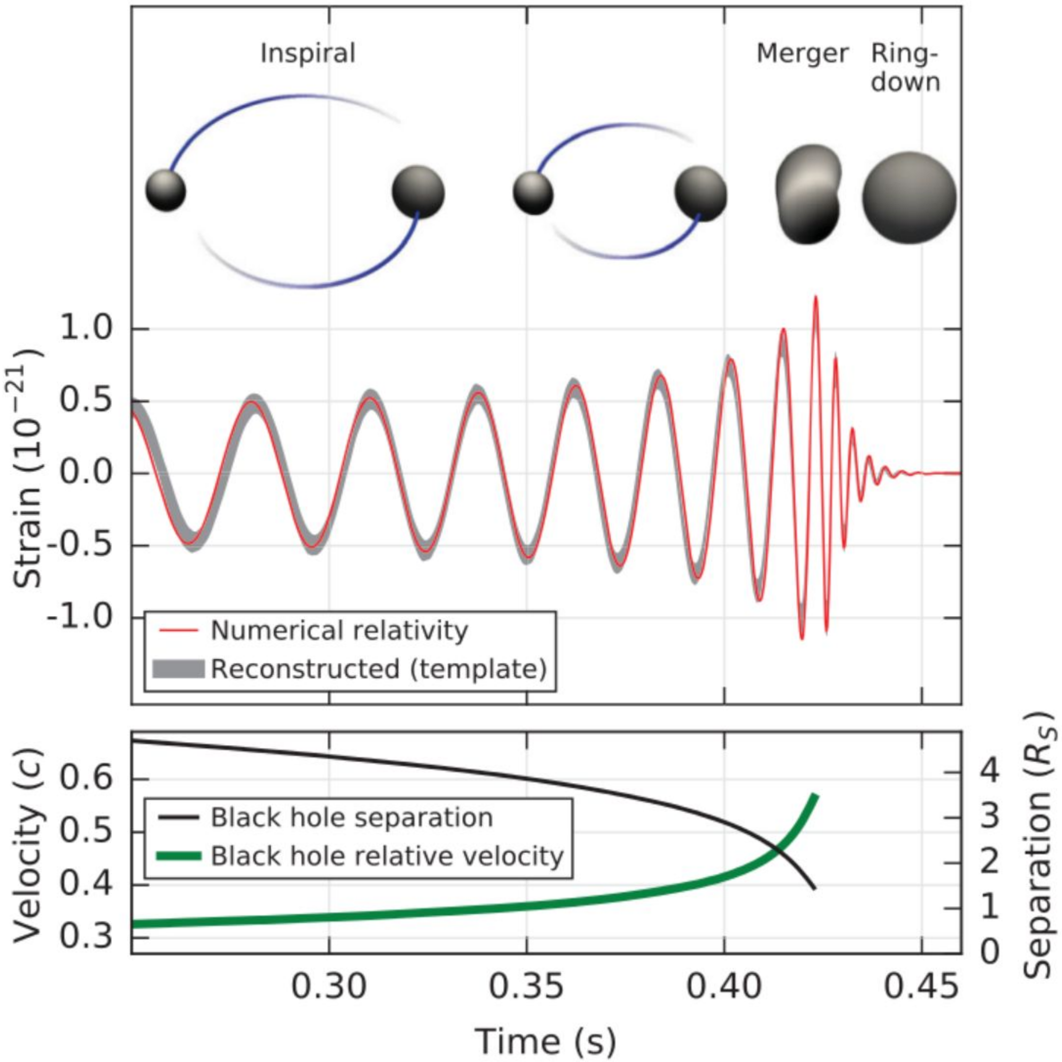
Gravitational Waves

- Accelerating massive objects, e.g. merging black holes, will create ripples in spacetime
  - Ripples propagate with the speed of light
  - Should dislocated objects in their path
  - Observed for the first time by Laser Interferometer Gravitational-Waves Observatory LIGO in 2015 and published in 2016

Livingston, LA

Laser Interferometry

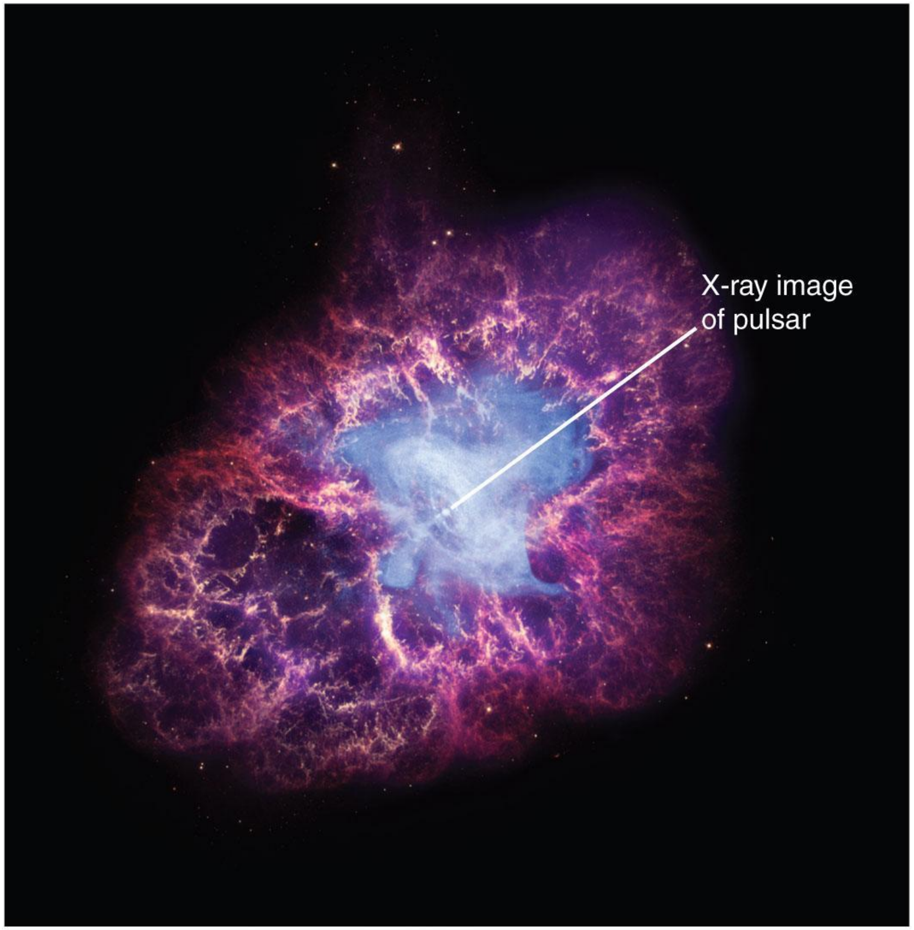
https://www.ligo.caltech.edu/mit/video/ligo20170601v2

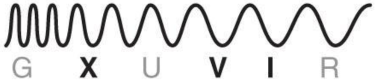


PRL 116, 061102 (2016)

Neutron Stars

- The Crab Nebula is the remnant of a massive star that exploded in 1054 AD
- At its center is a pulsar, a fast spinning neutron star
- The pulsar is the remnant of the former star
- If the neutron star would exceed 3 solar masses, it would be a black hole





Black Holes

- Black holes can be created directly during a supernova of a very massive star
- It can also be created through accretion by a neutron star in a binary star system
- A neutron star size is determined by gravity (mass) and neutron degeneracy pressure
- Adding mass will reduce the size of the neutron star and hence increase the surface gravity

Black Holes

- Surface gravity determines the escape velocity
- If the escape velocity exceeds the speed of light, c, the neutron star becomes invisible (black hole)

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM}{r}} = c$$

- How small for the sun to be a black hole

$$M_{\mathrm{sun}} = 1.989 \times 10^{30}\ \mathrm{kg}$$

$$r = \frac{2GM_{\mathrm{sun}}}{c^2} = 3\ \mathrm{km}$$

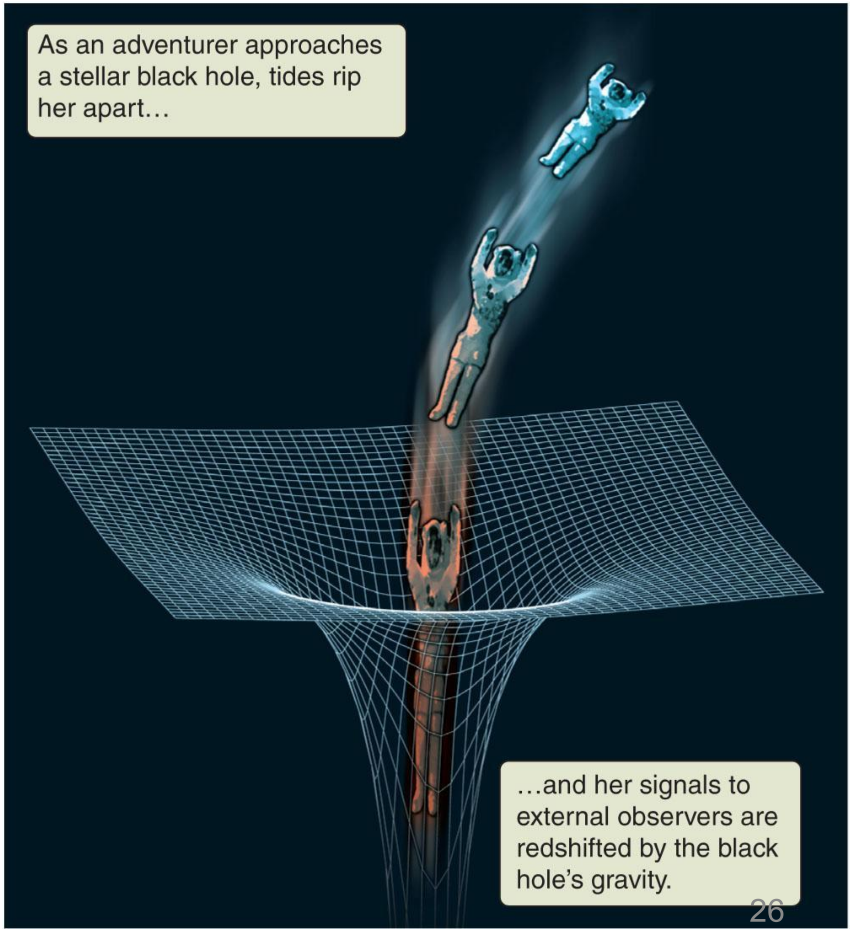
Black Holes

- General Relativity describes a black hole as a infinitely deep well in spacetime
- All mass can be described as having collapsed into a single point in spacetime
  - Singularity
  - Infinitely dense matter
- Event horizon given by the Schwarzschild radius determines the boundary of no-return, even for light

$$R_S = \frac{2GM_{BH}}{c^2}$$

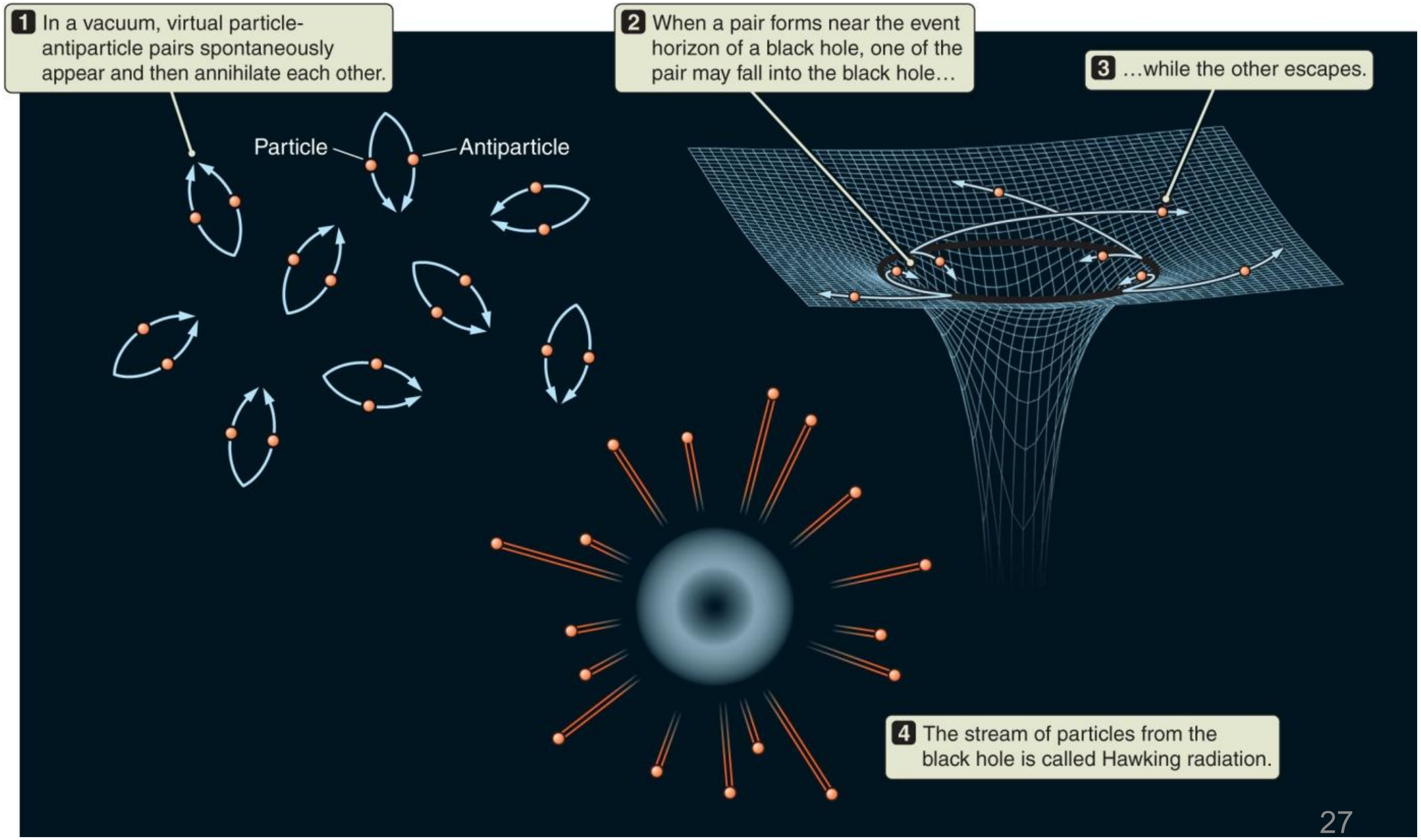
Black Holes

- Schwarzschild radius for one solar mass is about 3 km
- As an object approaches this event horizon, it will be torn by tidal forces
- Gravitational time dilation and redshift are infinite
- Death by spaghettification



Are Black Holes Observable?

- Stephen Hawking showed the possibility of pair-creation out of vacuum near the gravitational field of a black hole
  - The black hole loses gravitational energy

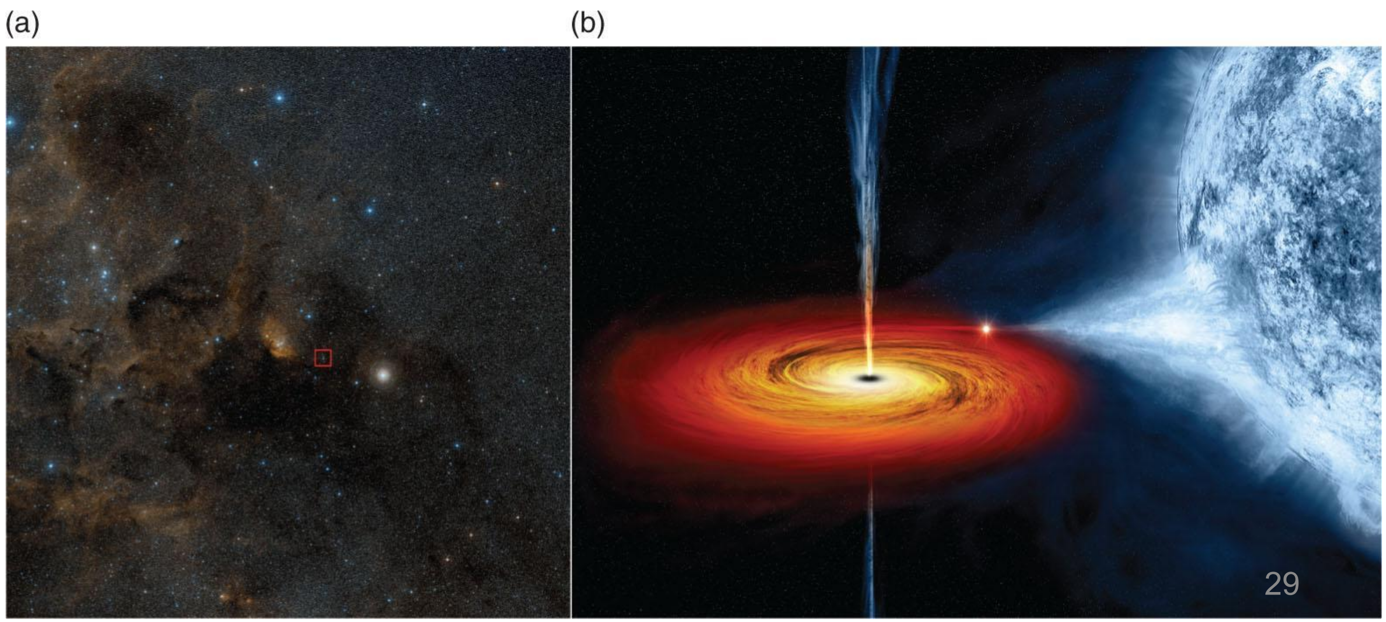


Are Black Holes Observable?

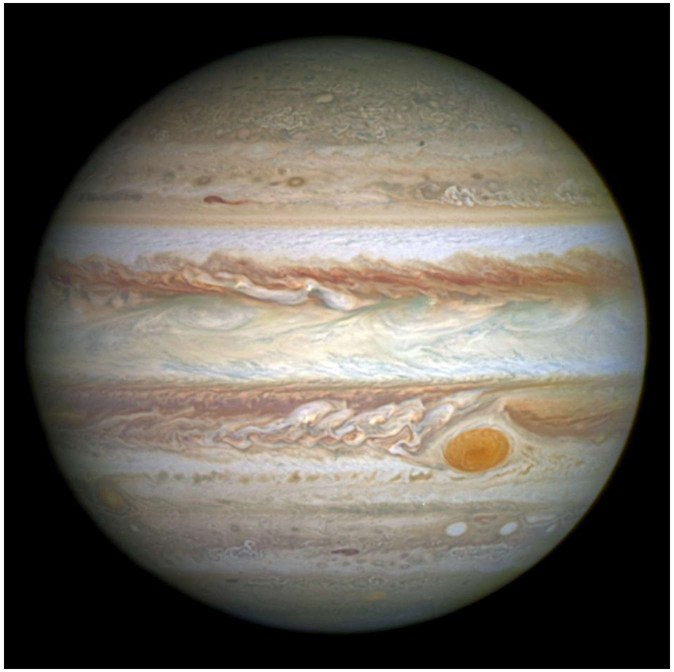
- One of the particles will be inside the event horizon, the other one might not and can escape
- The radiation is referred to as Hawking radiation
- In effect, a black hole without any companion star to supply additional mass will eventually evaporate by losing mass (radiating energy)

Are Black Holes Observable?

- Black holes in binary systems can be detected by X-ray radiation from infalling accelerated material from the companion
- Rapidly varying X-ray pulses of X-ray binary systems can only be produced by a very compact and massive object



Fun Fact



Jupiter
Roman God

Io, Europa, Ganymede, Callisto
Jupiter's Lovers

Juno spacecraft sent to study Jupiter

Jupiter's Wife