# Today's Topics

Friday, March 28, 2025 (Week 8, lecture 22) – Chapter 24.

A. Einstein's Theory of Relativity.

B. Special Relativity.

C. Length contraction.

D. Time dilation.

E. General Relativity.

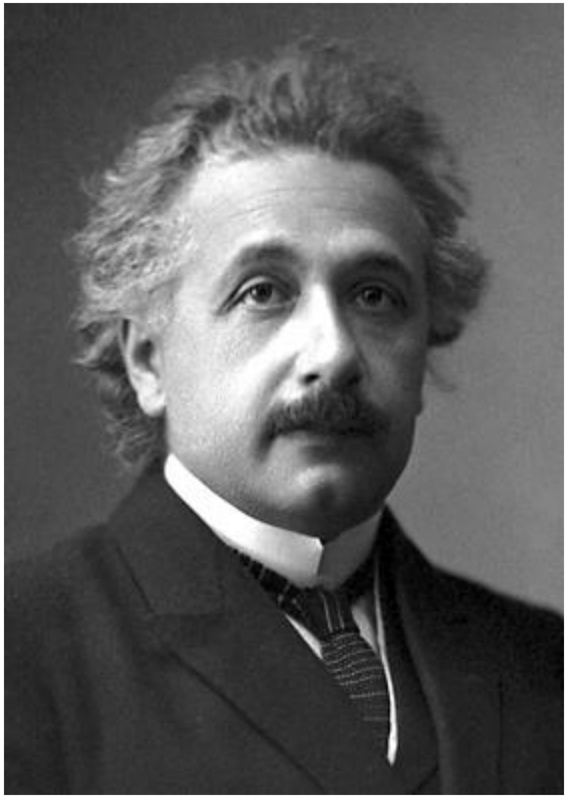
**Problem Set #7** is due on ExpertTA on Friday, April 4, 2025, by 9:00 AM

**Midterm #2** will be on Monday, April 7, 2025.

# Einstein's Theory of Relativity

1905: Annus Mirabilis

- Brownian motion (motion of atoms in a gas).
- Photo-electric effect (discovery of the photon, $E = hf$)
- **Special theory of relativity**.
  - → Major revision of Galilean relativity.
  - → Equivalence of energy and matter: $E = mc^2$



Albert Einstein, 1921.
*(1879-1955)*

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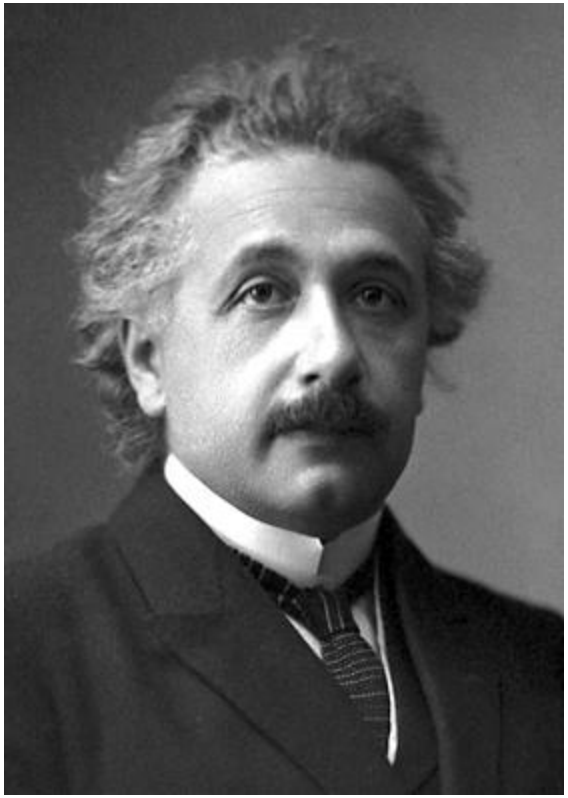
## 1907-15: General Relativity

Theory of relativity applied to gravity.
→ gravity = curved space-time.



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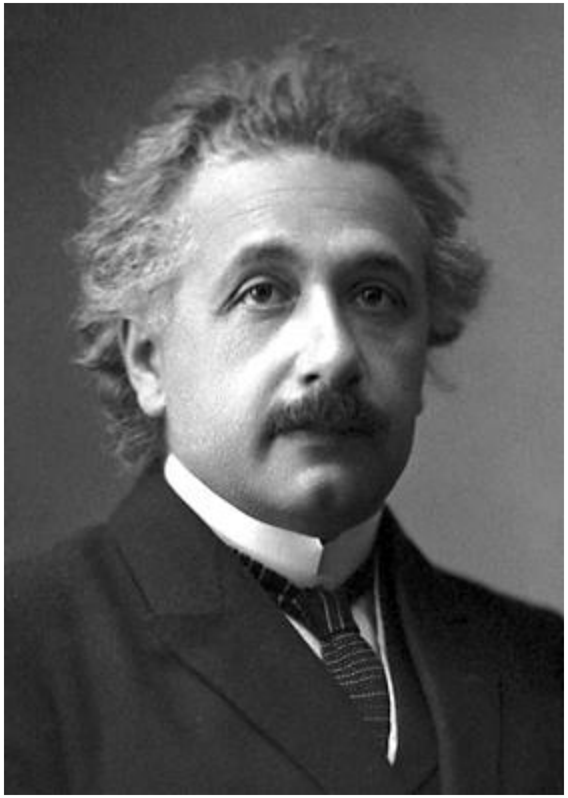
1921: Nobel Prize for photo-electric effect.

1924: Bose-Einstein Condensation
Predicts the existence of a new type of quantum matter.
→ Builds on the work of Satyendra Bose.
→ First observed in 1995
→ There is a BEC in the basement of Small Hall (room # 069).



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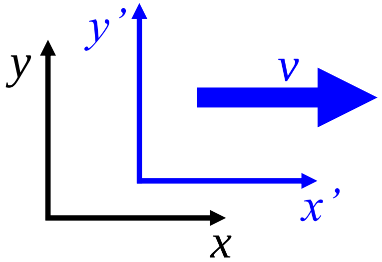
# Inertial Frames (Galileo & Einstein)

## Inertial Frame

Coordinate system at constant velocity in a rest frame.

*think of it as a box*




## Rest Frame

A coordinate system that is not moving.

*Note: a rest frame is an inertial frame.*

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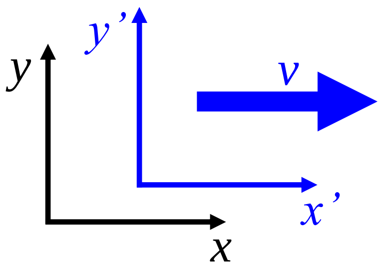


## Rest Frame

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## Important

- **You cannot tell if you are moving** based on local measurements inside your inertial reference frame (the frame attached to you).
- If you are **accelerating/decelerating**, then you can tell based on local measurements (i.e. there is a force on you that you can measure, $F = ma$).

# Special Relativity (Einstein)

**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

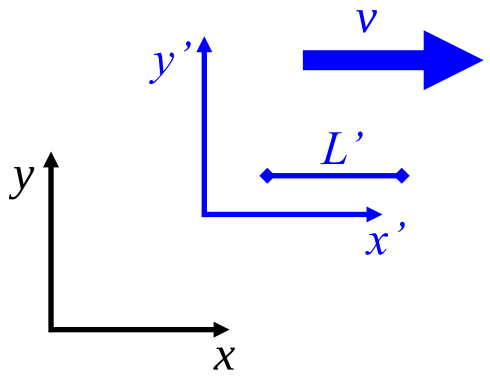
*Special Relativity*

# Length Contraction

## In the x'-y' inertial frame

Consider a rod of length $L' = L_0$, as measured in the x'-y' inertial frame (i.e. the rest frame of the rod).

*Note: The rod is aligned with the axis of motion along x'.*



# *Special Relativity*
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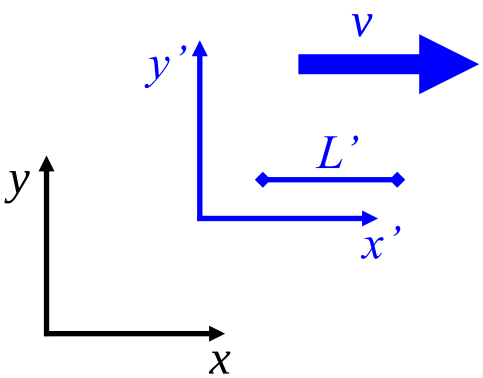



## In the x-y inertial frame

If you measure the length of the rod, then you will get a shorter length: $L = \frac{L_0}{\gamma}$.

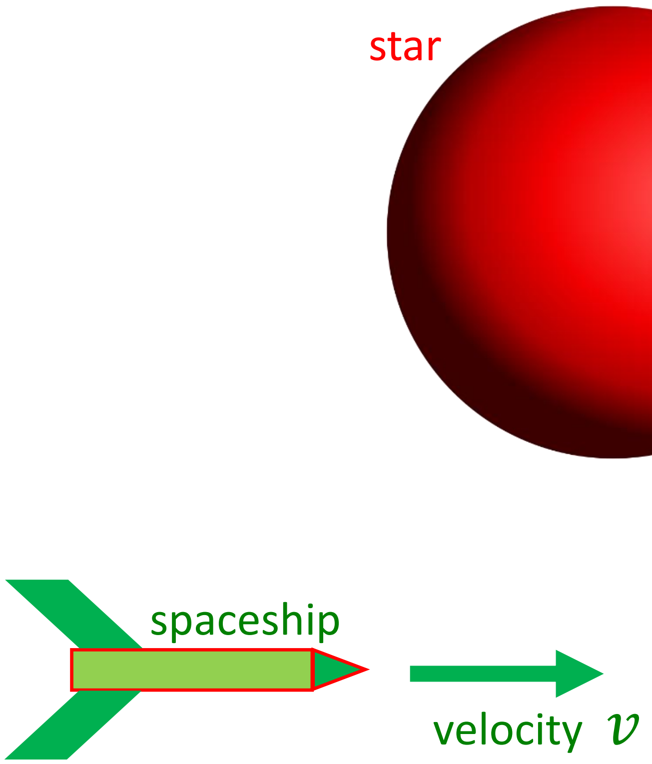
Gamma factor: $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

$\gamma \geq 1$

**Note:** the length contraction is only along the axis of motion. Along axes perpendicular to the motion, there is no change in length.

# Length Contraction: Example

Consider a spaceship travelling past a spherical star at 90% of the speed of light.




**Question:** What is the shape of the star in the frame of the spaceship?

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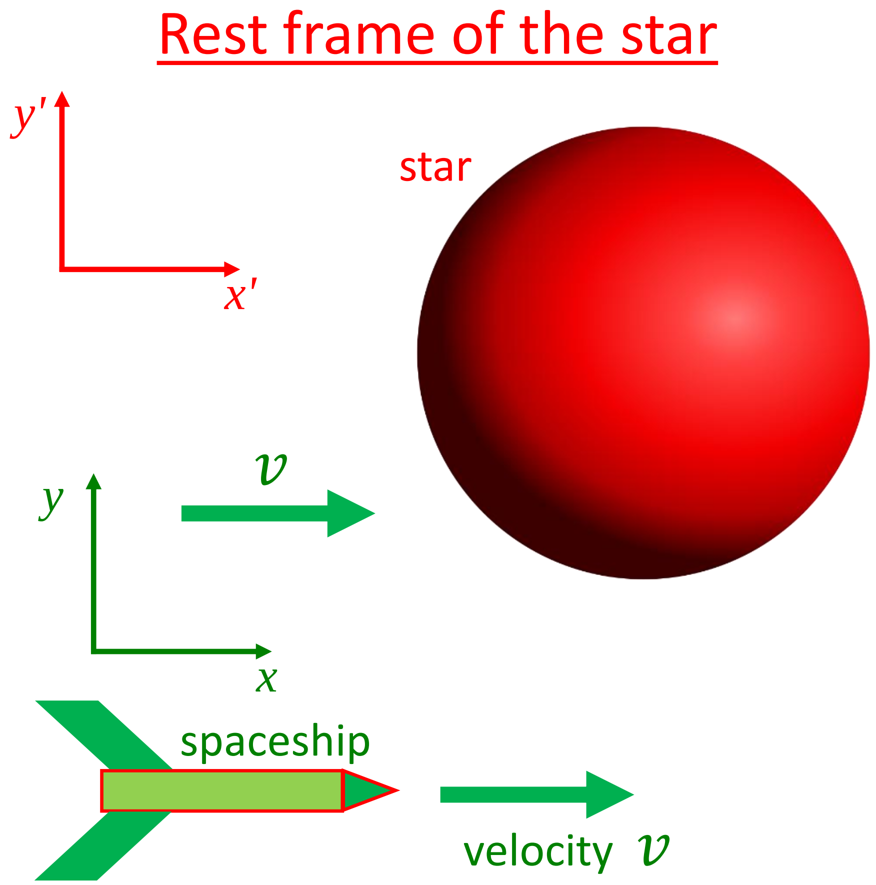


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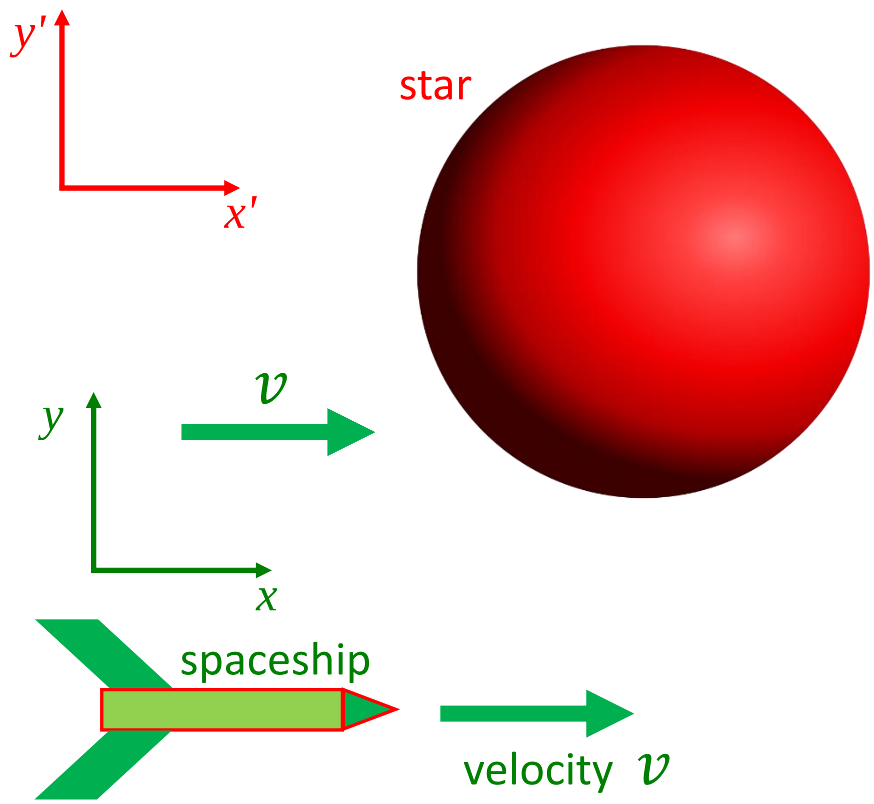


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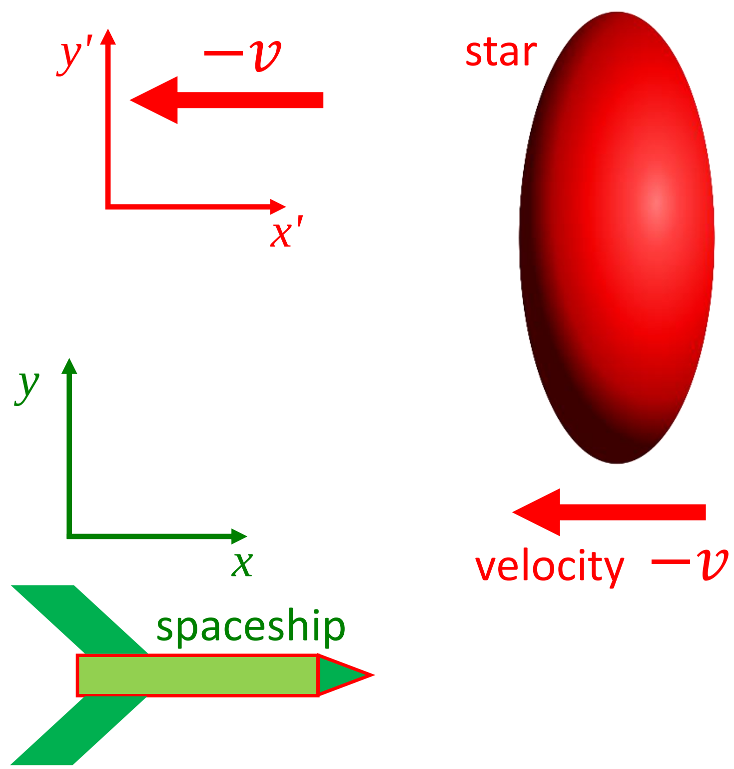


**Answer:** The star appears/is compressed along the axis of travel.

*The transverse directions are unaffected.*

# Length Contraction: Example

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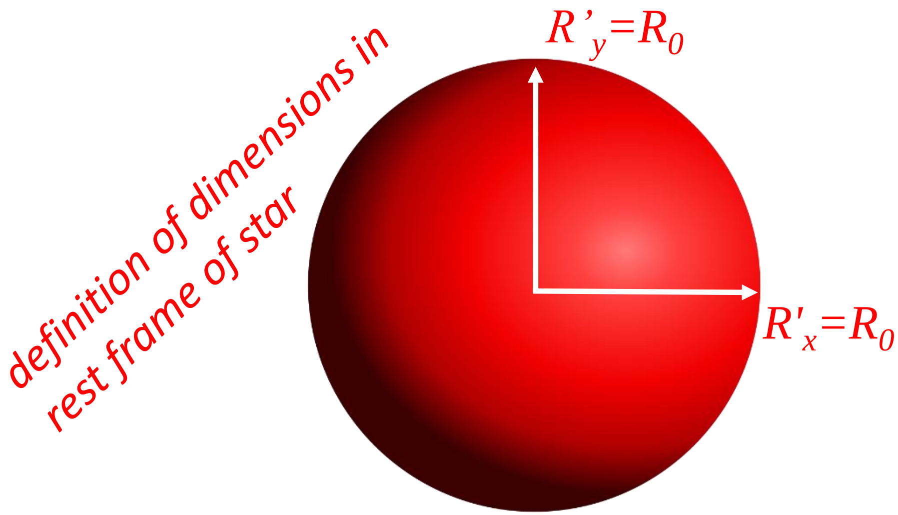
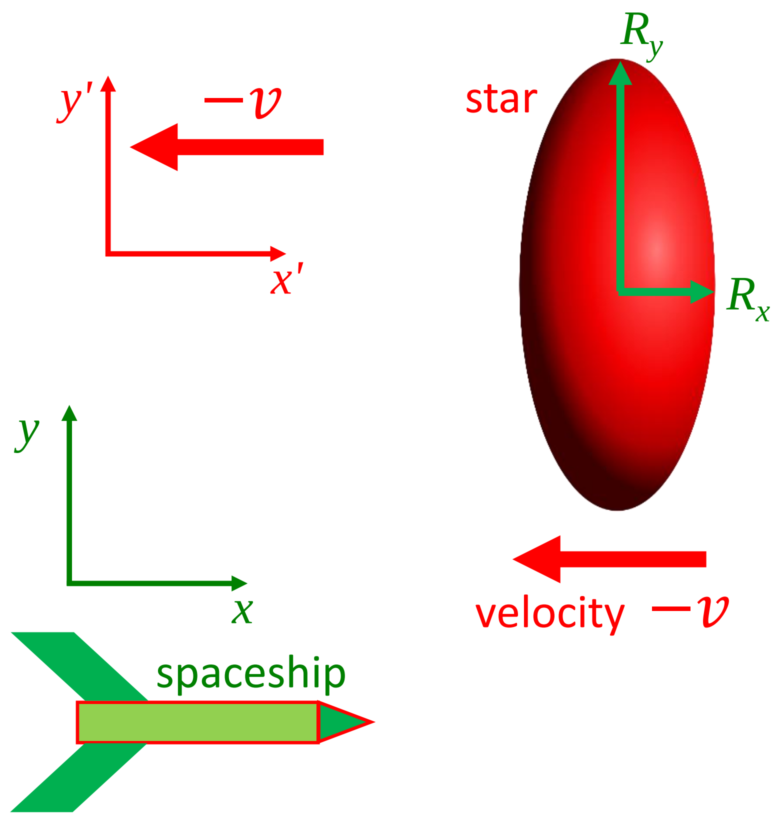
## Quantitative answer




## Rest frame of the spaceship

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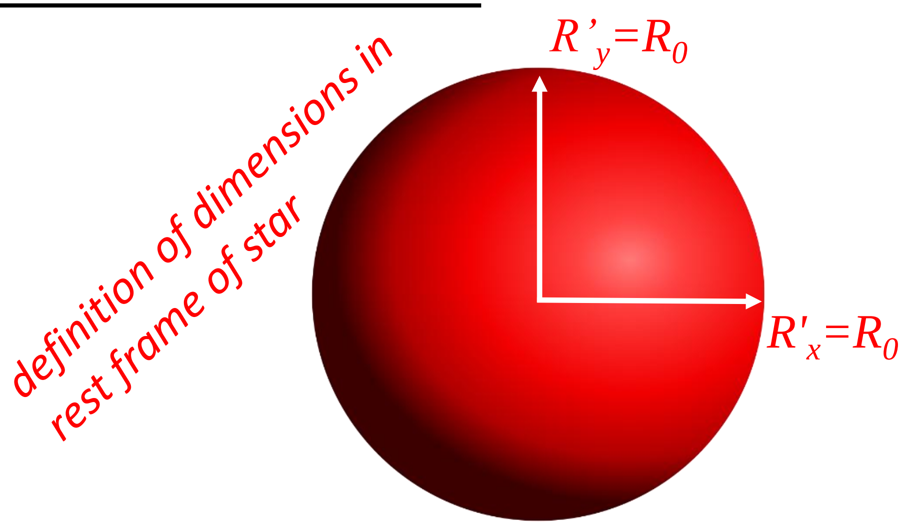
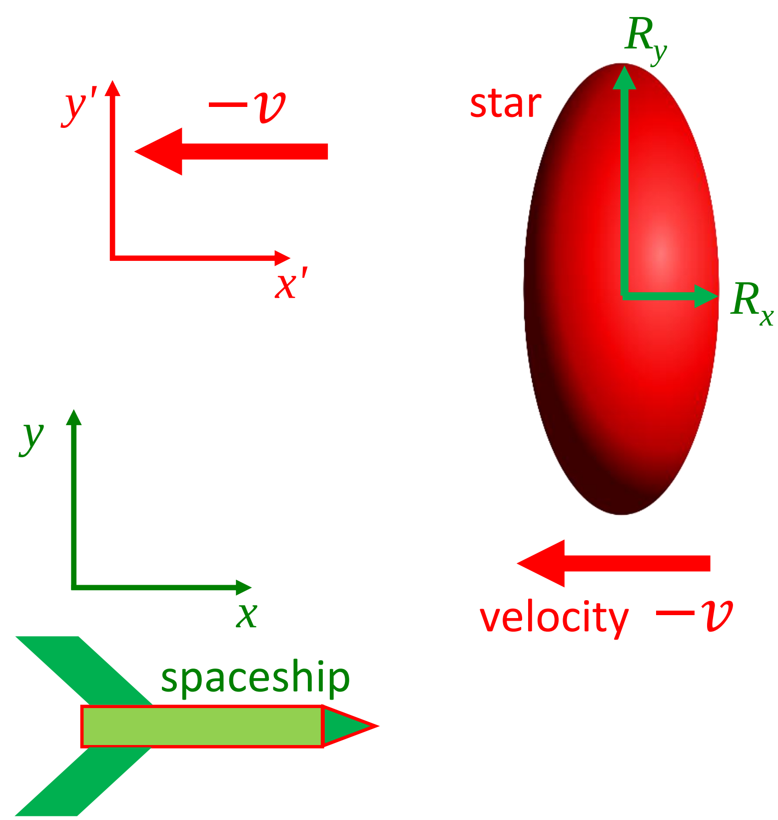



In the rest frame of the spaceship, we have

$$R_x = \frac{R_0}{\gamma} \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

## Rest frame of the spaceship

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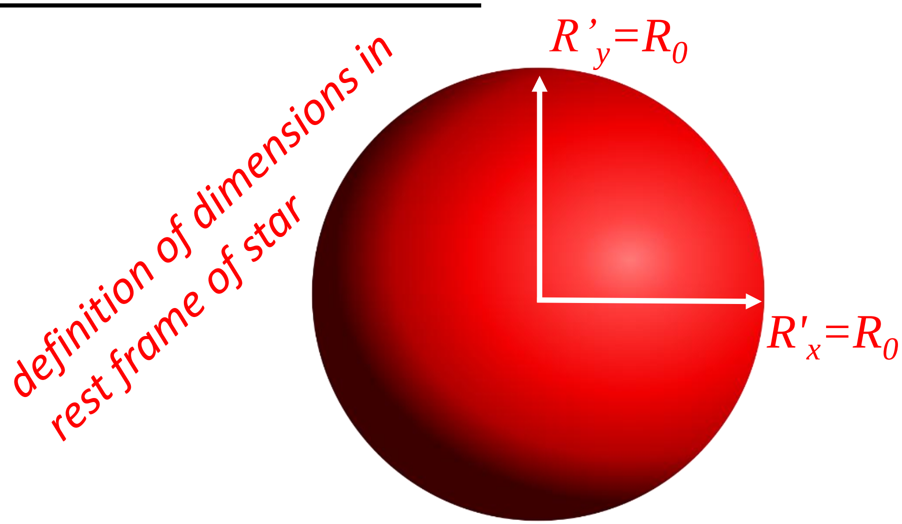
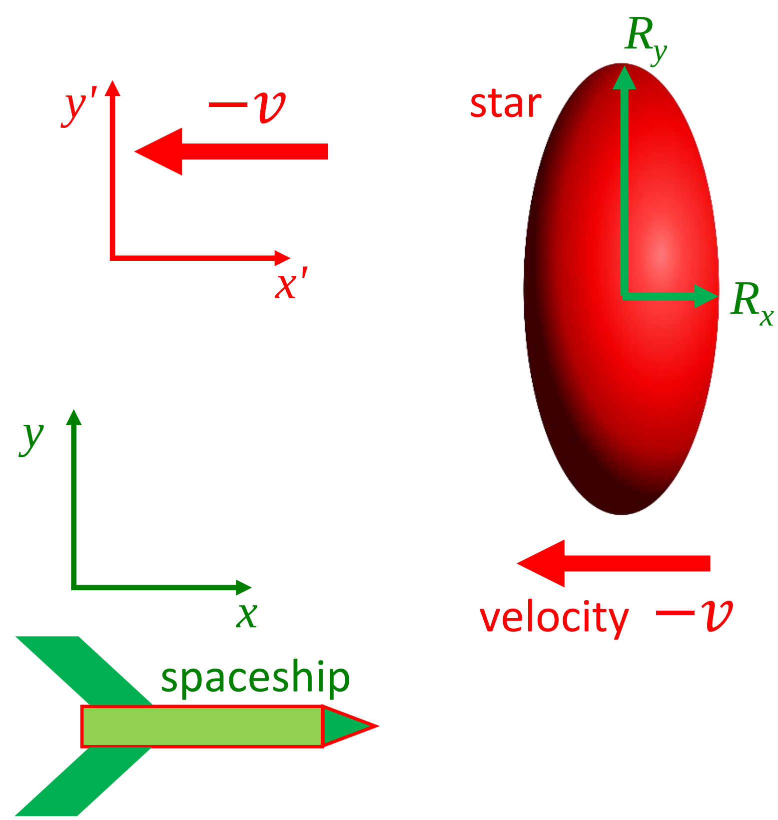



In the rest frame of the spaceship, we have

$$R_x = \frac{R_0}{\gamma} \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(-0.9c)^2}{c^2}}}$$

$$= \frac{1}{\sqrt{1-0.81}} = 2.29$$

## Rest frame of the spaceship

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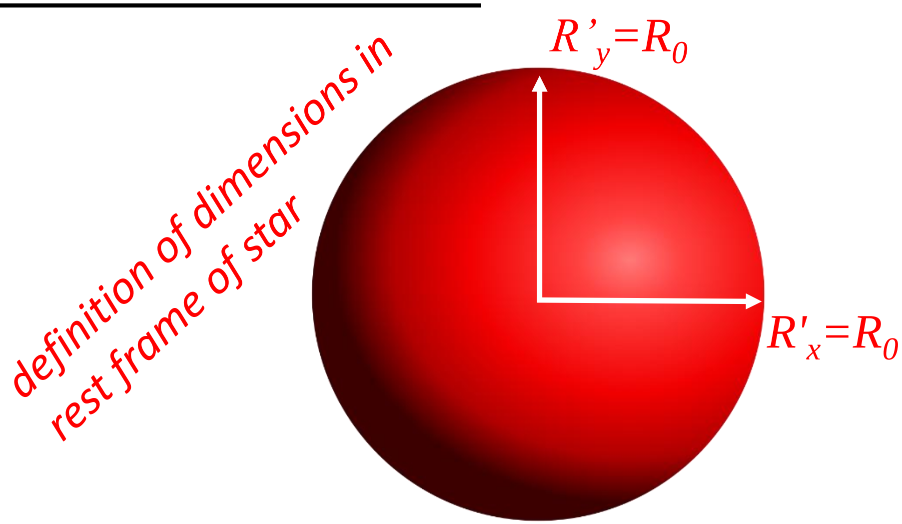


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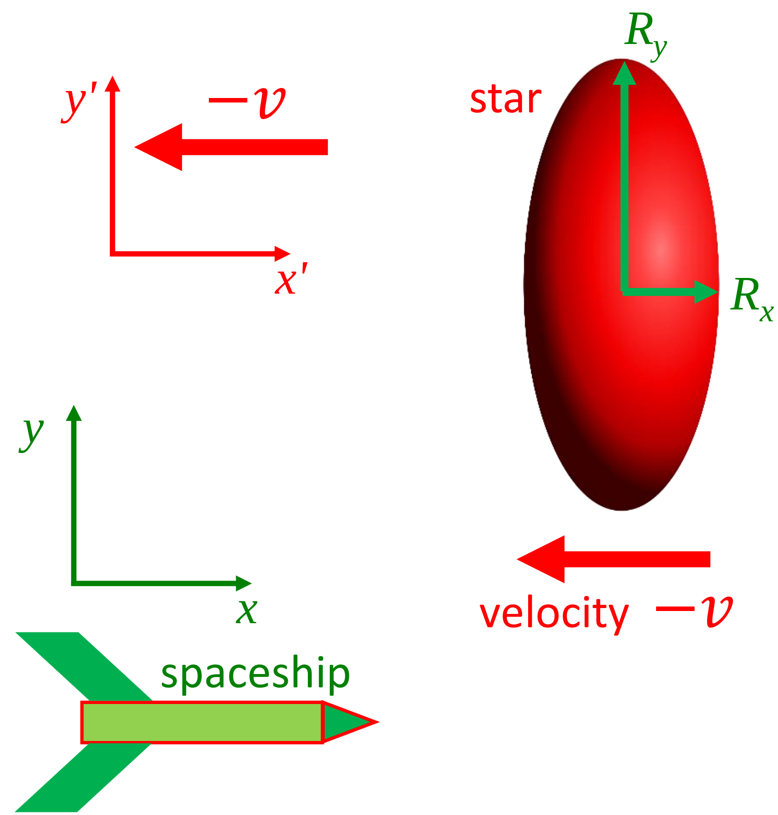
Thus $R_x = \frac{R_0}{2.29} = 0.43 R_0$

## Rest frame of the spaceship

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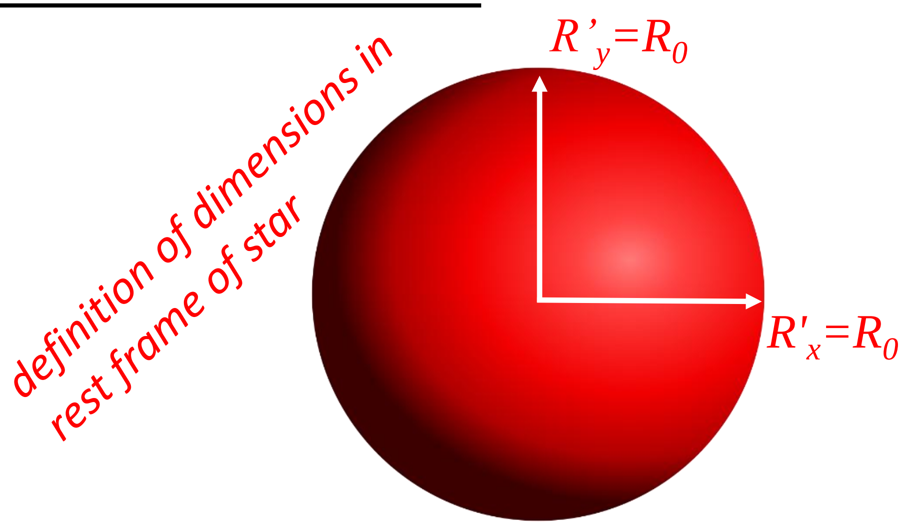


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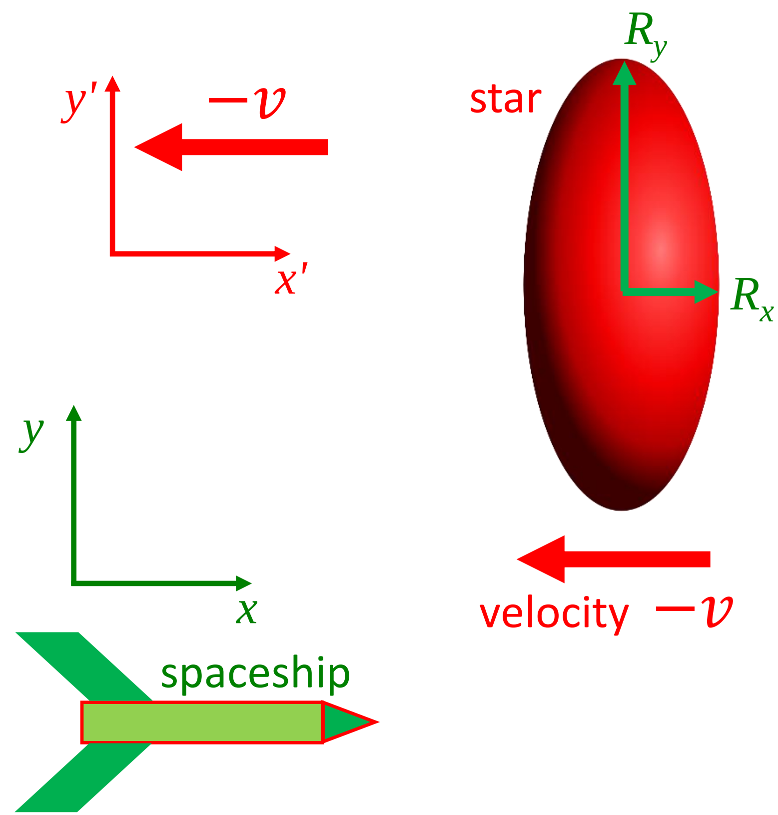


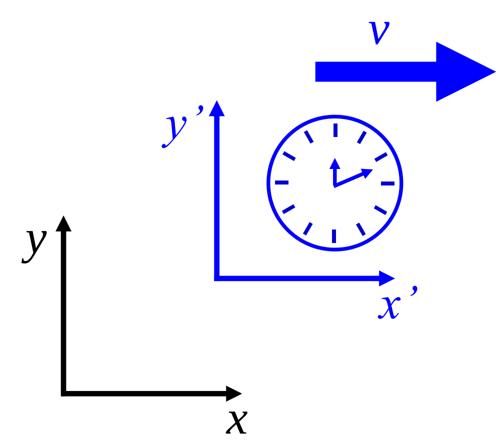

**Answer:** The star appears/is compressed to 43% of its original size along the direction of travel.
*The transverse directions are unaffected.*

# PollEv Quiz: PollEv.com/sethaubin

# *Special Relativity*
# **Time Dilation**

## In the x'-y' inertial frame

Consider a clock at rest in the x'-y' inertial frame that measures a time interval of $\Delta T' = T_0$, i.e. the time for the big clock hand to go from noon to the 2 o'clock position (10 minutes).



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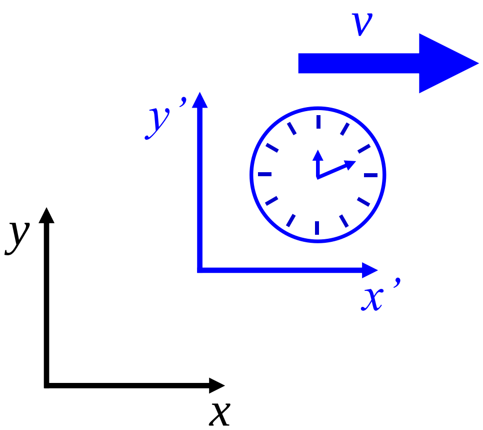


## In the x-y inertial frame

If you measure the same elapsed time (with your own timepiece) from the x-y inertial frame, i.e. as the clock flies past you at speed $\boldsymbol{v}$, then you will measure a longer elapsed time: $\boxed{T = \gamma T_0.}$

# Time Dilation Example
# The Twin Paradox

- Twin A travels to a distant star at a velocity of $v = 0.9c$ and then returns also at a velocity $v = 0.9c$, while twin B remains on Earth.
- Twin A measures a travel time of 10 years (according to twin A's clock) to get to the star, and then 10 years to return to Earth.

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**Question 1**

How much older is twin A, when twin A returns to Earth?

**Answer 1**

Since we are using twin A's clock, we know that

$$\Delta T' = T_0 = 2 \times 10\, years = 20\, years$$

Twin A has aged 20 years (in the physics-biology sense).

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How much older is twin B, when twin A returns to Earth?

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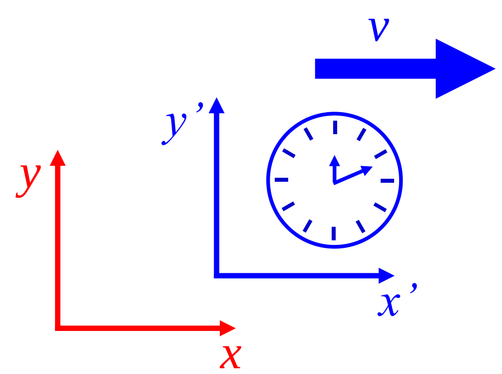


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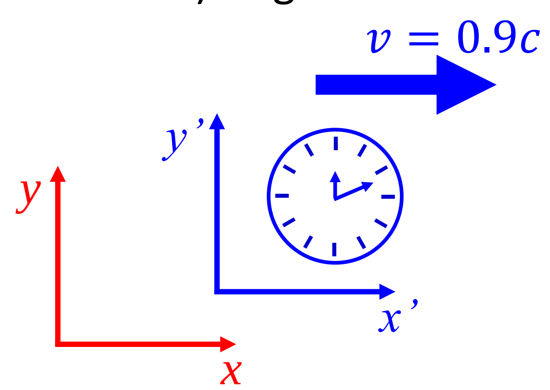


**Question 2**

How much older is **twin B**, when **twin A** returns to Earth?

**Answer 2**

If twin B is in the x-y frame (Earth), and twin A is in the x'-y' frame (spaceship), then

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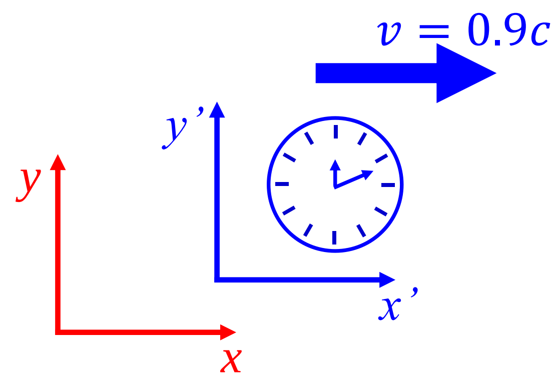


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**Answer 2**

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$$\Delta T = \gamma \Delta T' = \gamma T_0 = 2.29 \times 20\, years = 45.8\, years$$

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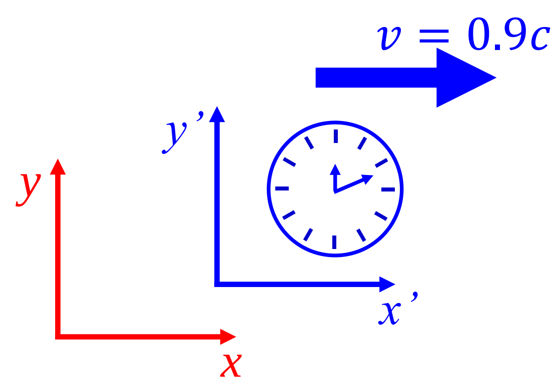


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Twin B has aged 45.8 years while remaining on Earth !!!

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Twin A sees twin B travelling away from the spaceship on "spaceship Earth", so why doesn't twin A age faster instead?

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**Question 3: the paradox**
Twin A sees twin B travelling away from the spaceship on "spaceship Earth", so why doesn't twin A age faster instead?

**Answer 3**
Twin A must accelerate and decelerate, so twin A is briefly in a **non-inertial frame**. The motions of twin A & twin B are not symmetric.

# General Relativity

## Equivalence Principle

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

## Corollary

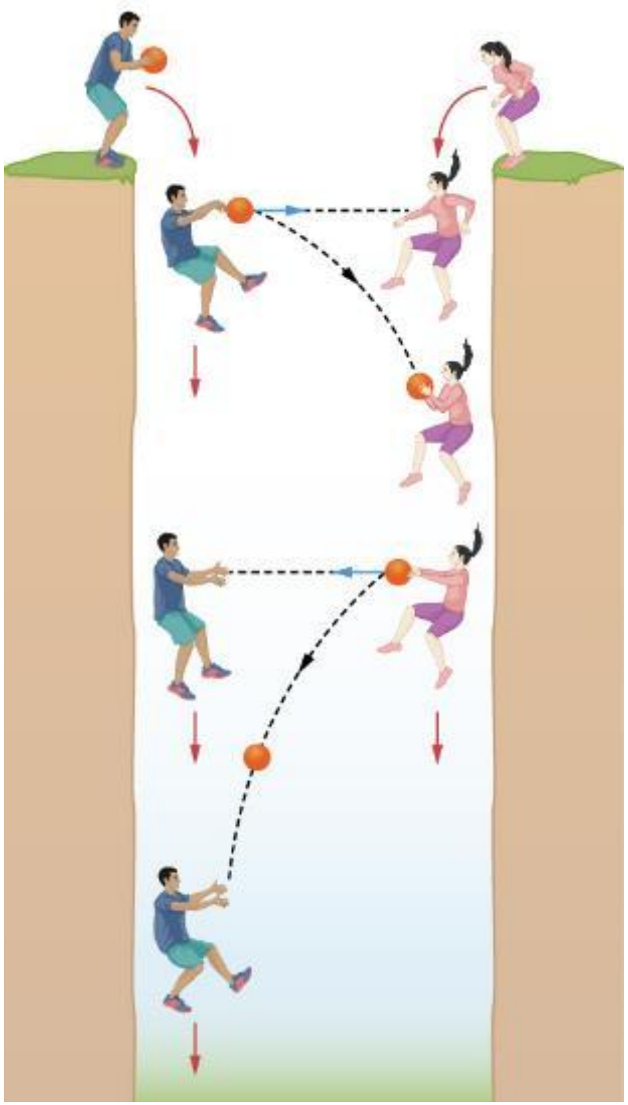
You cannot tell if you are at rest in a non-gravitational field (i.e. in a standard inertial frame) or freely falling under gravity based on local measurements.

# Equivalence Principle

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

**Example**

- Two people play catch as they descend into a bottomless abyss.
- Since the people and ball all fall at the same speed, it appears to them that they can play catch by throwing the ball in a straight line between them.
- Within their frame of reference, there appears to be no gravity.

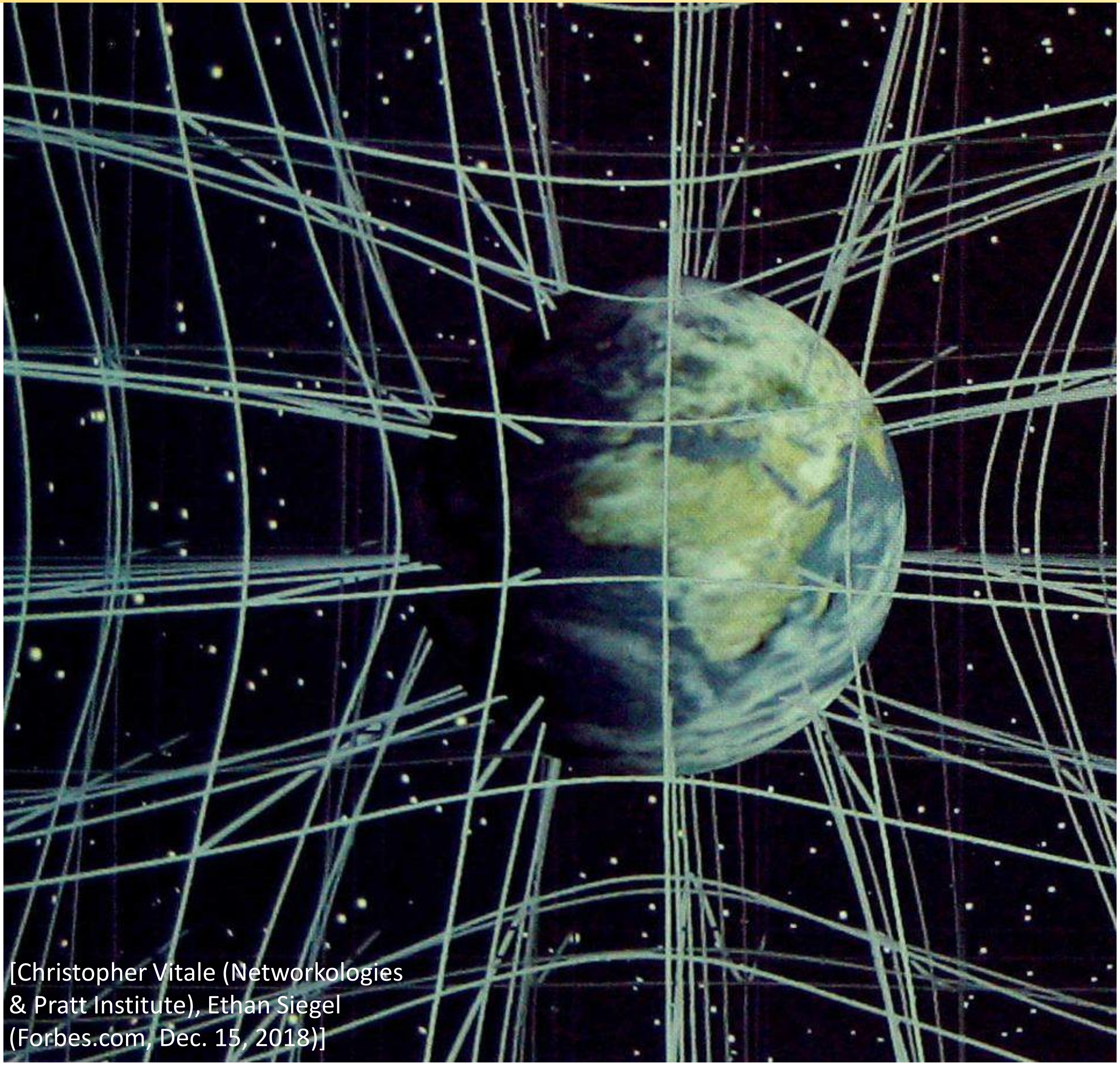


[OpenStax: Astronomy]

# Equivalence Principle on ISS

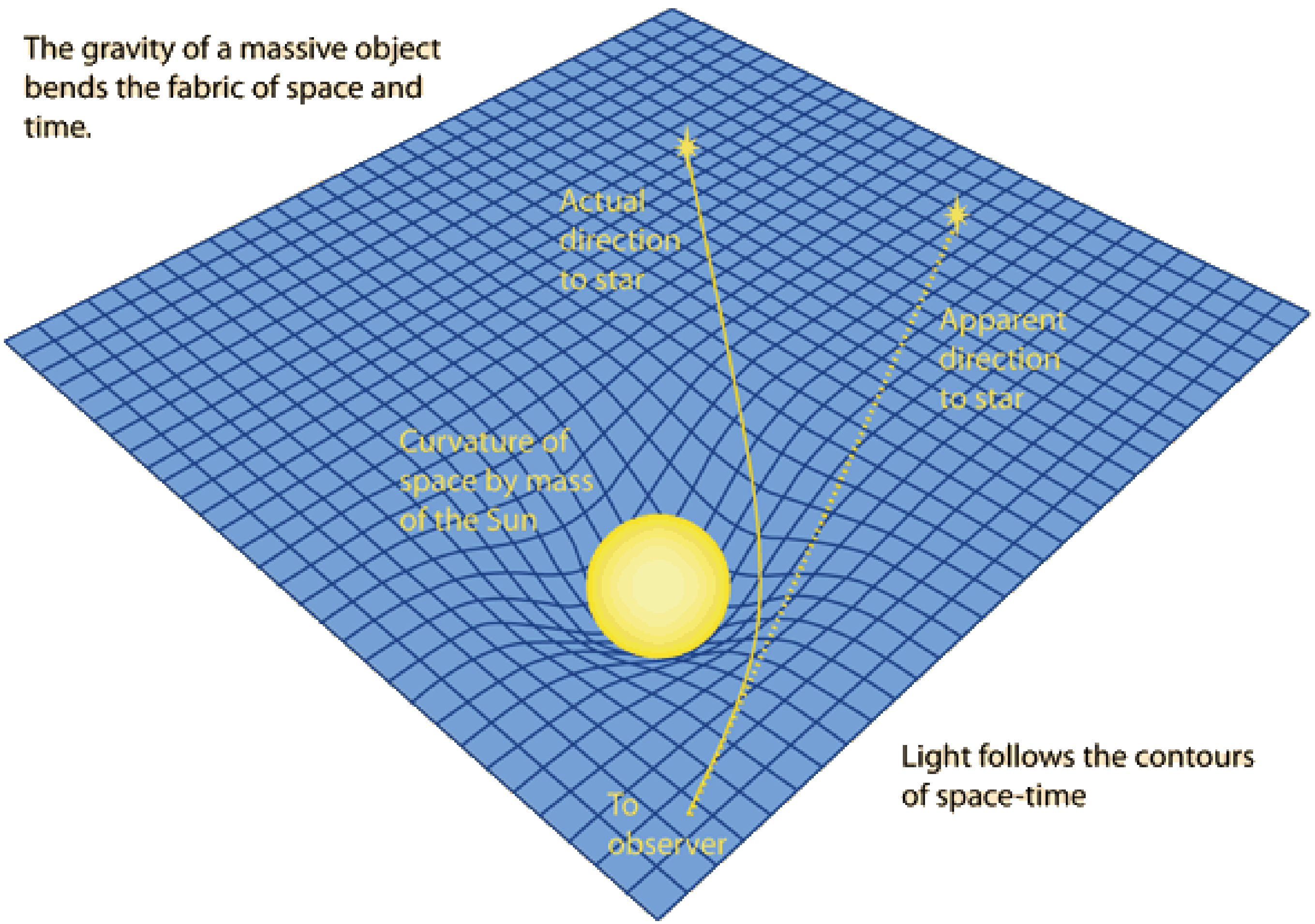
[NASA]

# Curved Space-Time



[Christopher Vitale (Networkologies & Pratt Institute), Ethan Siegel (Forbes.com, Dec. 15, 2018)]

# Curved Space-Time: light rays in 2D




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