Recap:

- **What is “relative” about relativity?**
  - Motion is relative
  - We must define motion relative to some reference frame

- **What is absolute about relativity?**
  - The speed of light is absolute (always the same, regardless of motion)
  - The laws of physics are always the same

Recap:

- **What is surprising about the absoluteness of the speed of light?**
  - Velocities in different reference frames do not add up like we expect them to, because the speed of light must be the same for everyone
  - (Relativity involves weird math)

- **Why can't we reach the speed of light?**
  - No matter how fast we go, light always appears to move away from us, so we are always moving slower than light

Recap:

- Time appears to slow down
- Distances appear shorter (in the direction of motion)
- The amount of “time dilation” and “length contraction” is such that light appears to travel at the same speed, no matter how fast you are moving
- Mass also increase when objects are moving close to the speed of light
- when speaking about energy we also need to consider the mass at rest

General Relativity: Einstein's view of gravity

Chapter S3

"The chief attraction of the theory lies in its logical completeness. If a single one of the conclusions drawn from it proves wrong, it must be given up."

- A. Einstein, 1919

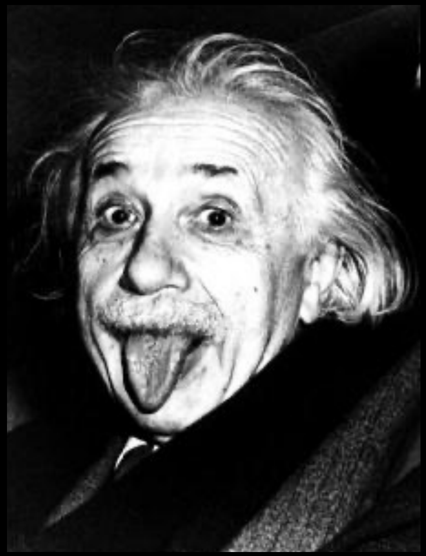
Questions of the day

- What are the major ideas of General Relativity?
- What is Einstein’s view of gravity?
- What is a black hole?

The different views of gravity

- Newton

Taught us how gravity <u>behaves</u>



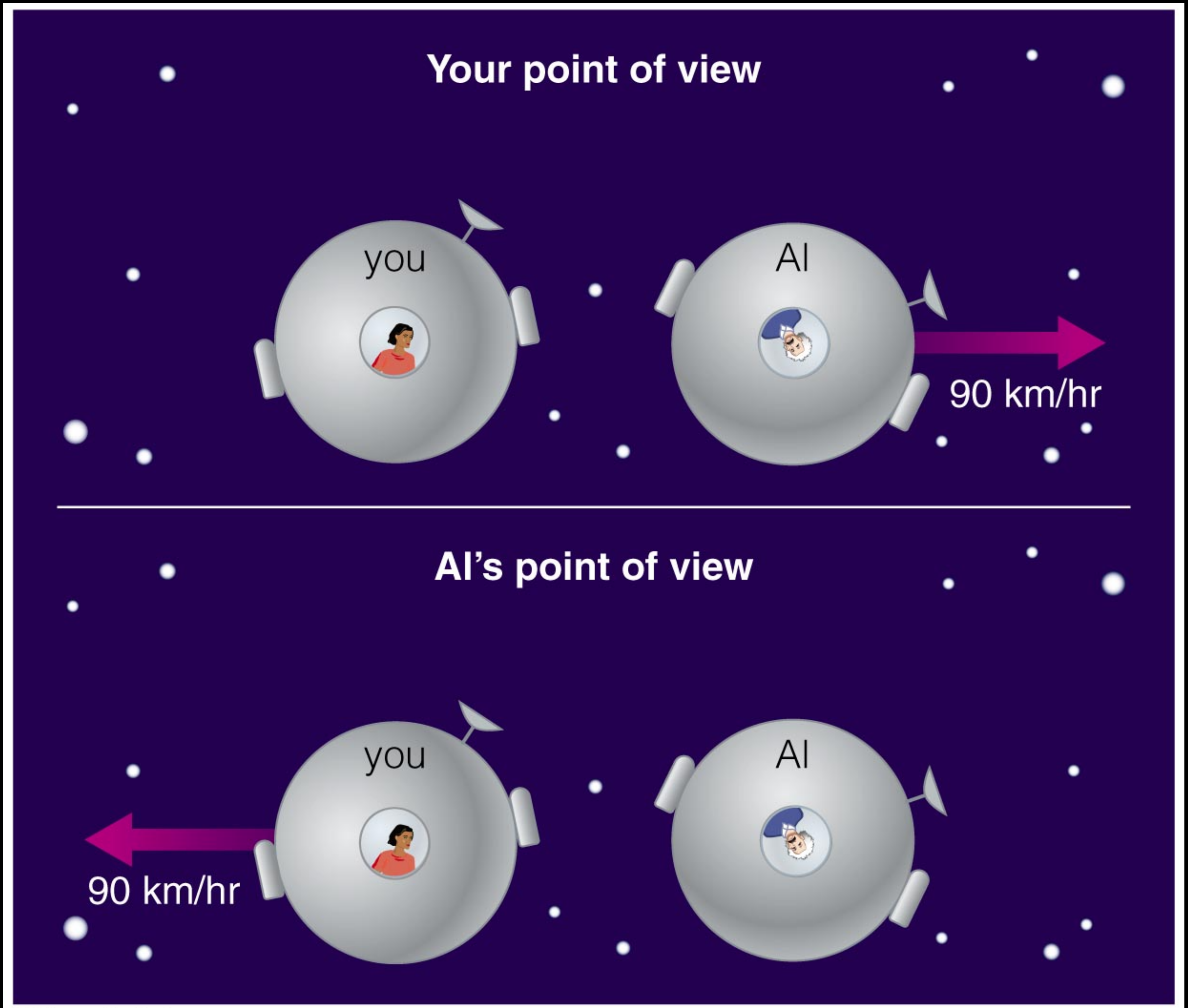
- Einstein

Taught us what gravity <u>is</u>

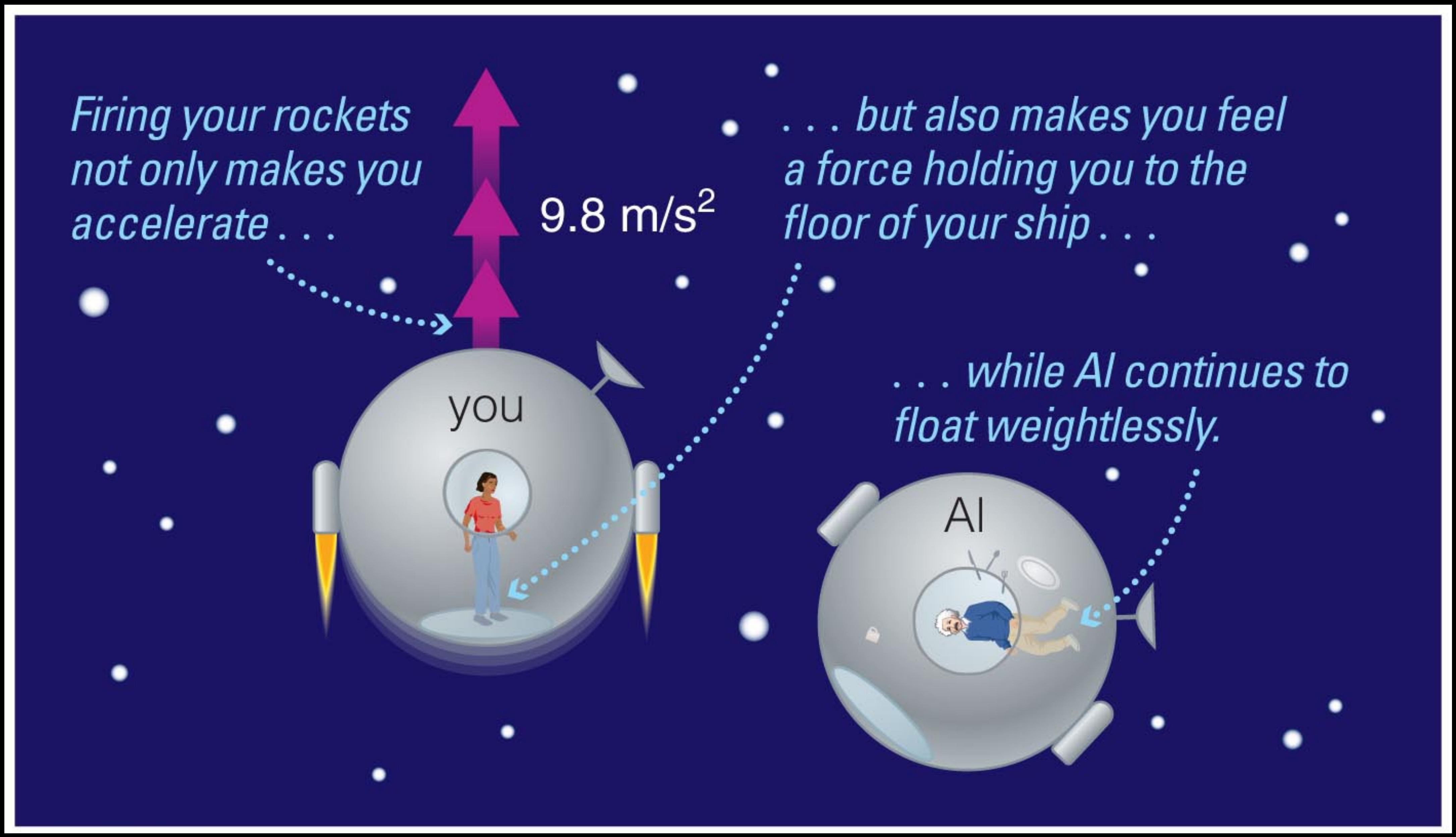
Let's go back to our spaceships and "thought experiments" (lecture 19)

All motion is relative.

(And the speed of light is absolute.)



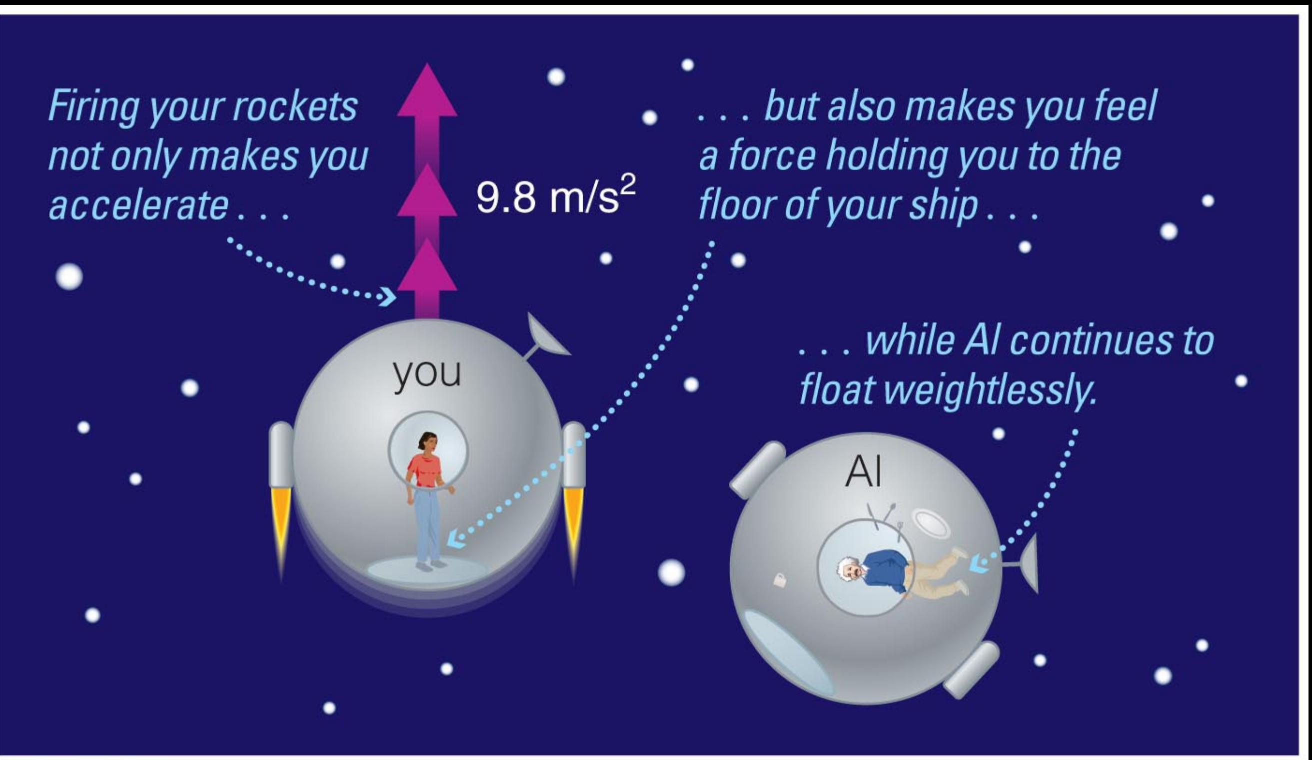
Relative motion: acceleration and "weight"

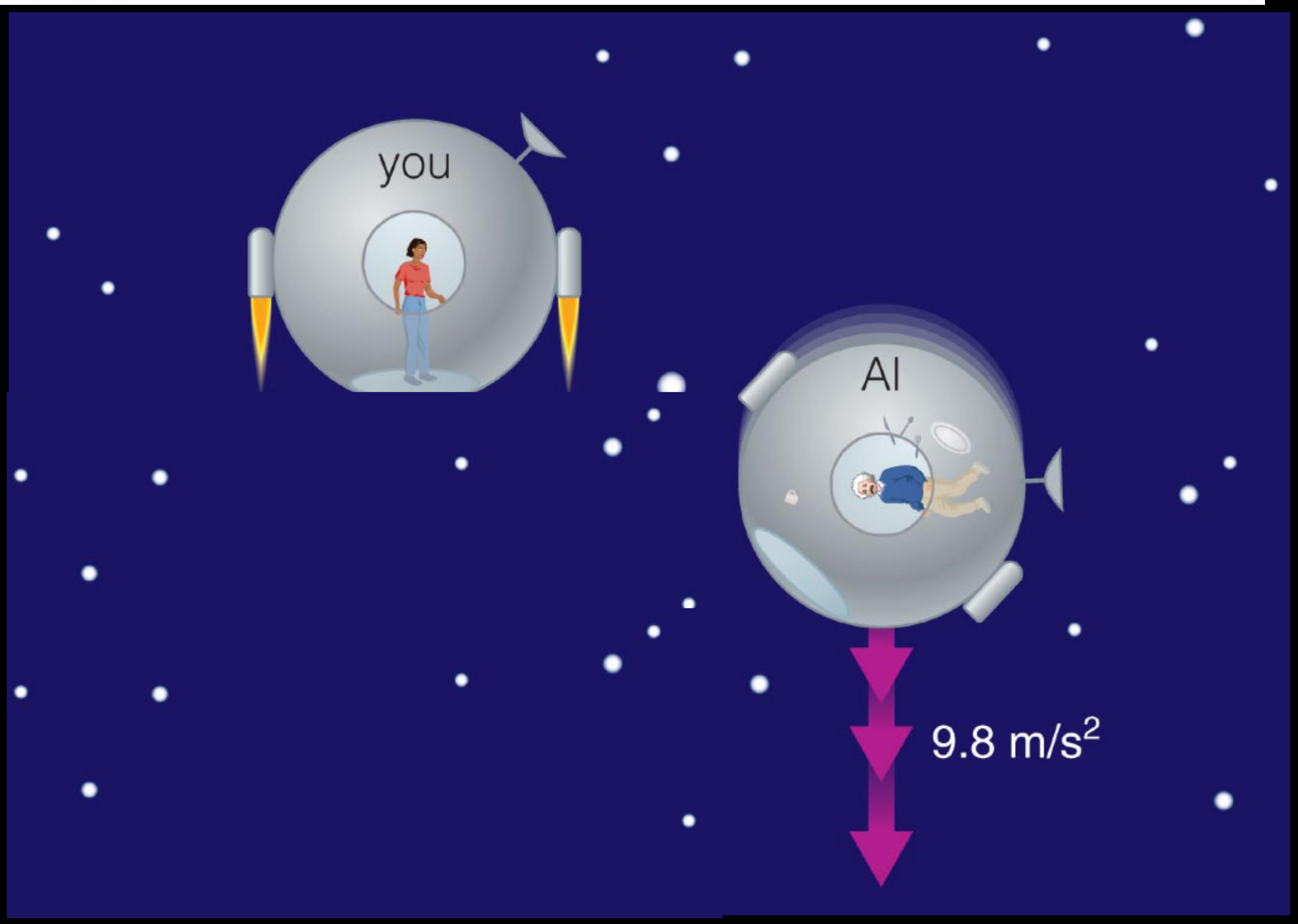


Motion is entirely relative to the observer's "reference frame".

But what about acceleration and "weight" or force?

Relative motion: acceleration and "weight"

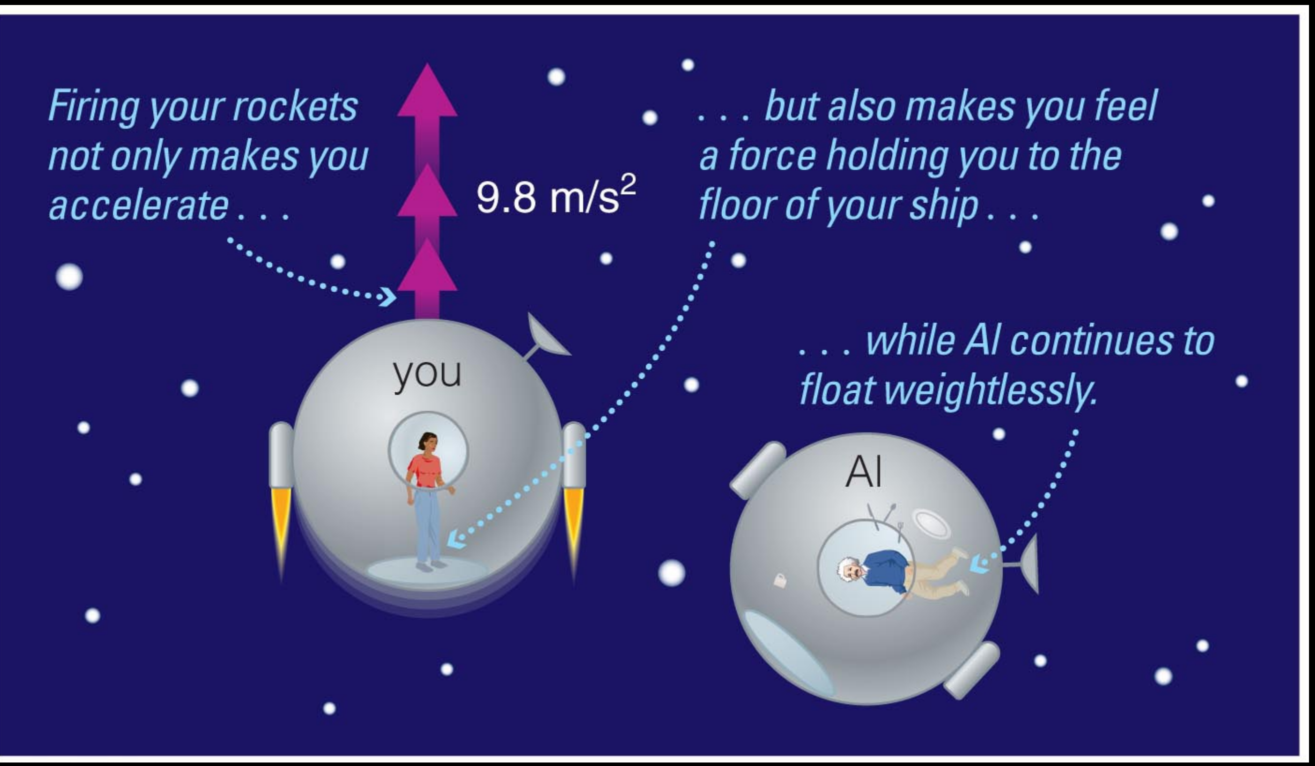


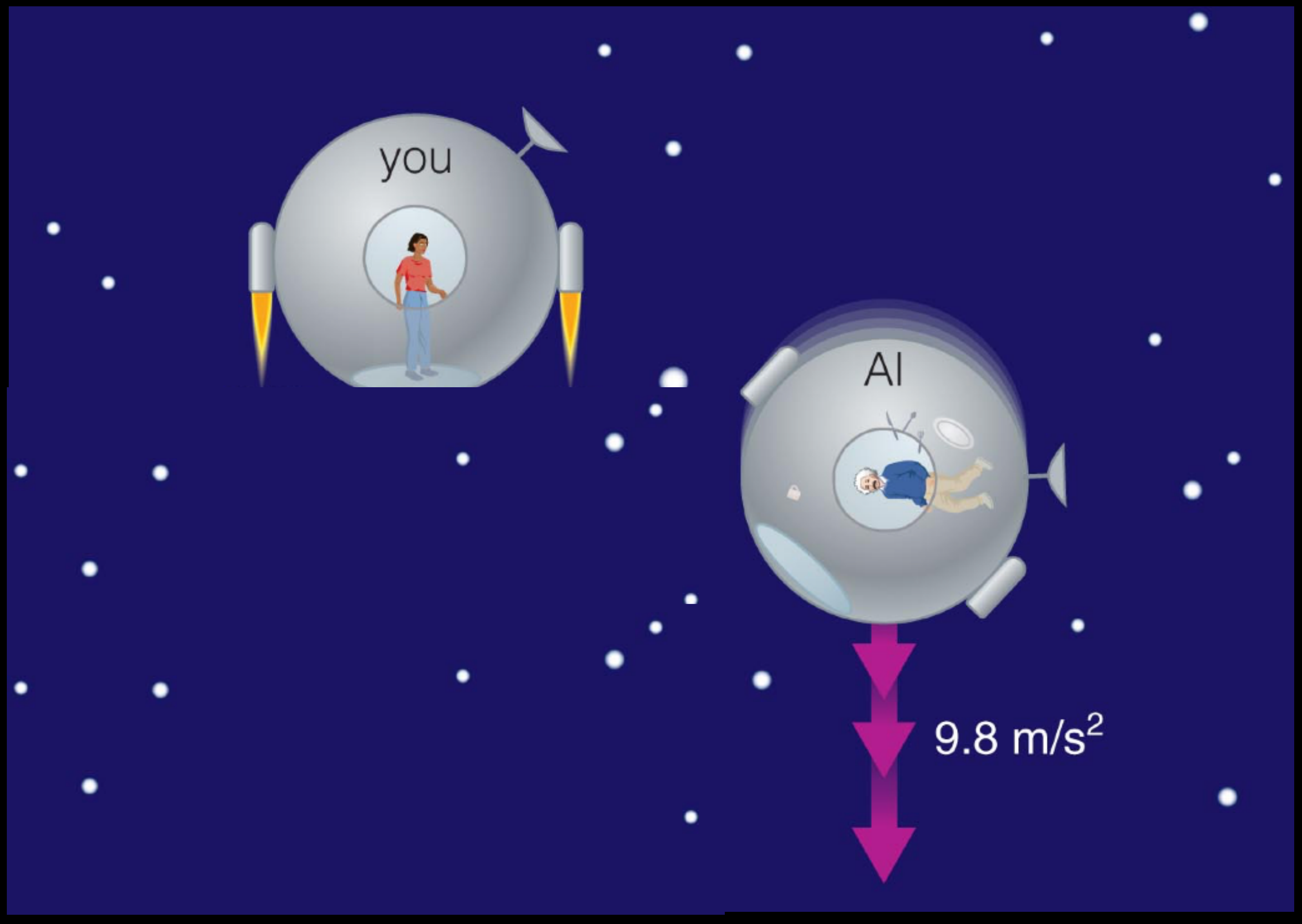


- Al sees that you are accelerating, and feel a net force (weight)

- You see Al moving away, but how you explain that you are not weightless?
- Are both reference frame still valid?

Relative motion: acceleration and "weight"

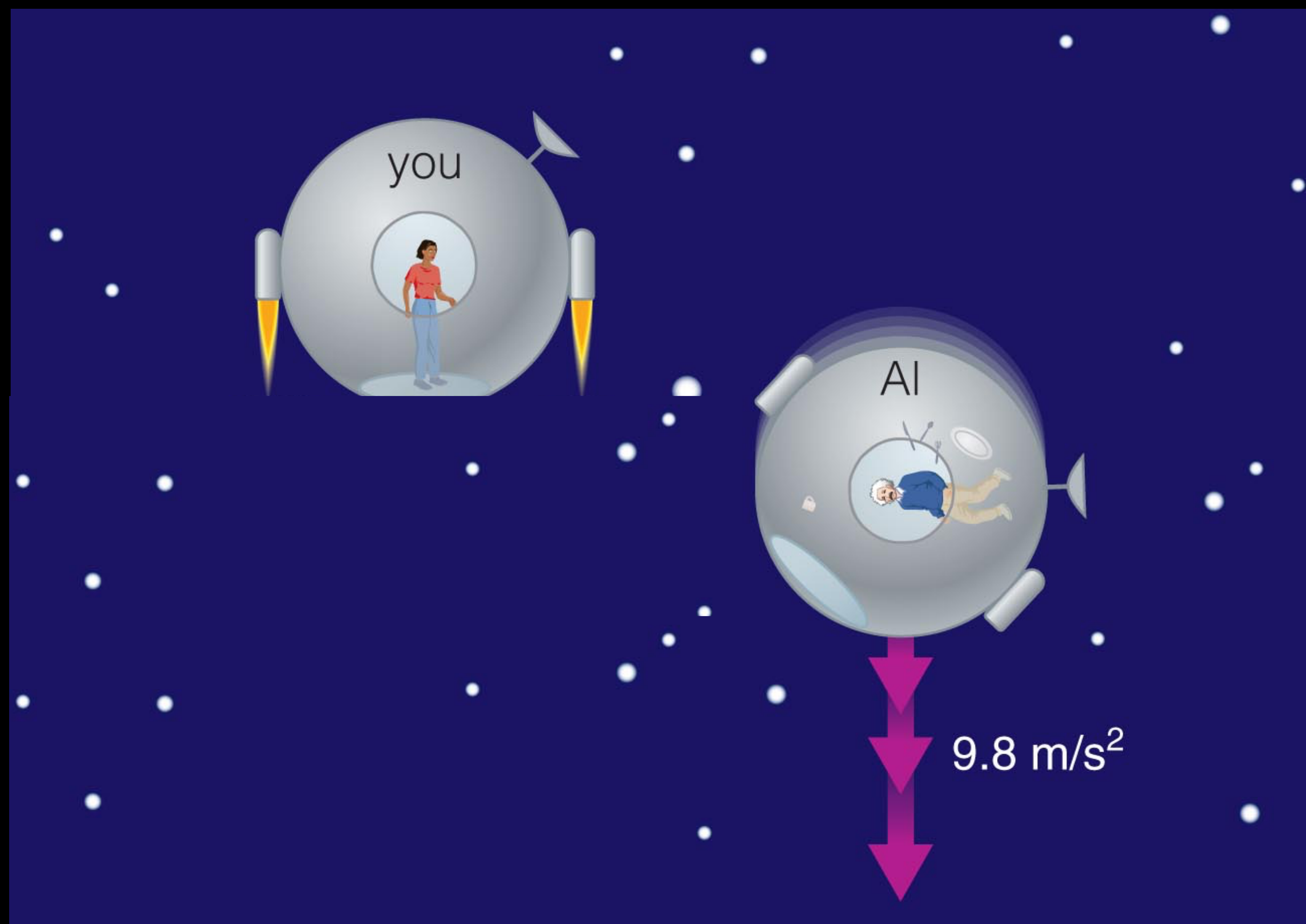




- Al sees that you are accelerating, and feel a net force (weight)

- You see Al moving away, but how you explain that you are not weightless?
- Are both reference frame still valid?
- Who is right?
- isn't motion alway relative to the reference fame?

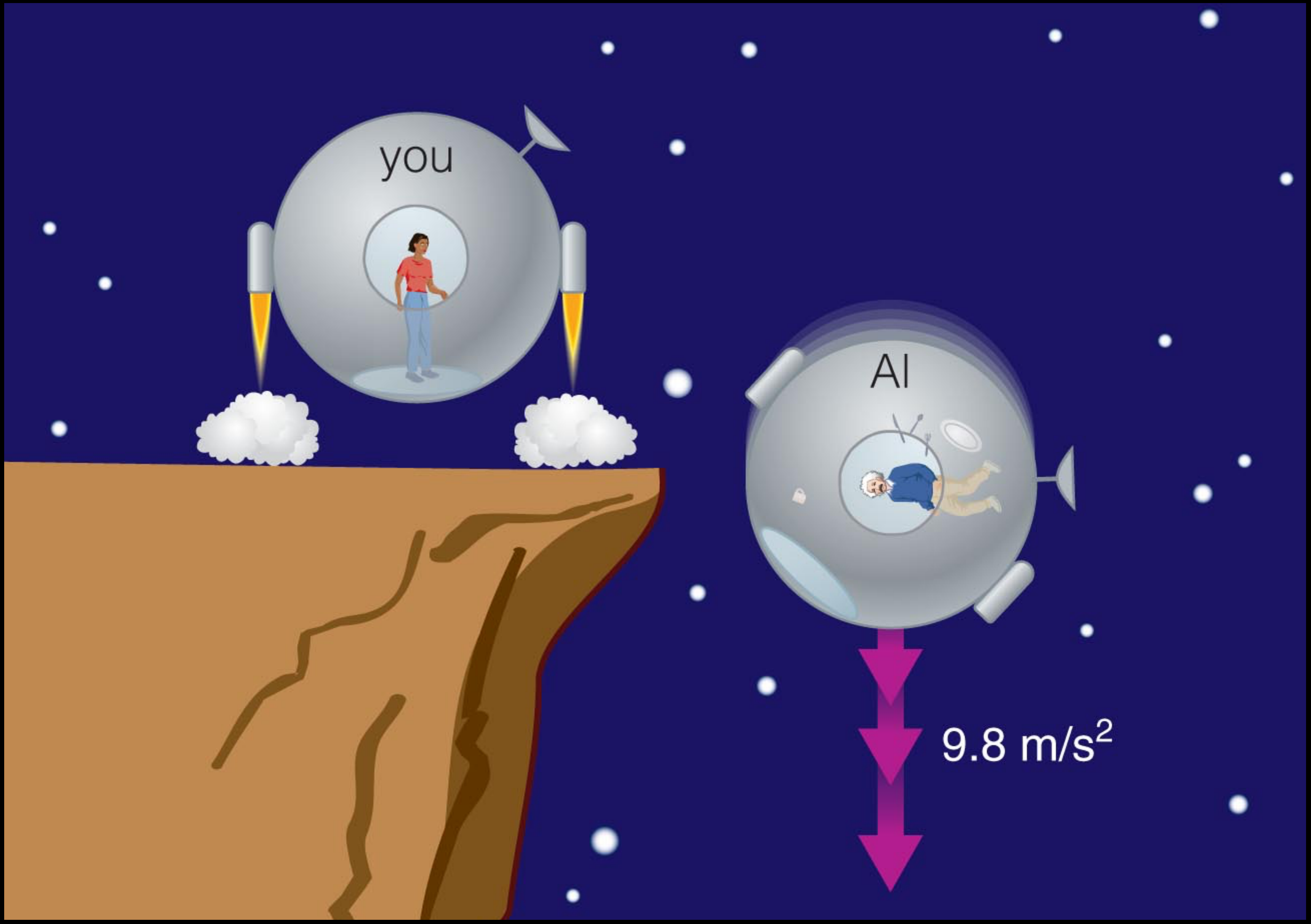
Relative motion: acceleration and “weight”



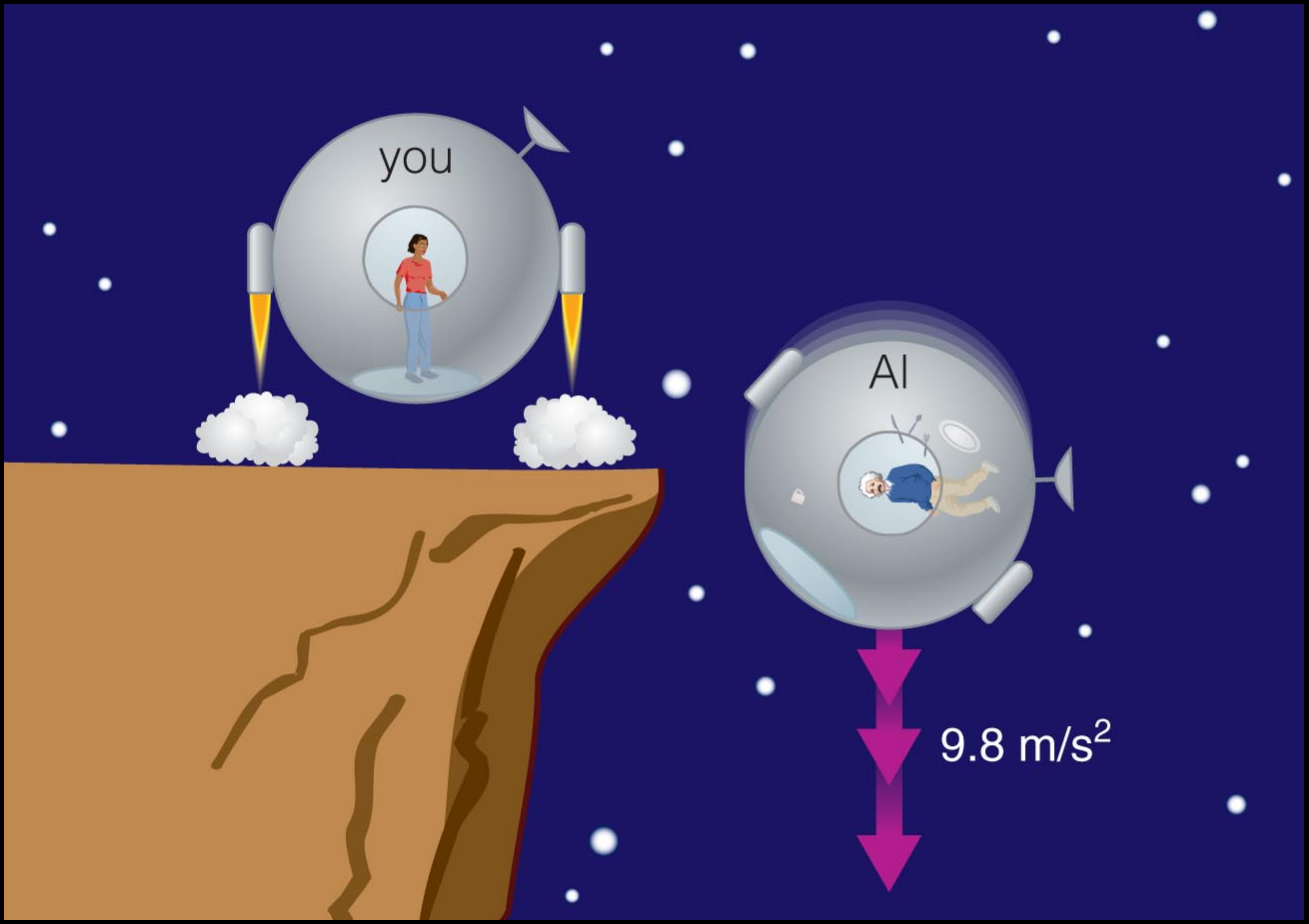
Does your picture still make any sense???

Relative motion: acceleration and "weight"

This picture still make sense if you and Al are in a gravity field

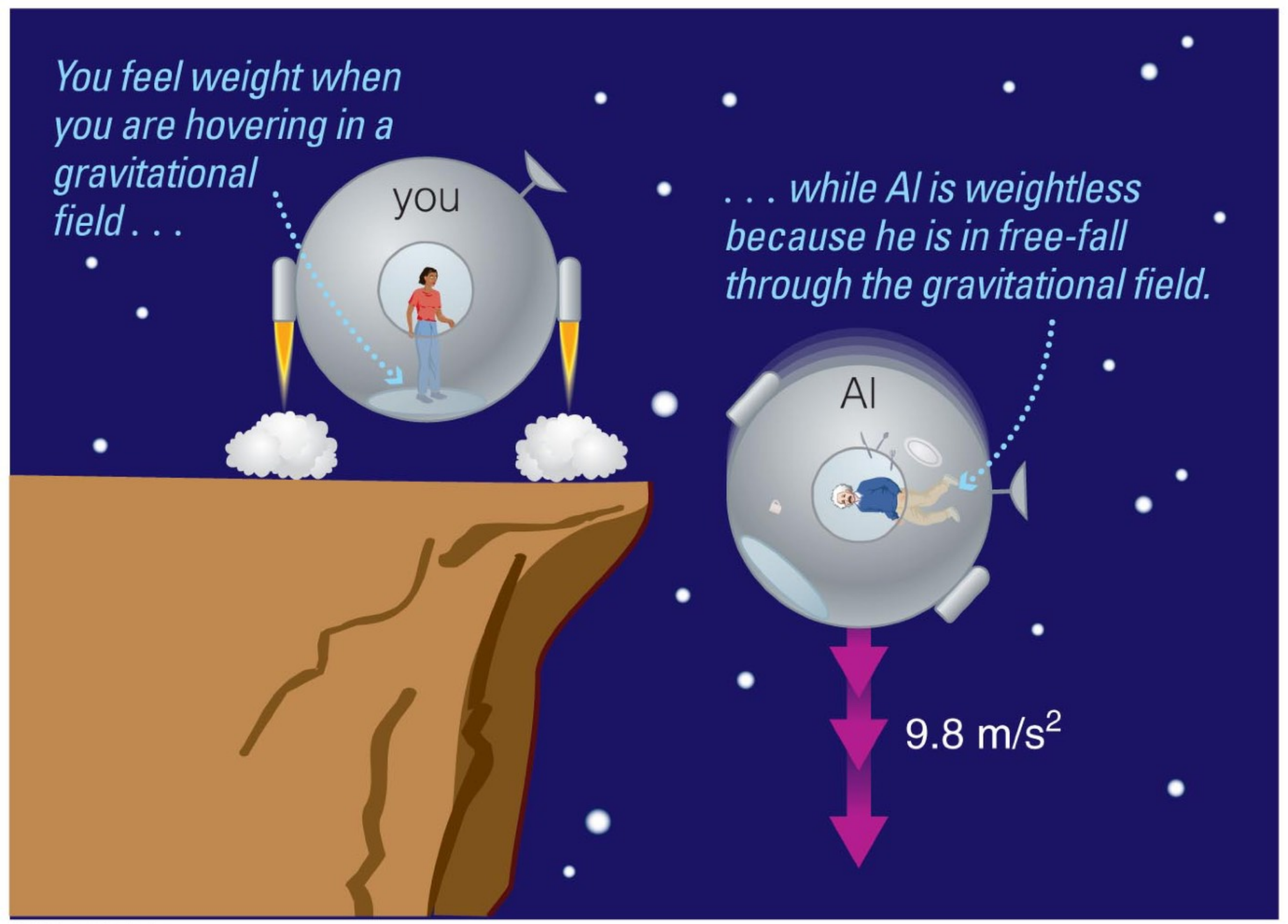


The fundamental assumption of general relativity:
acceleration = gravity



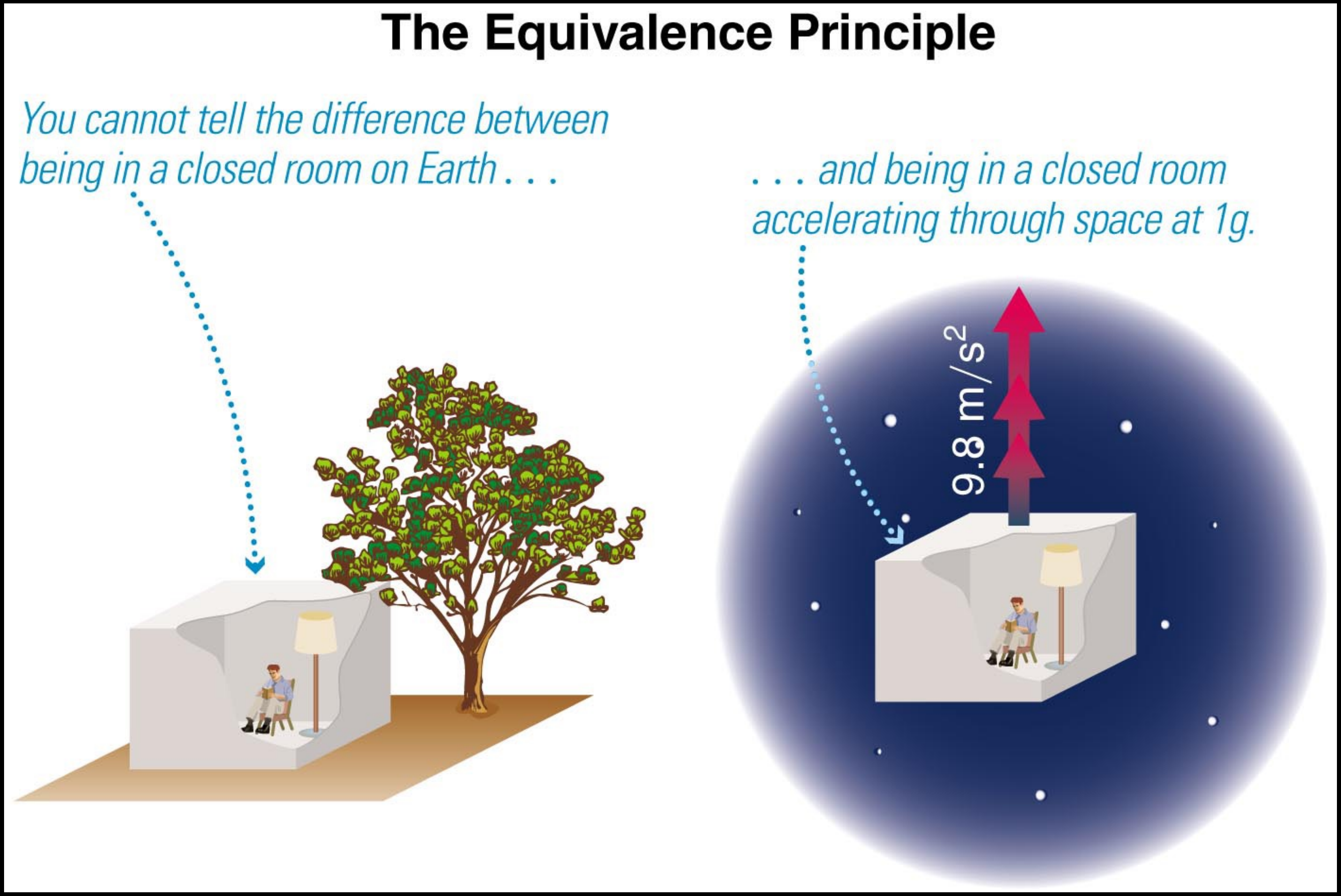
Einstein preserved the idea that all motion is relative, by pointing out that the effects of acceleration are **exactly equivalent** to those of gravity

Gravity and Relative Motion (Acceleration)



- Someone who feels a force may be hovering in a gravitational field
- Someone who feels weightless may be in free-fall

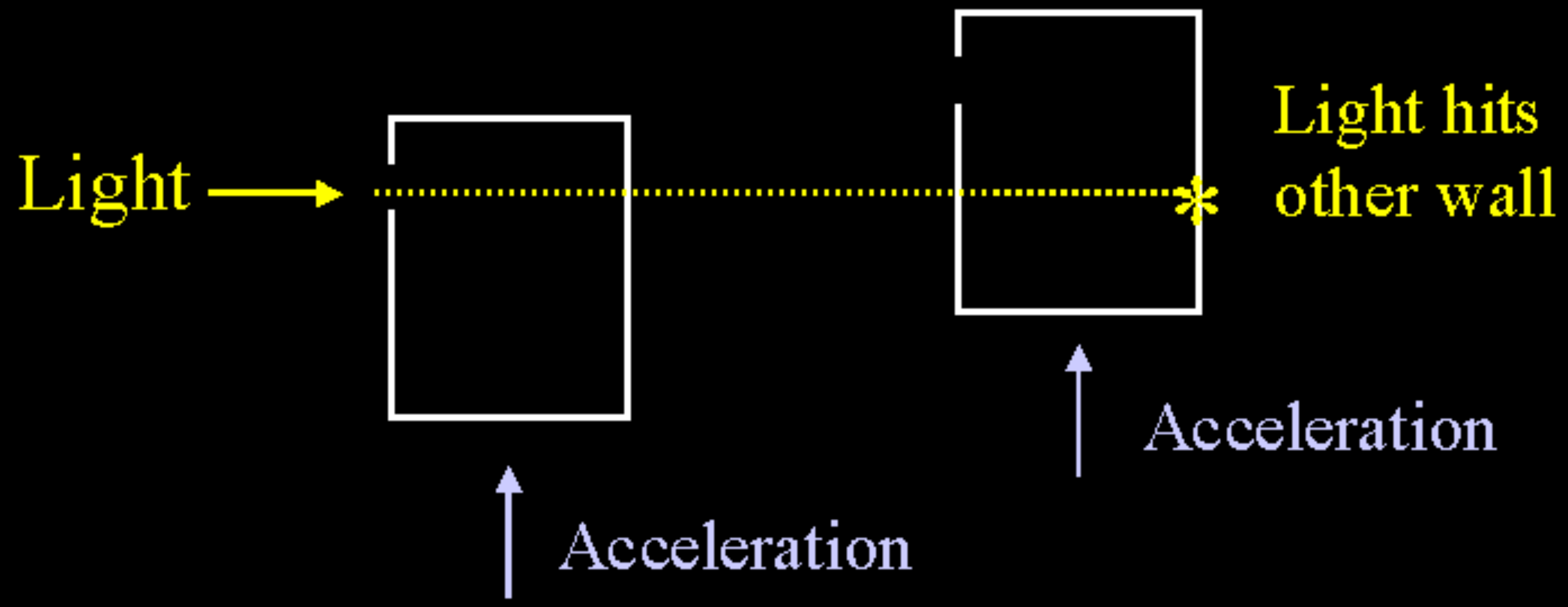
The “Equivalence Principle”



Key idea: the effects of acceleration are **exactly equivalent** to those of gravity.

Acceleration

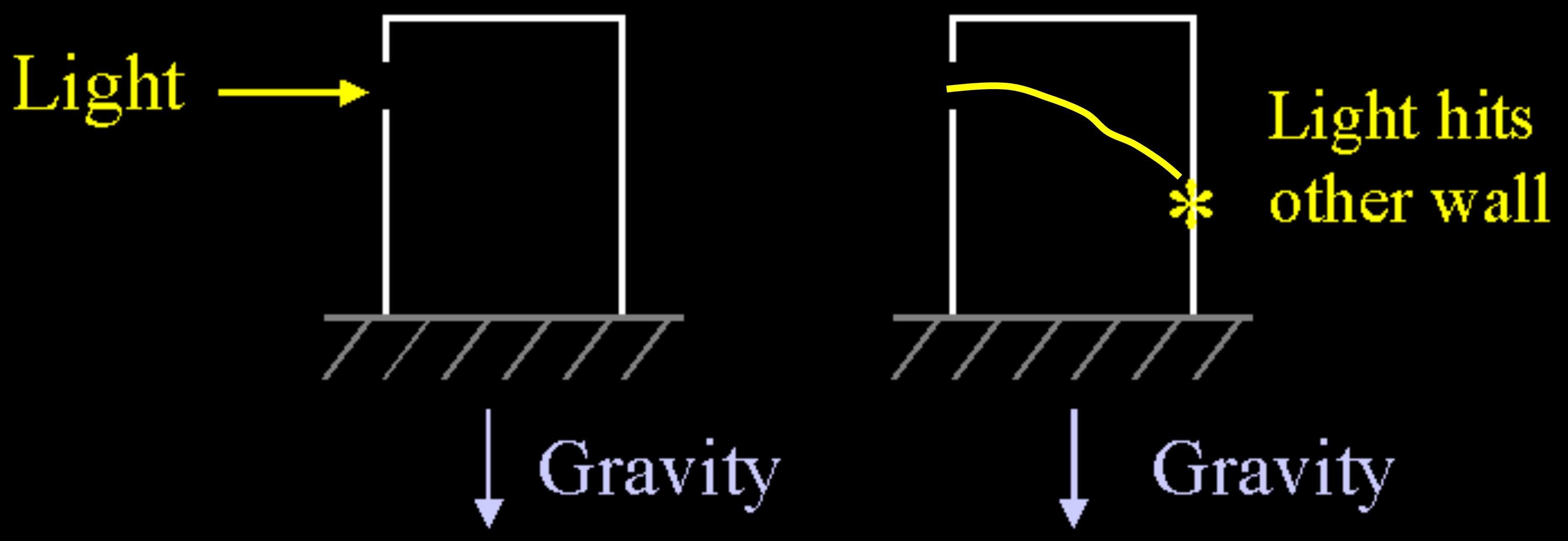
- Consider a light ray moving through an accelerating spaceship



For an observer in the spaceship, the light will appear to "curve" downward

Acceleration = gravity

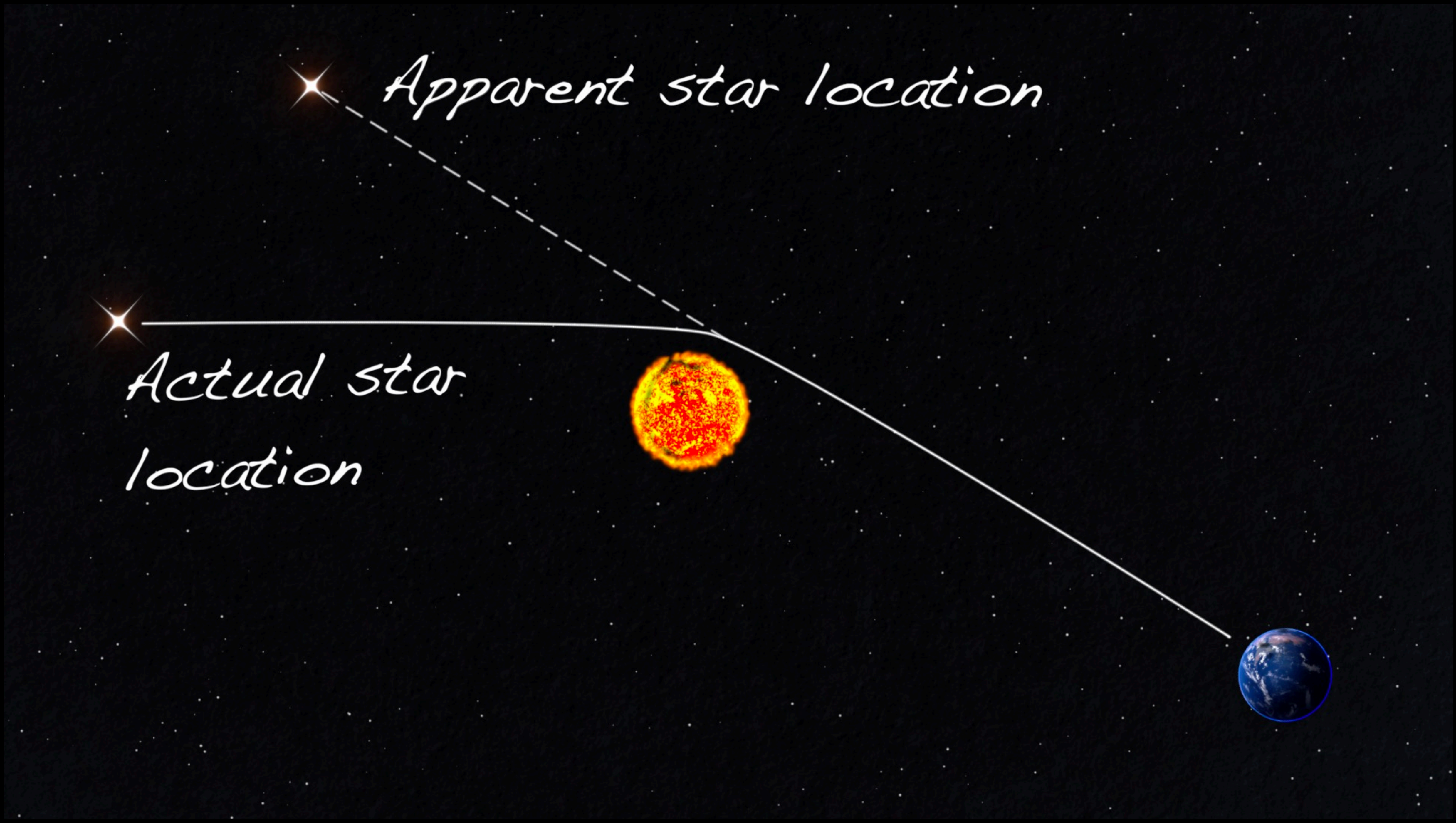
- Now consider the same situation seen in a gravitational field



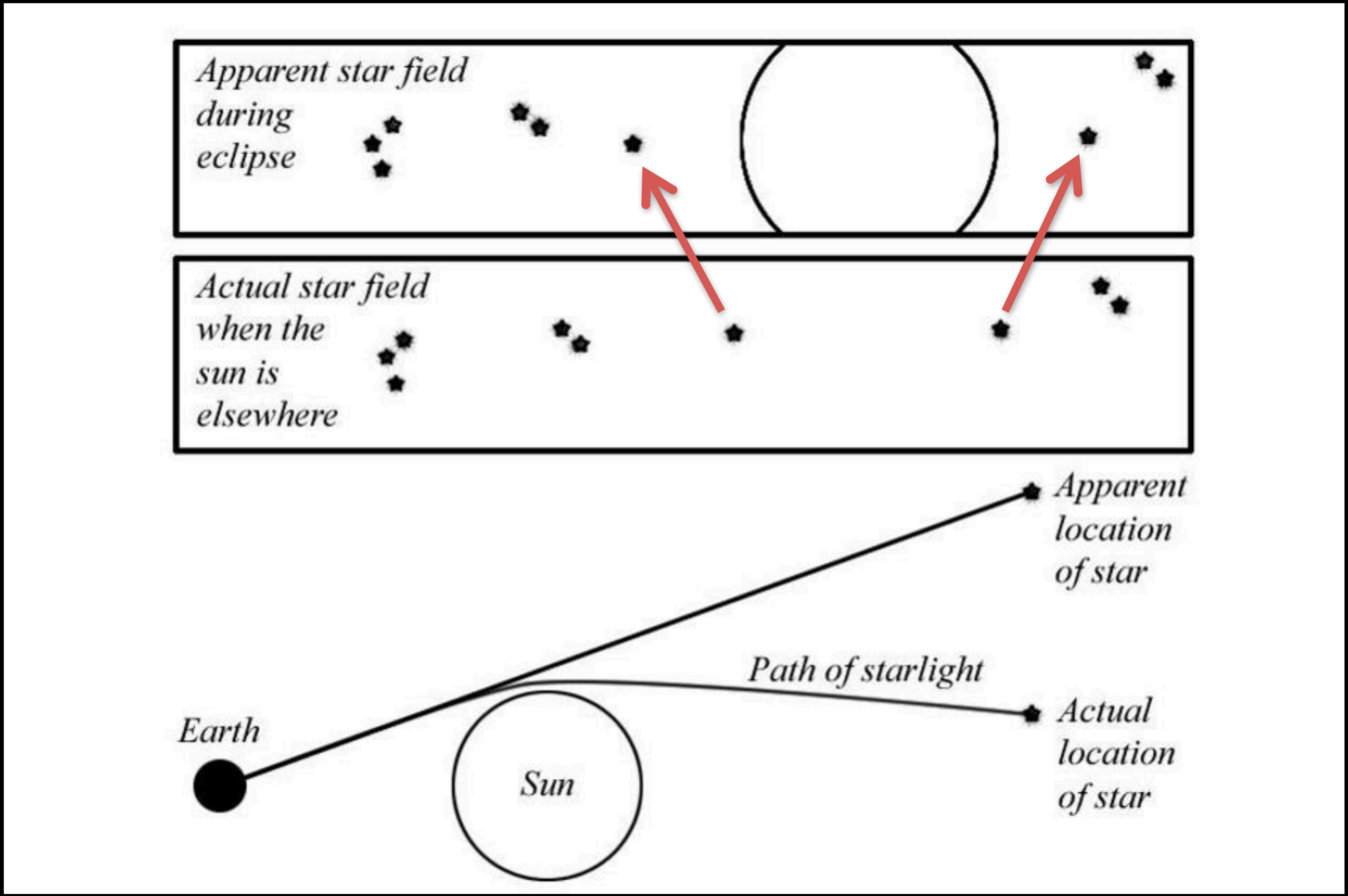
Light paths should appear to be deflected by mass!
(Or rather, by "gravity")

Light paths should appear to be deflected by mass!

"Gravitational Lensing"

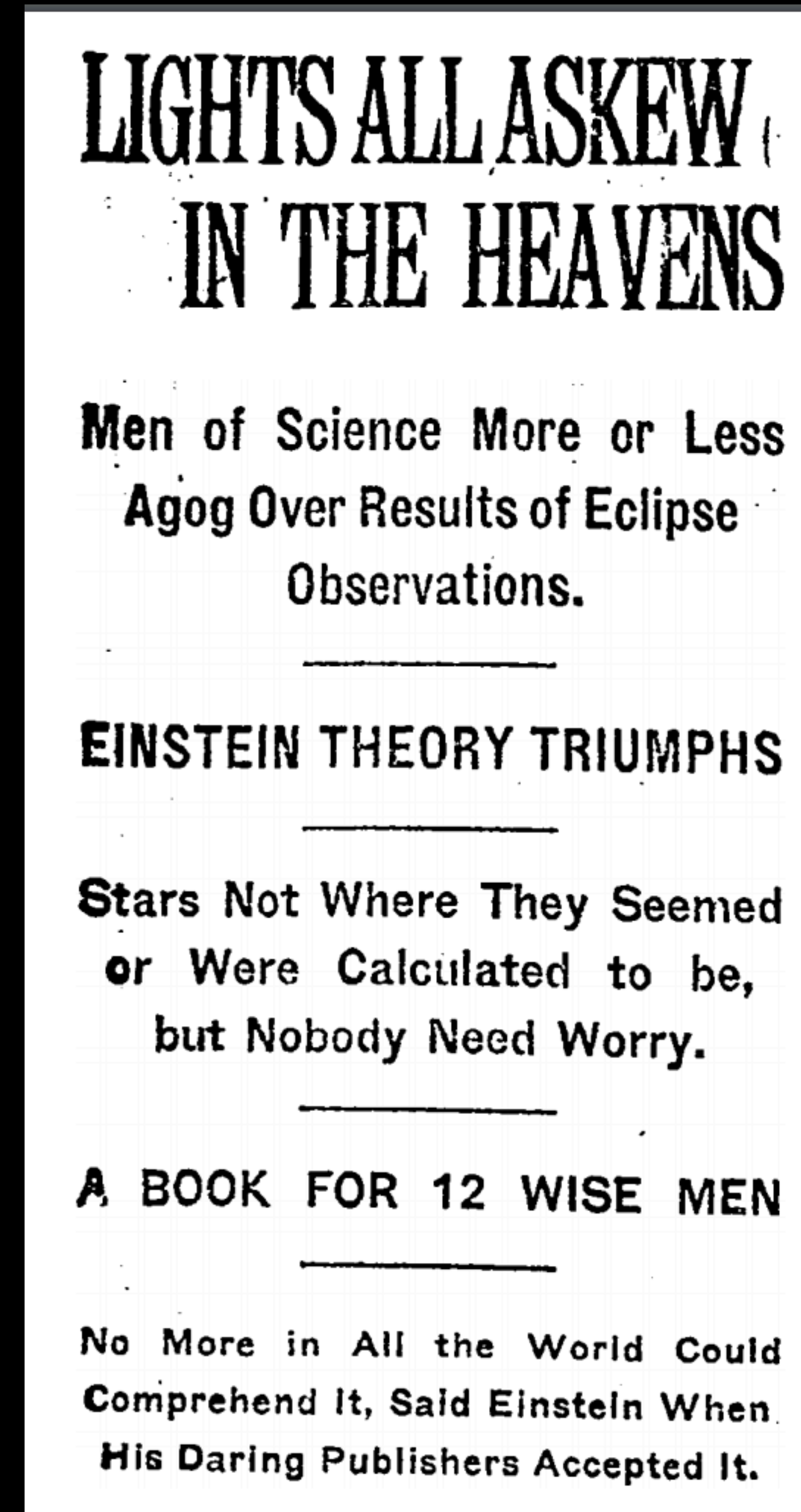


Critical test: deflection of light near massive objects ("Gravitational Lensing")



Starlight passing near the Sun should be deflected

Critical test: deflection of light near massive objects ("Gravitational Lensing")



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

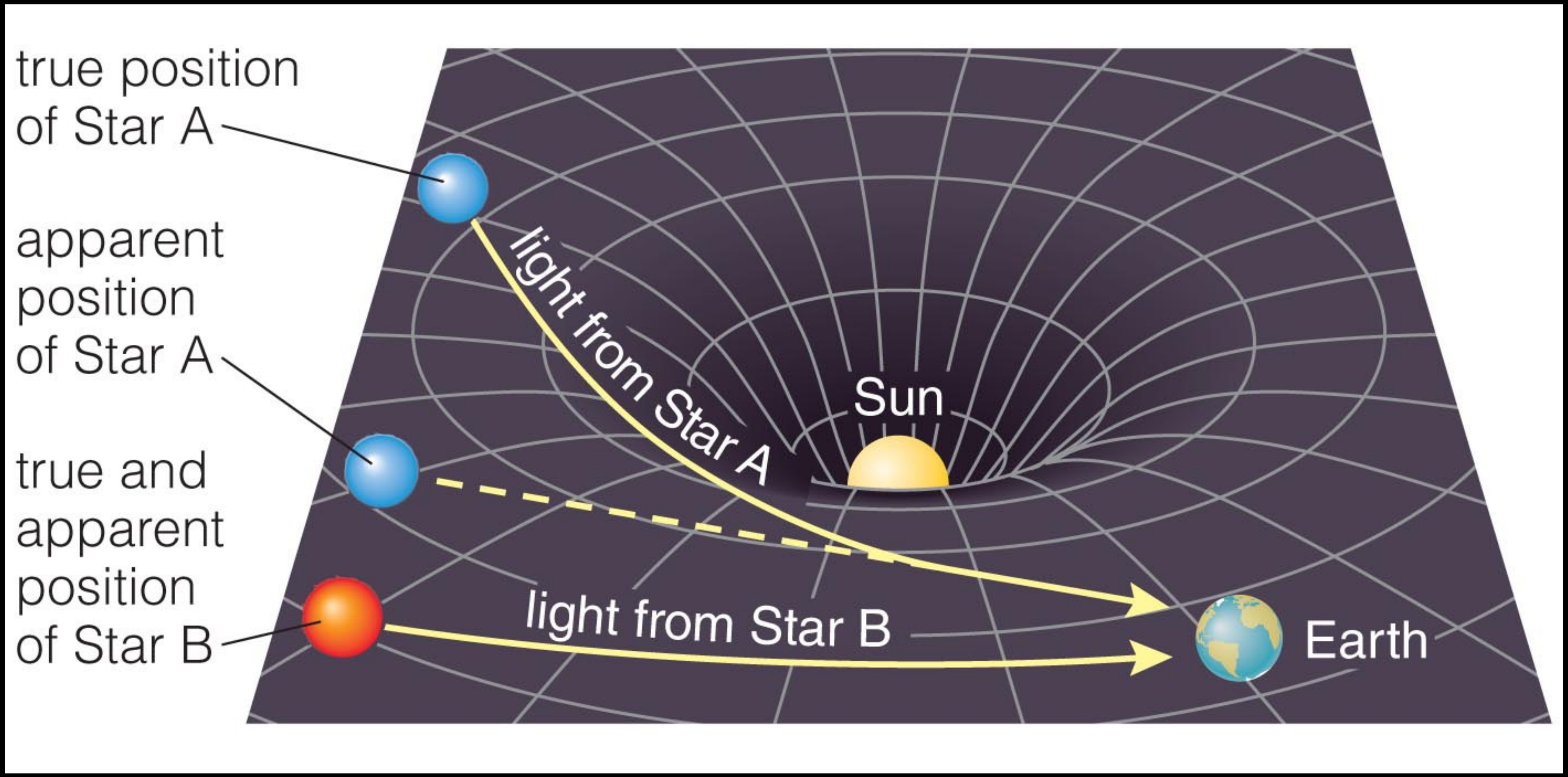
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

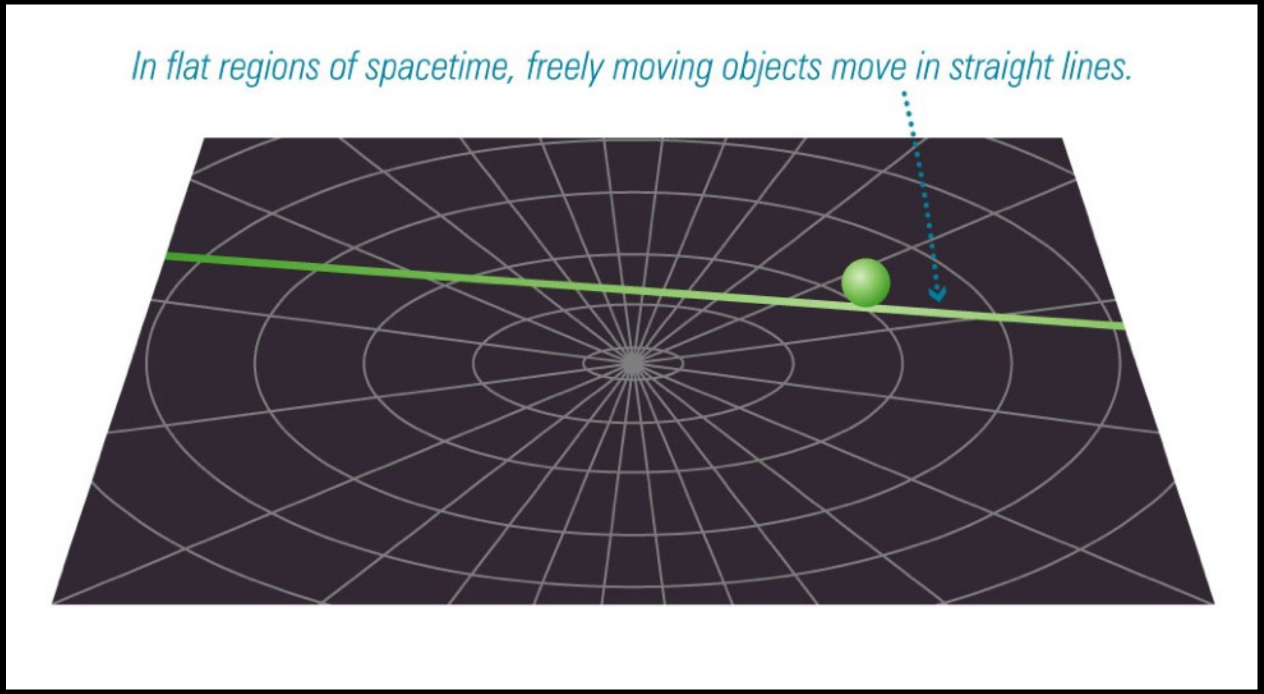
1919 solar eclipse (& New York Times headline)

Einstein's view:
Light appears to "bend" because **space is "curved"**

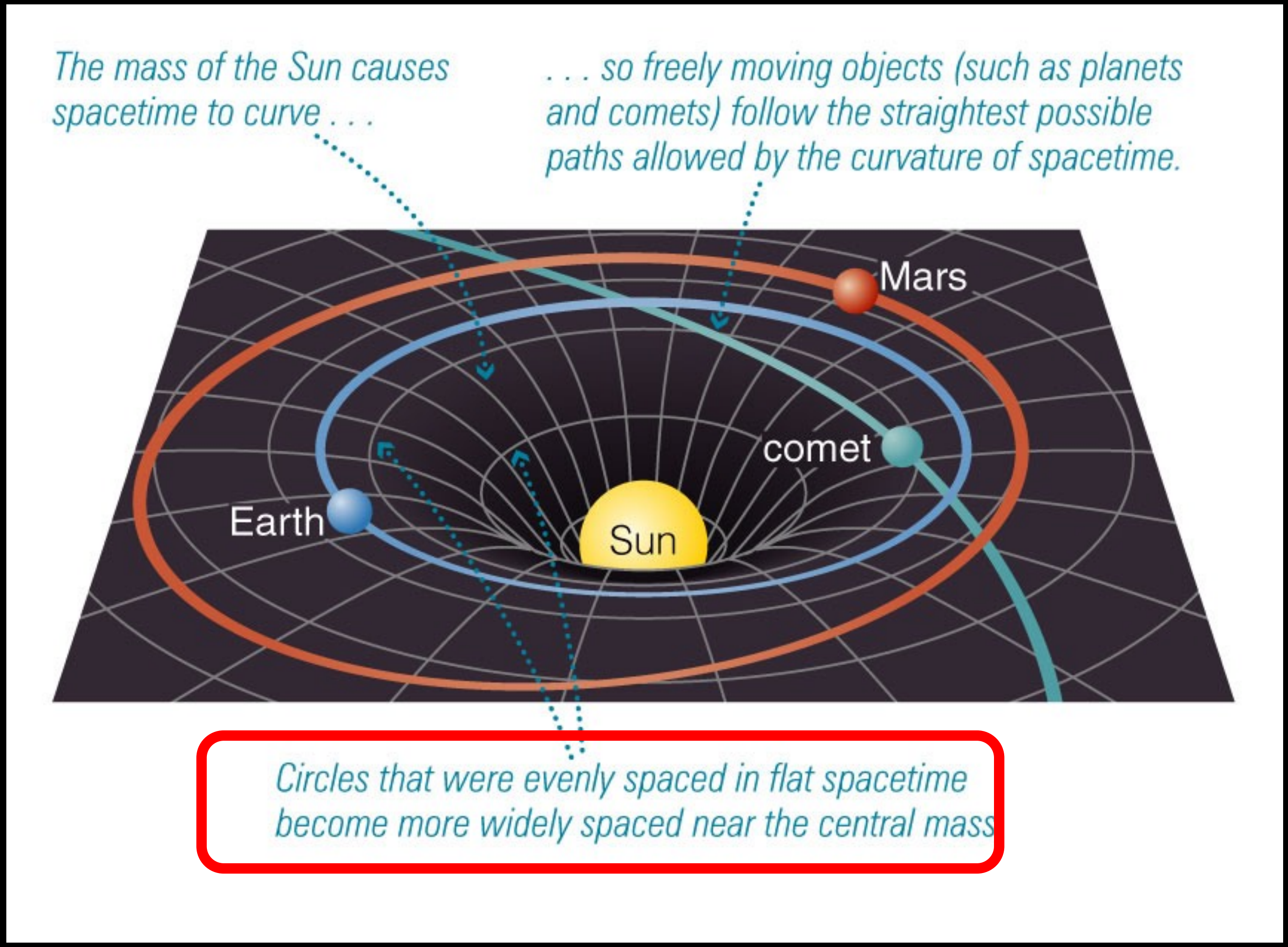


- Spacetime = space+time = 4-dimensional concept
  - 3 dimensions of space
  - 1 dimension of time
  - Recall from special relativity, that motion changes our view of space & time
  - **We can combine these into a "spacetime" which all observers agree on**
- Mass of any kind makes **spacetime** curve

The "curvature" of spacetime leads to curved orbits



Note: the slope of the surface gives the acceleration of gravity



This is Einstein's view of gravity!

- Mass tells spacetime how to curve, and curvature of spacetime tells objects how to move

This works even better for more massive objects (galaxies, and clusters of galaxies)

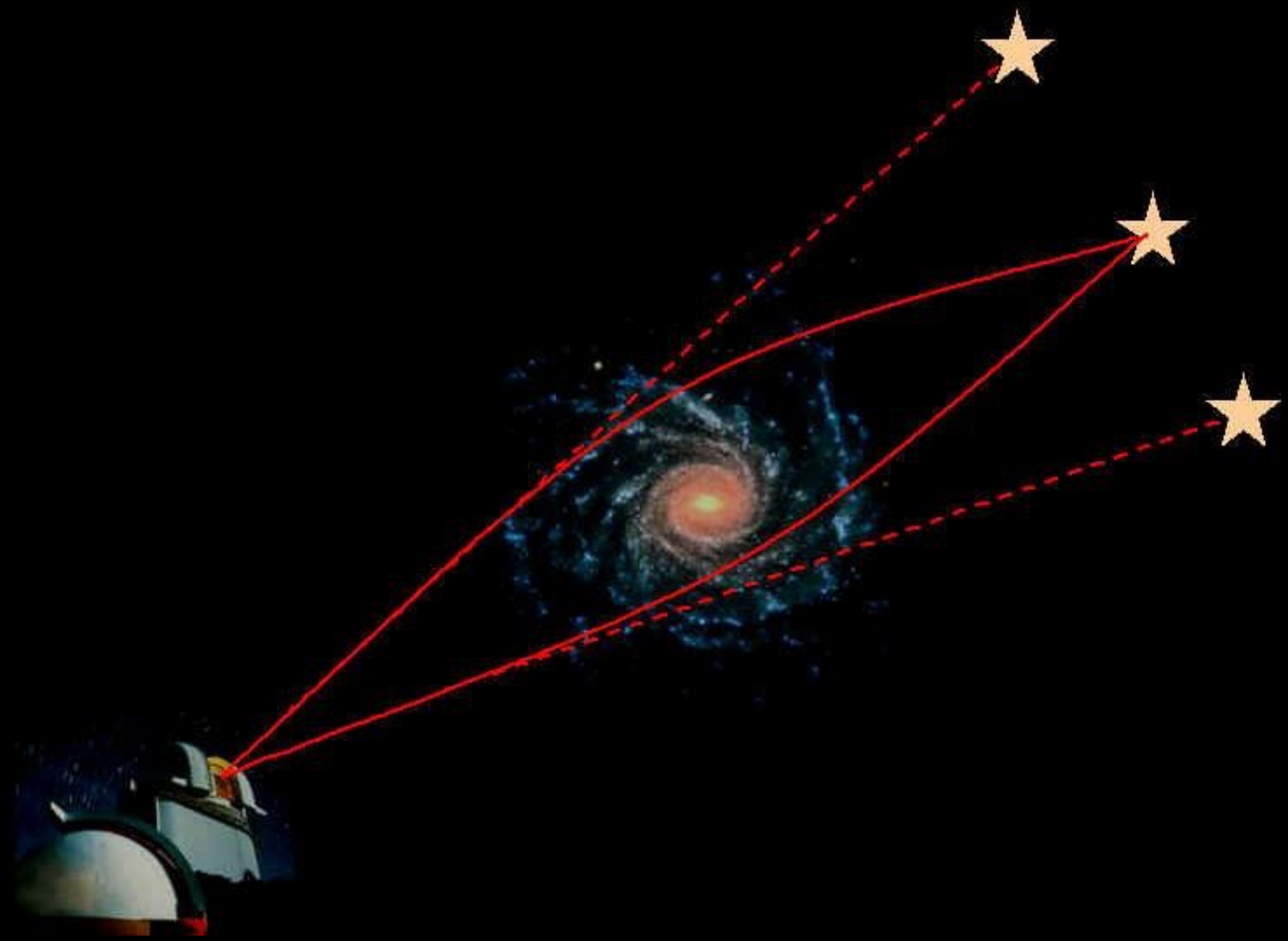
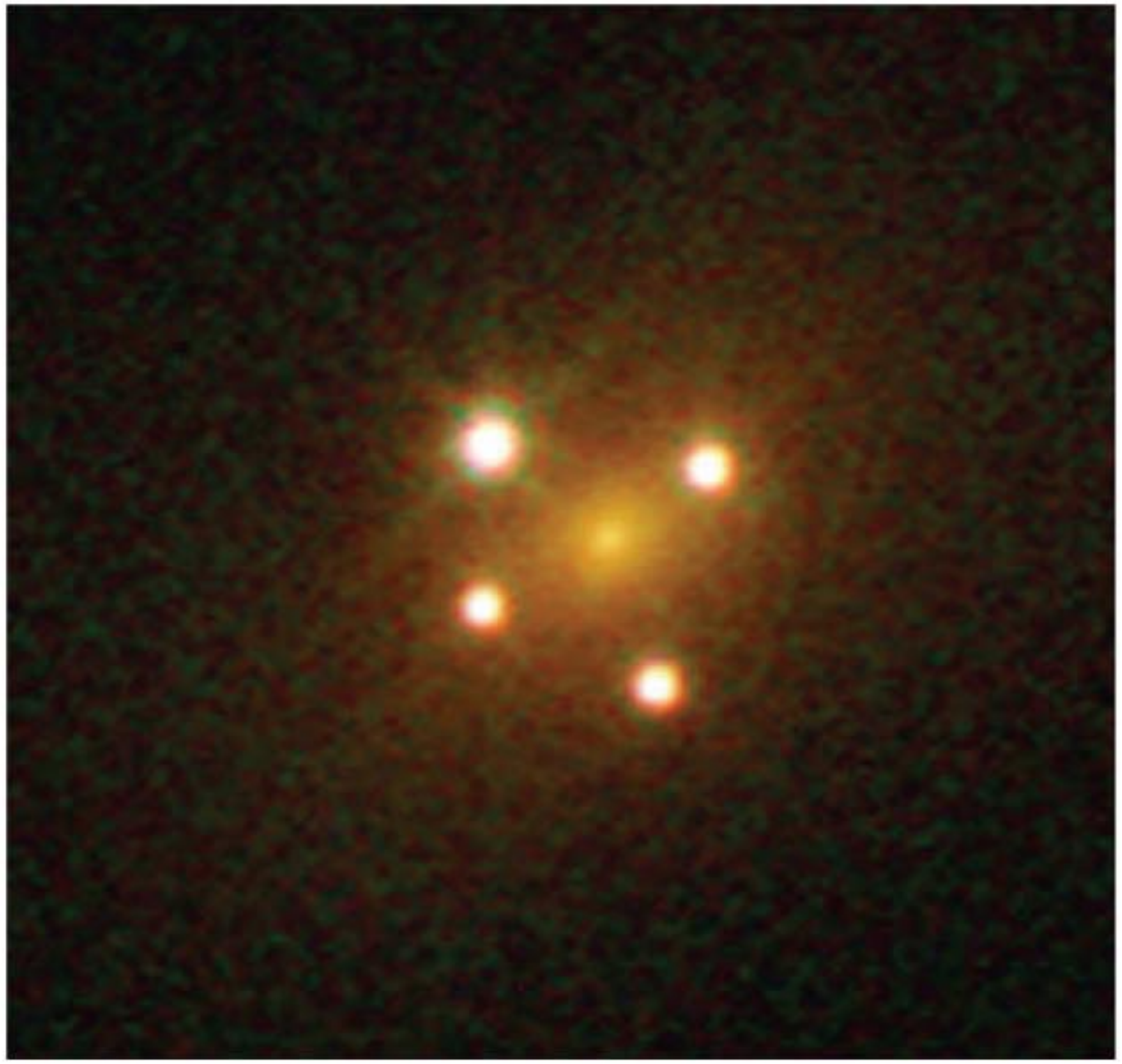


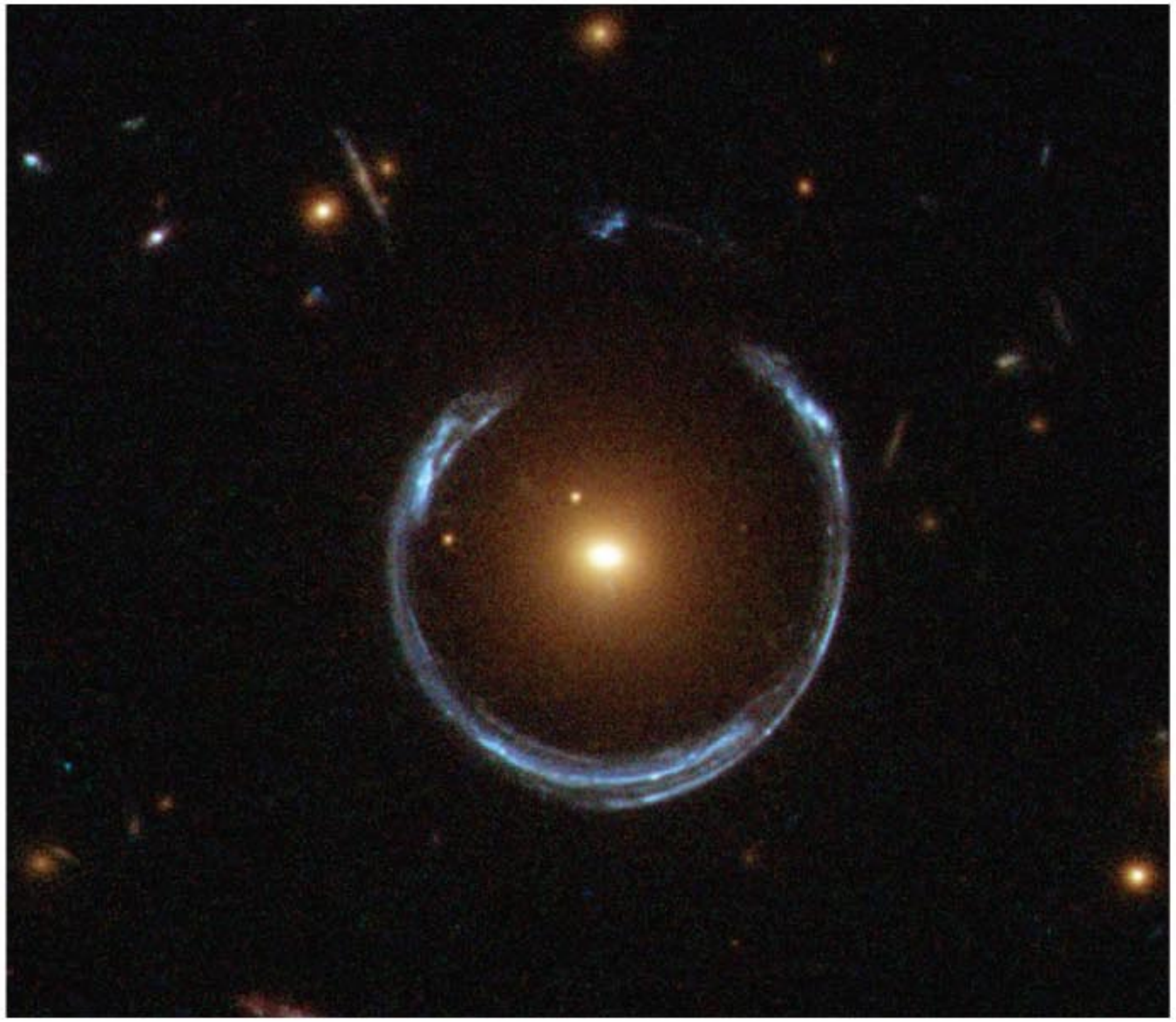
Image courtesy of Liege University

We'll learn more about gravitational lensing later, when we talk about galaxies. For now, though, here are some nice images of real lenses!

Gravitational Lensing by Galaxies



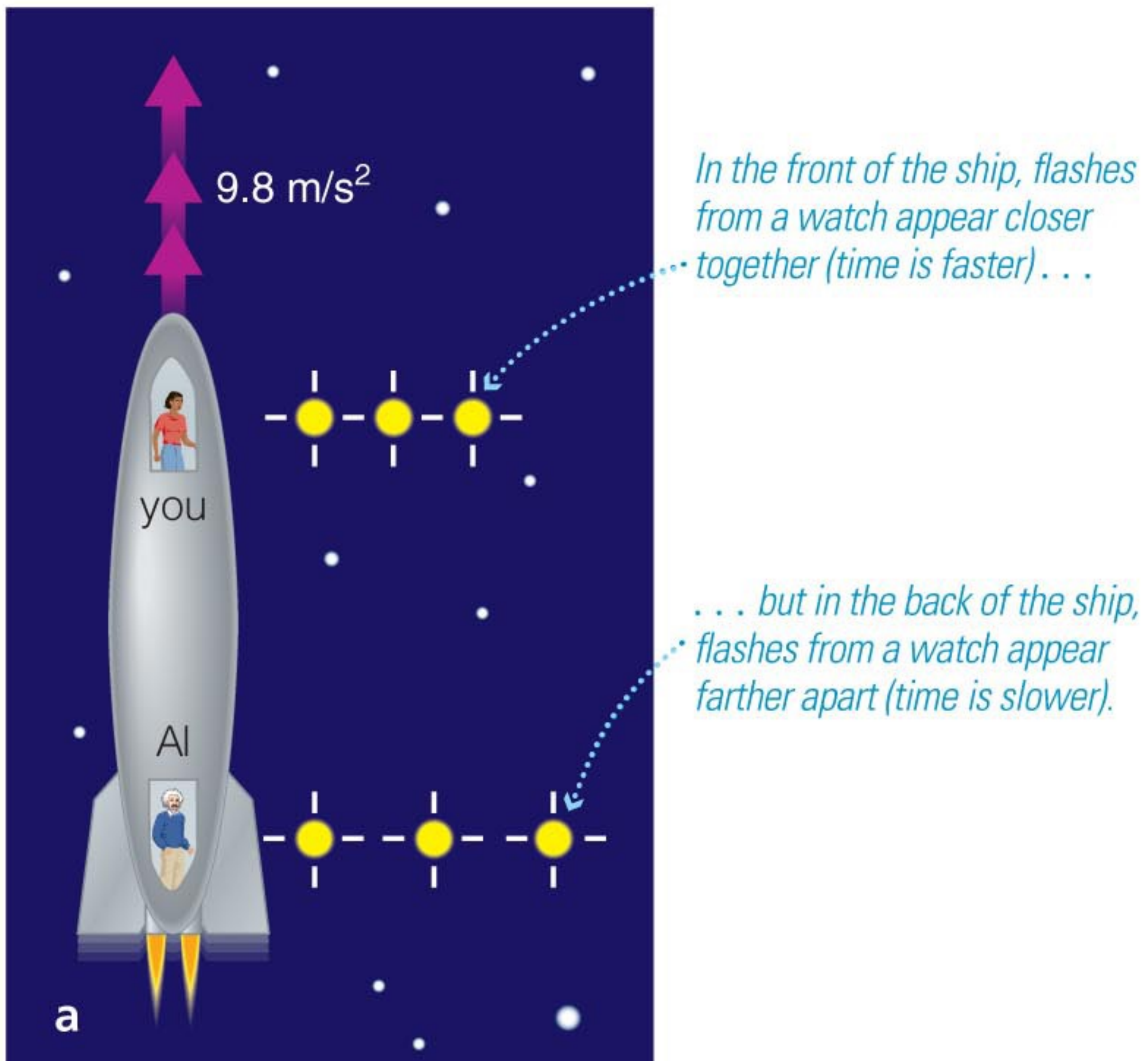
a This Hubble Space Telescope image shows an *Einstein cross*, in which light from a single distant quasar has been bent so that it reaches us along four different paths, creating four distinct images of the single object.



b The blue ring in this Hubble Space Telescope image, called an *Einstein ring*, is an example of the gravitational lensing that occurs when one galaxy lies almost directly behind another.

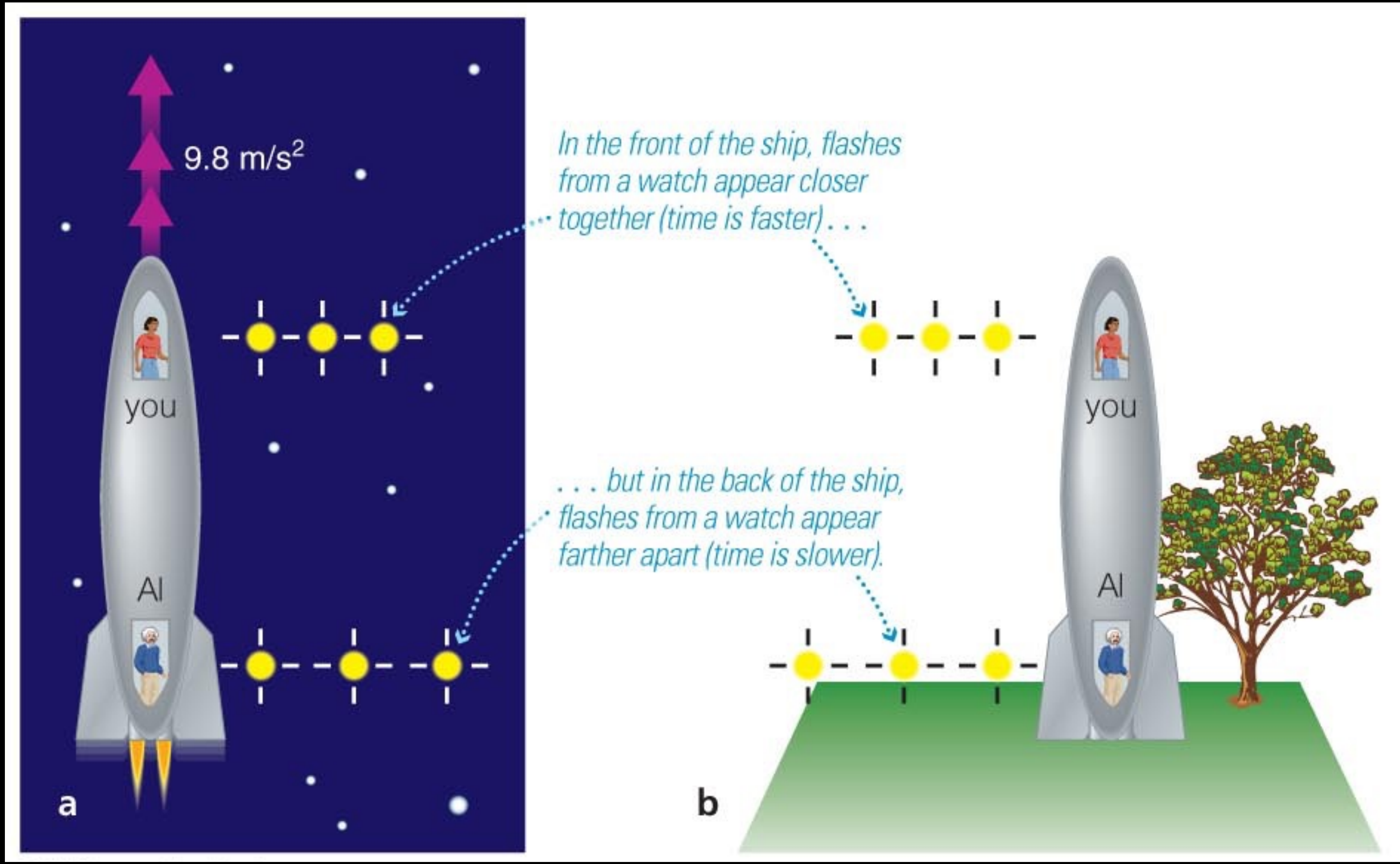
Time in an accelerating spaceship

- Light pulses travel more quickly from front to back of an accelerating spaceship than in other direction
- Everyone on the ship agrees that time runs faster in front than in back



a In an accelerating spaceship (but not in one at constant velocity), time must run faster at the front end and more slowly at the back end. The yellow dots represent the flashes from the watches, and the spacing between the dots represents the time between the flashes.

How does gravity affect time?



a In an accelerating spaceship (but not in one at constant velocity), time must run faster at the front end and more slowly at the back end. The yellow dots represent the flashes from the watches, and the spacing between the dots represents the time between the flashes.

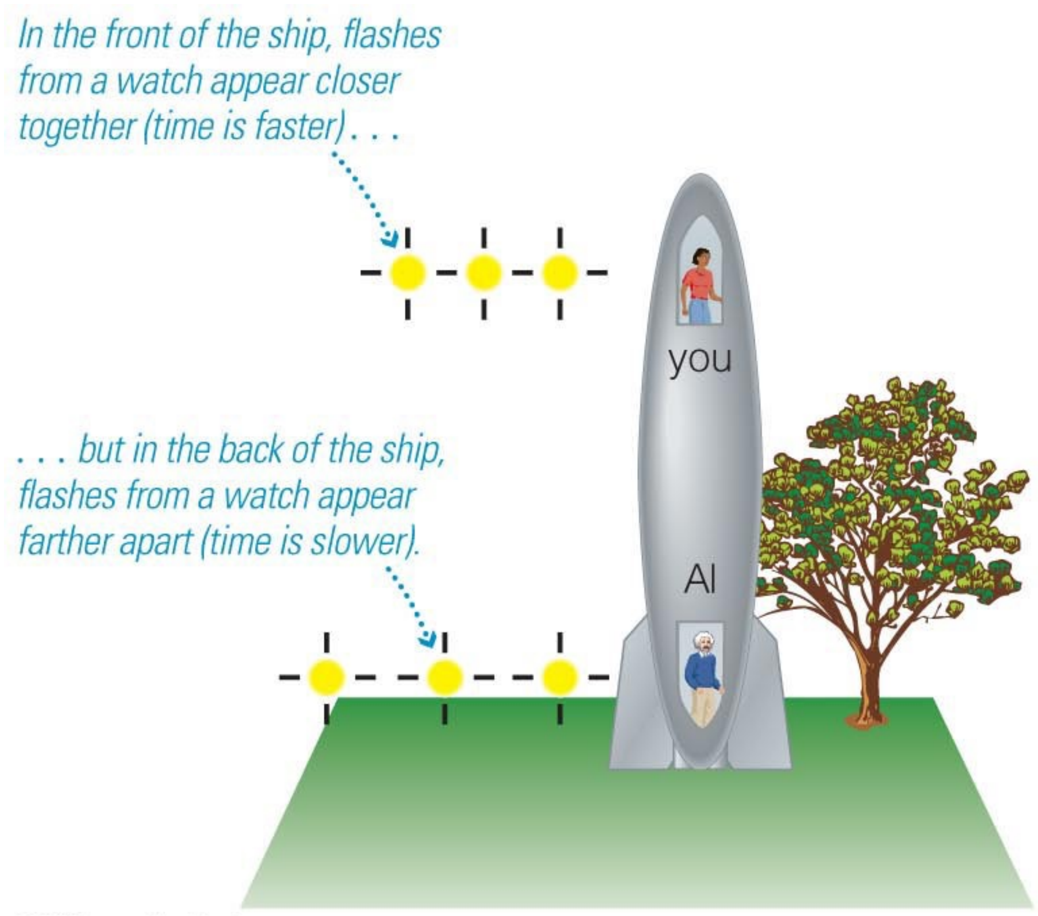
b By the equivalence principle, time must also run more slowly at lower altitudes in a gravitational field.

Effects of gravity and acceleration must be equivalent!

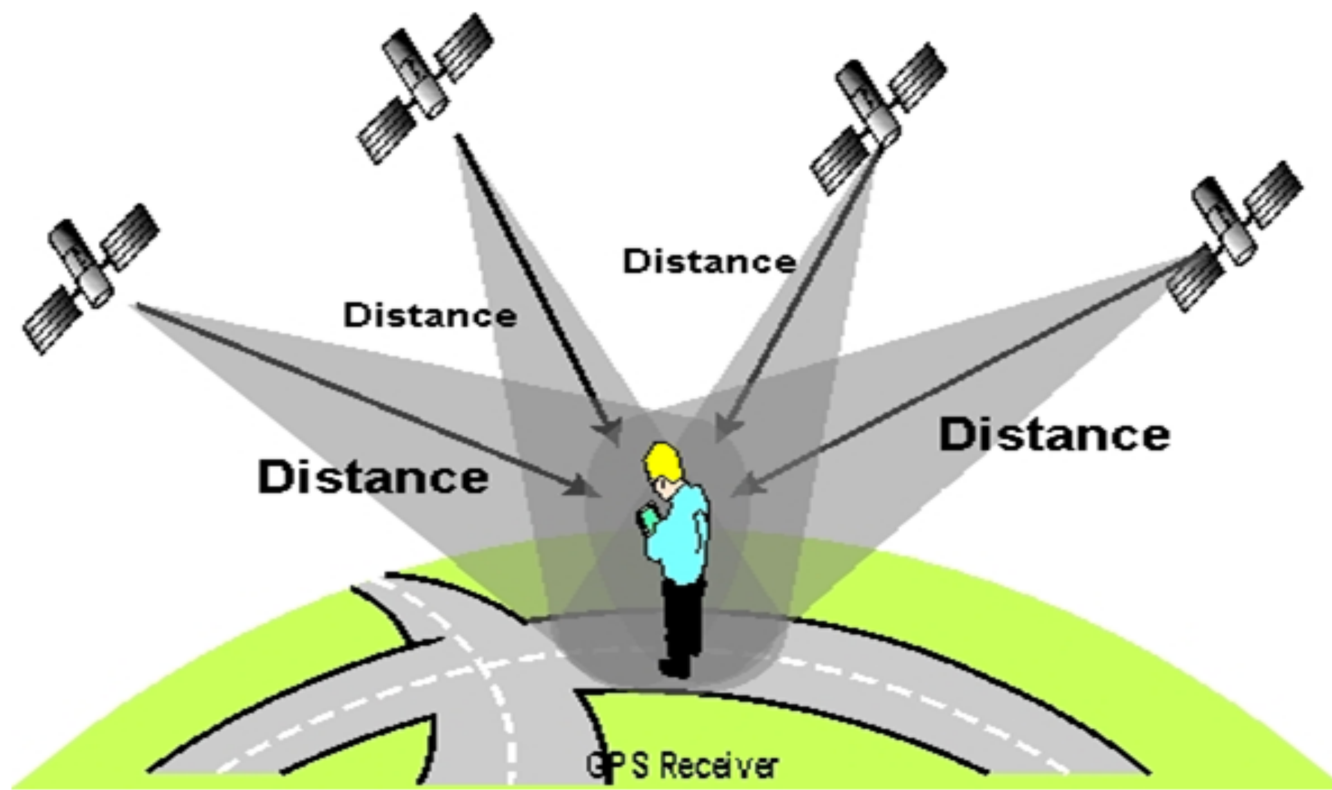
- Time runs faster at higher altitudes: **Gravitational Time Dilation**
- Example: time runs faster on GPS satellites than on Earth (their "day" is 40 microseconds longer)
- Slower time means that frequency of light appears to go down

Time in an Gravitational Field

- The effects of gravity are exactly equivalent to those of acceleration
- Time must run more quickly at higher altitudes in a gravitational field than at lower altitudes
- This is called *gravitational time dilation*



Implication of time dilation: GPS



- distance accuracy of a few meters requires 30 nanosecond accuracy in timing
- because of time dilation, clocks on communication satellites run 40 microseconds (38,000 nanoseconds) faster each day than on the surface of the earth
- GPS systems would infer your position about 3 kilometers offset (wrong)!

What does that mean?

- Speed of light is constant so if frequency goes down, wavelength must go up
- Also, energy of a photon goes down as the photon rises since $E = h/\lambda$

    Longer wavelength means smaller energy

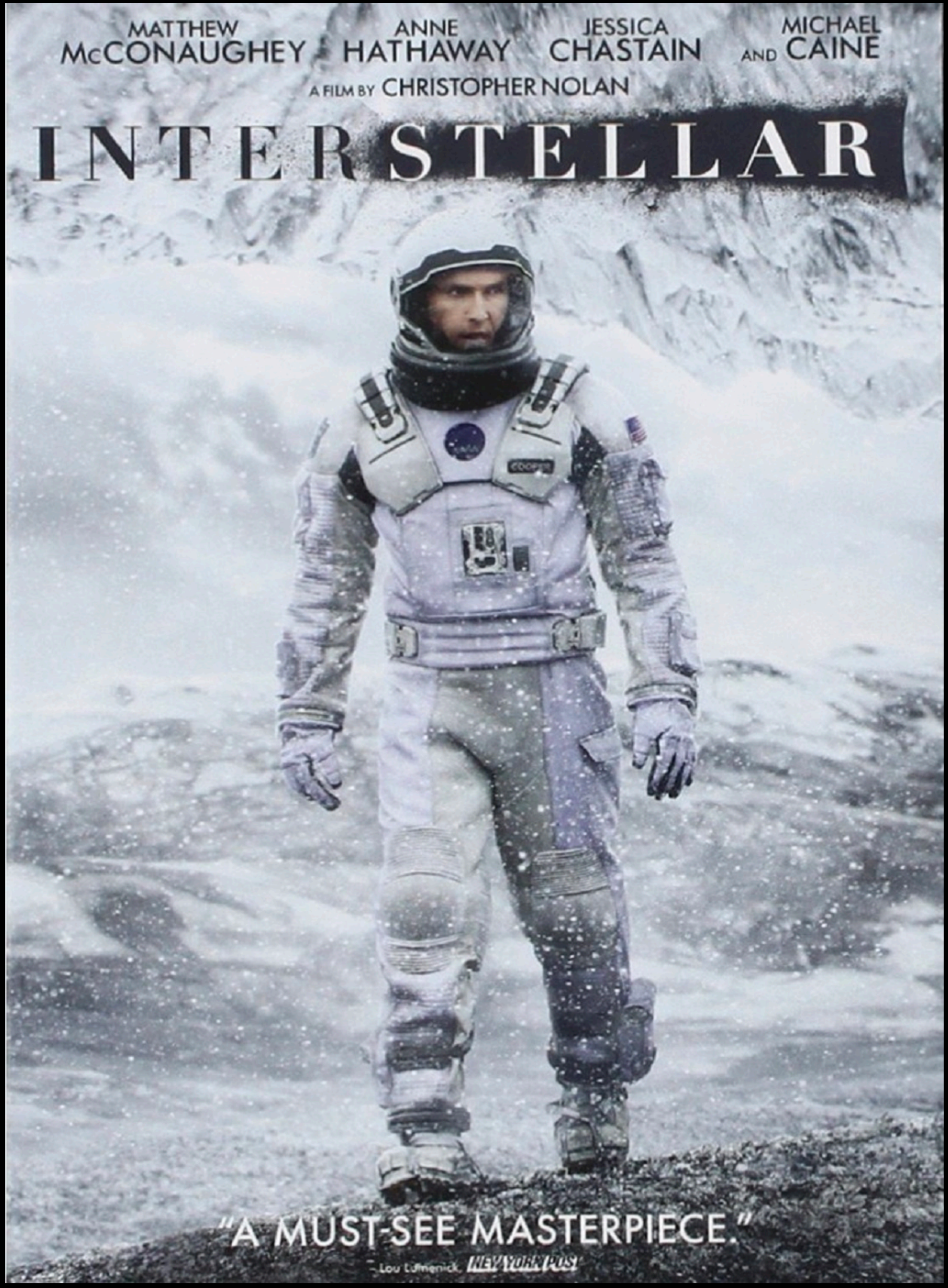
- The light gets **redder** as it climbs away from **any** mass

'GRAVITATIONAL REDSHIFT'

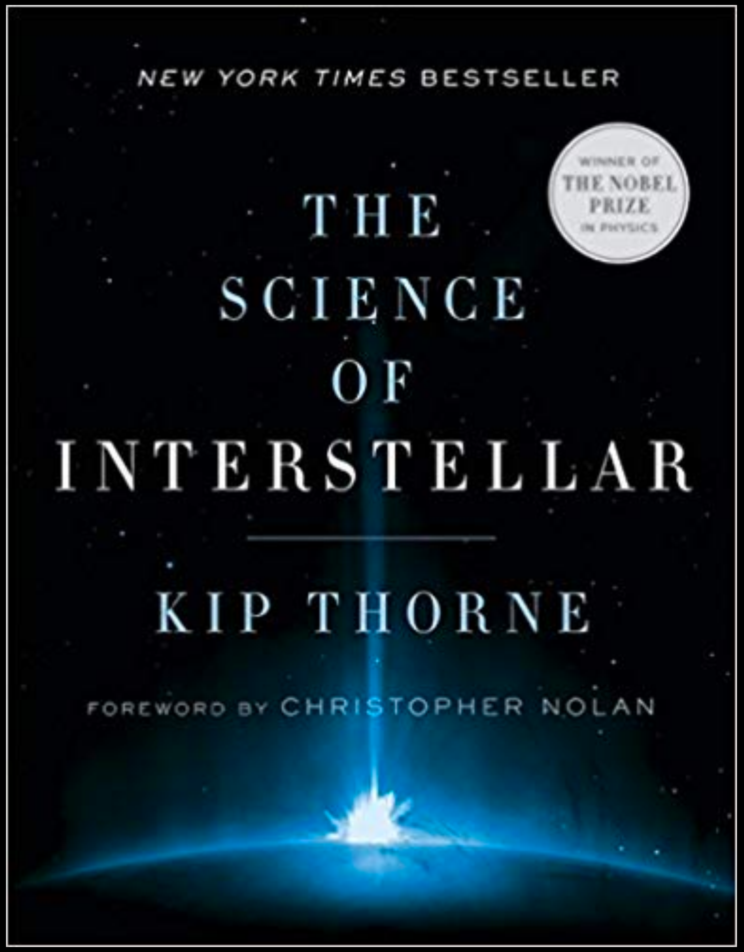
Gravitational Time Dilation:
Another bizarre effect of general relativity

- Time runs slower at locations deeper in the gravitational field
  - This is another example of the EQUIVALENCE PRINCIPLE
  - Clocks run slower if
    - They are accelerating more
    - They are in a stronger gravitational field
- Also, the **frequency** of light (number of cycles per second) **decreases** as light moves “upward”
  - This is called “Gravitational Redshift”

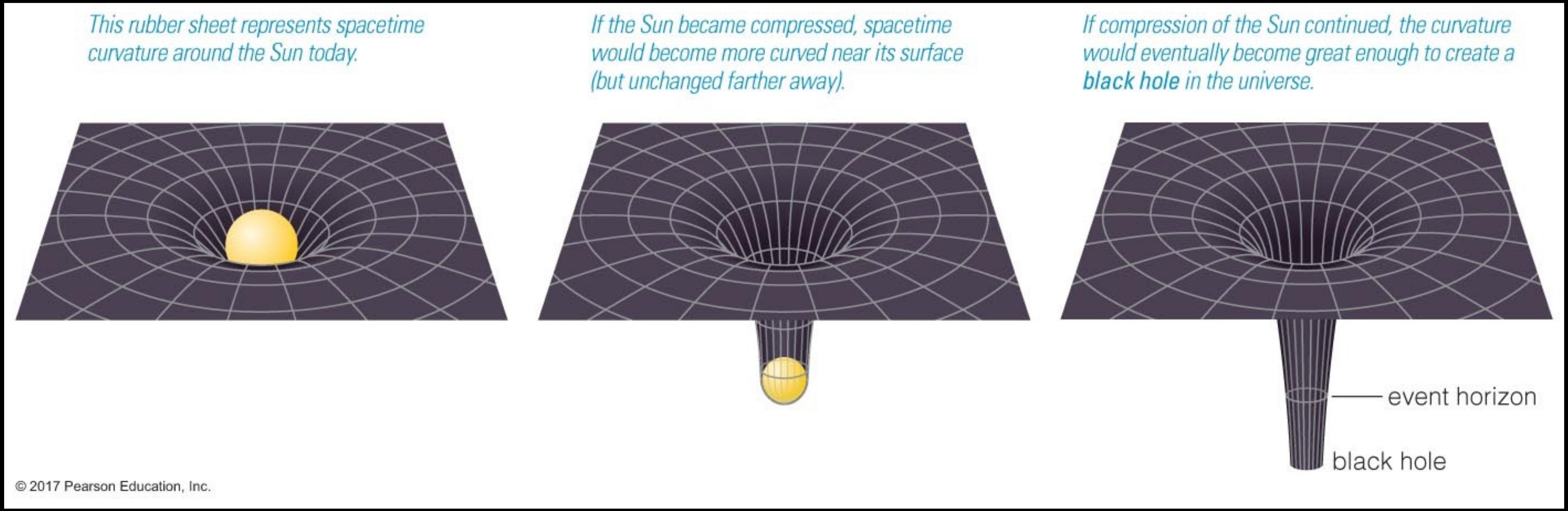
Gravitational Time Dilation



"Every **hour** we spend on that planet will be **7 years** back on Earth."



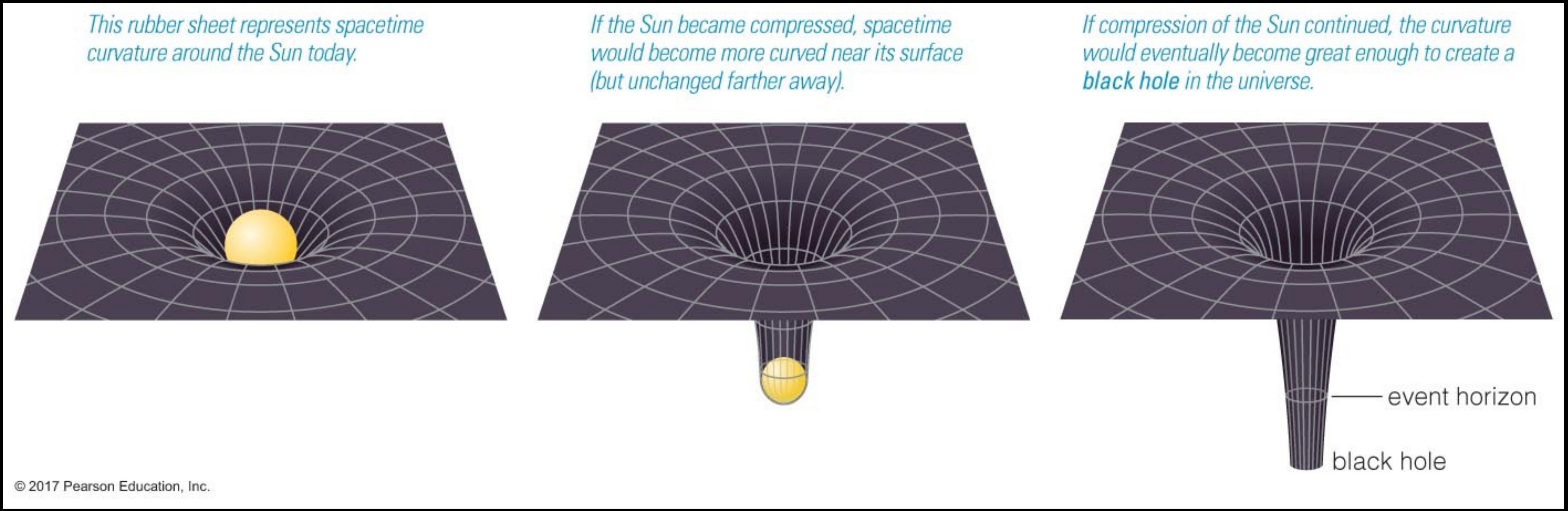
What happens when spacetime curves too much?



A **black hole**!

- Too much mass will cause space-time to curve so much that **nothing** can escape
- The slope of space-time becomes vertical
- Gravitational time dilation: clocks will appear to **stop completely**! (to an outside observer)

What happens when spacetime curves too much?

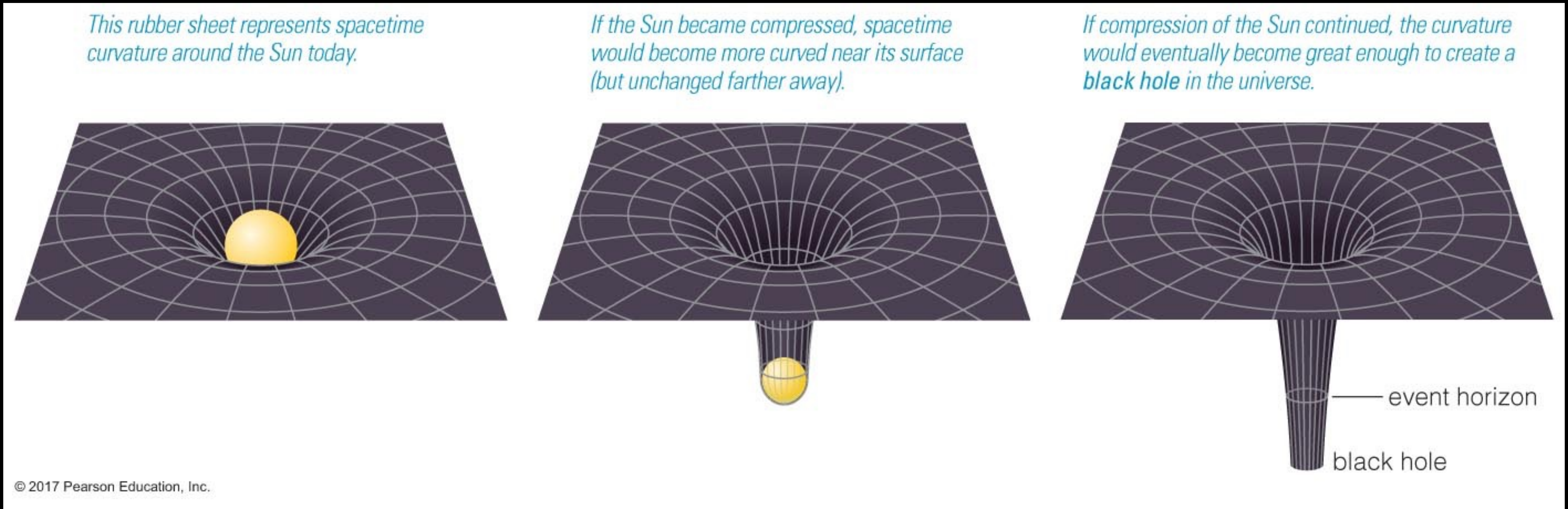


Another way to think about it:

- To escape Earth's gravity, you need to move very fast (~11 km/s)
- If Earth was more massive (or more compact!), you would need to move even faster
- If Earth's mass was ~2000 $M_{\odot}$, you would need to move at the speed of light to escape into space… not possible! **There is no escape!**

A "**black hole**" is what happens when the escape velocity exceeds the speed of light!

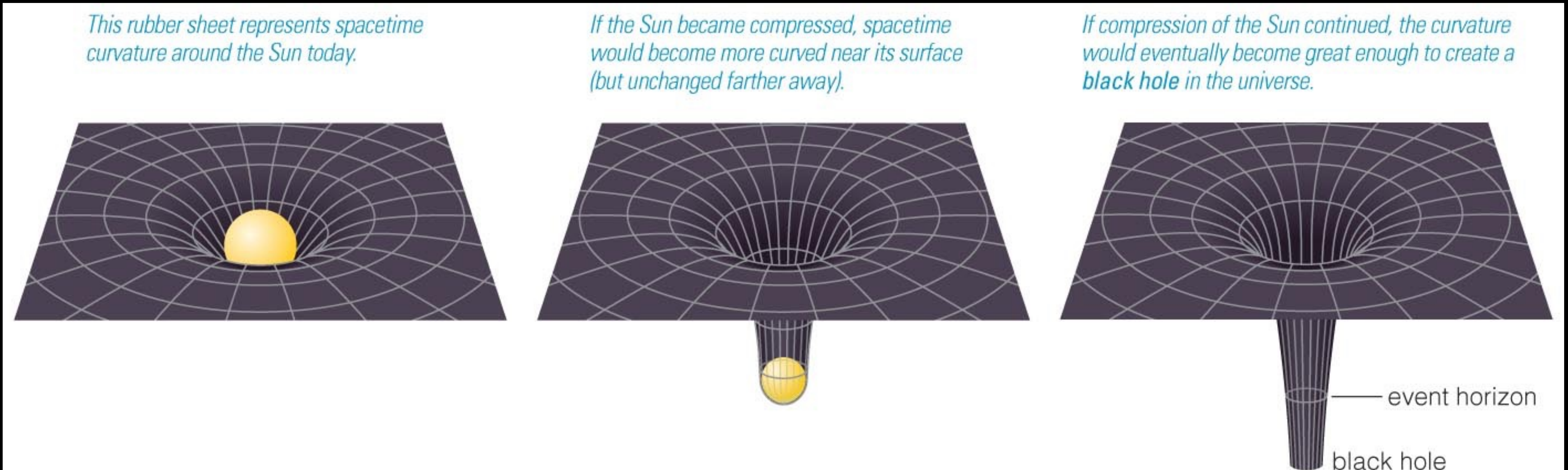
How much curvature is “too much”?



We can think of a black hole’s “surface” as the radius at which escape velocity = the speed of light

- This surface is called the **EVENT HORIZON**
- Radius is called the **Schwarzschild Radius**: $R_S = \dfrac{2GM}{c^2}$
- If a mass M is compressed to within this radius, the result is a black hole
  - R ≈ 3 km for Sun, R ≈ 1 cm for Earth, R ≈ 10^{-25} m for a human

Black holes don't "suck"!



If the Sun were to become a black hole, gravity would only be different near the "event horizon"

- Unchanged at larger distances
- Earth would keep orbiting as usual

Recap: what have we learned?

- **What are the major ideas of General Relativity?**
- **What is Einstein's view of gravity?**
- **What is a black hole?**

Recap: what have we learned?

- **What are the major ideas of General Relativity?**
  - The main idea is the **equivalence principle**, which states that the effects of gravity are exactly equivalent to effects of acceleration
  - We can combine “space” and “time” into a 4-dimensional space-time

- **What is Einstein’s view of gravity?**

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  - Mass causes space-time to curve, and the curvature determines the motion of objects
  - This view predicts deflection of light when it travels near massive objects, which we observe as **gravitational lensing**

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- **What is a black hole?**
  - A **black hole** is a region where space-time is curved so much that time appears to completely stop
  - Nothing can escape; not even light
  - This happens when a large mass is packed into a small volume