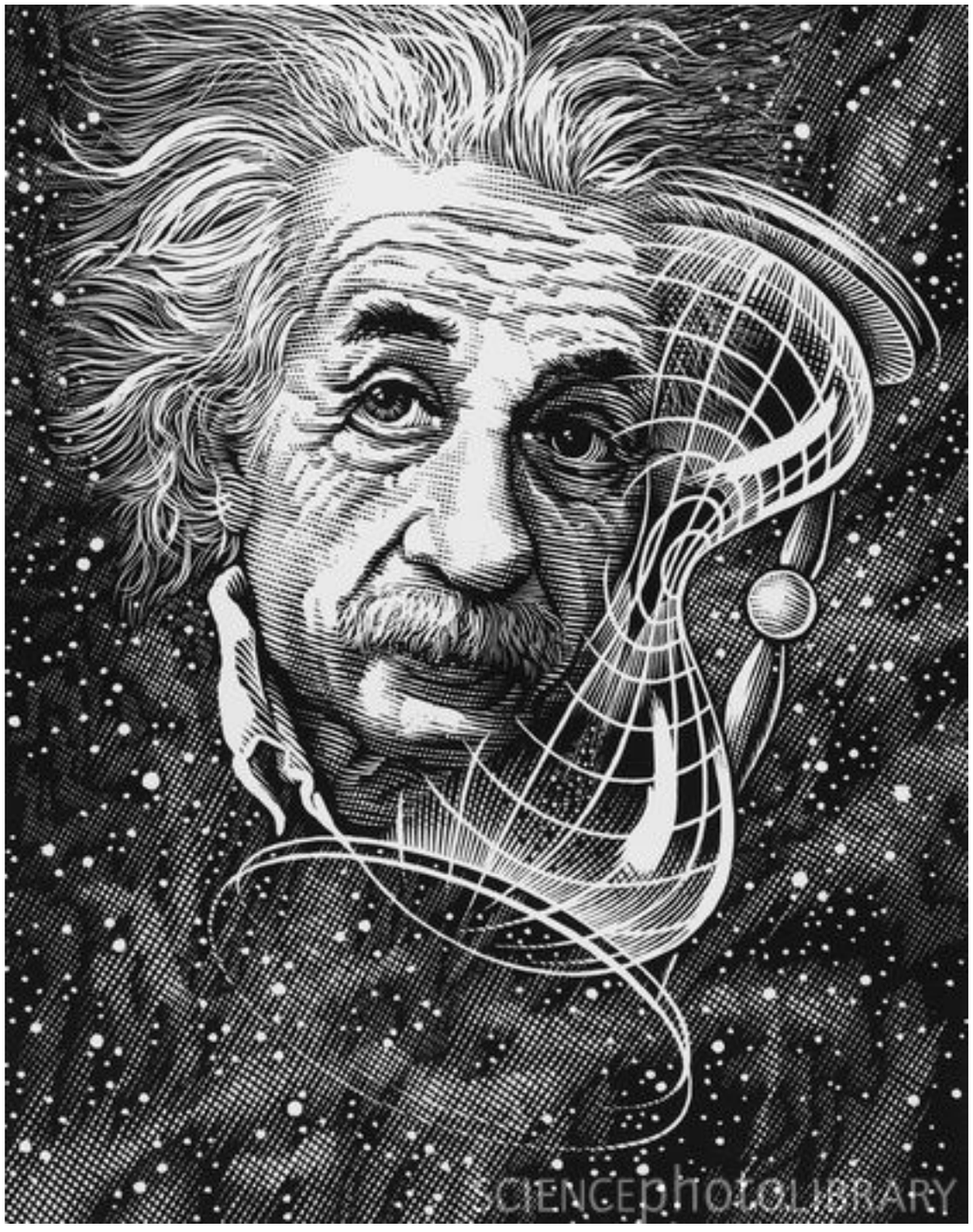


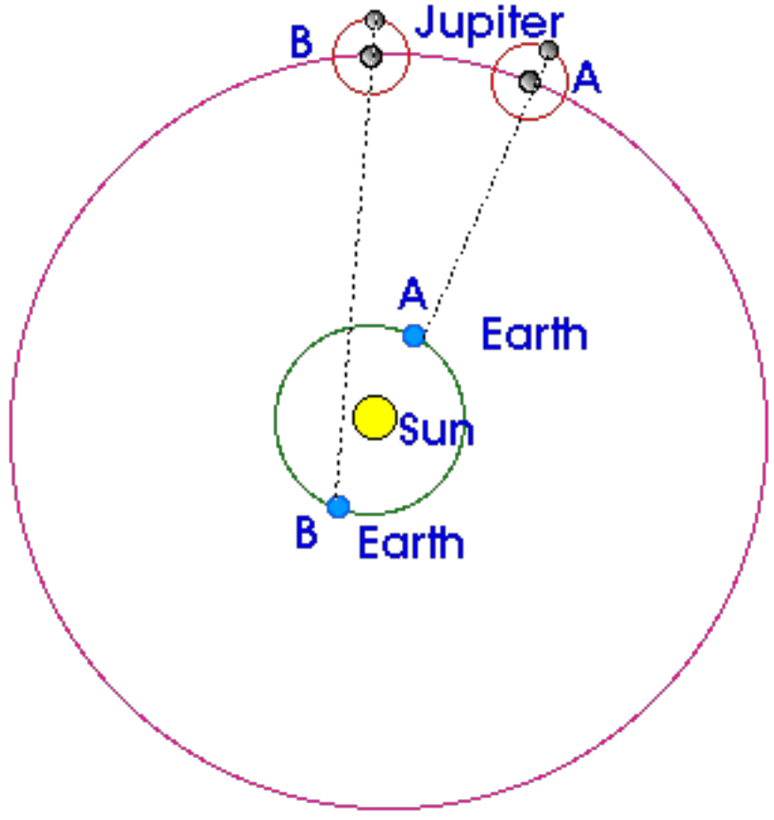

# Relativity:
# QuarkNet Lecture

# What we know circa 1900: Light travels at a finite velocity.


Galileo was among the first to try and measure the speed of light, using lanterns on distant hills.

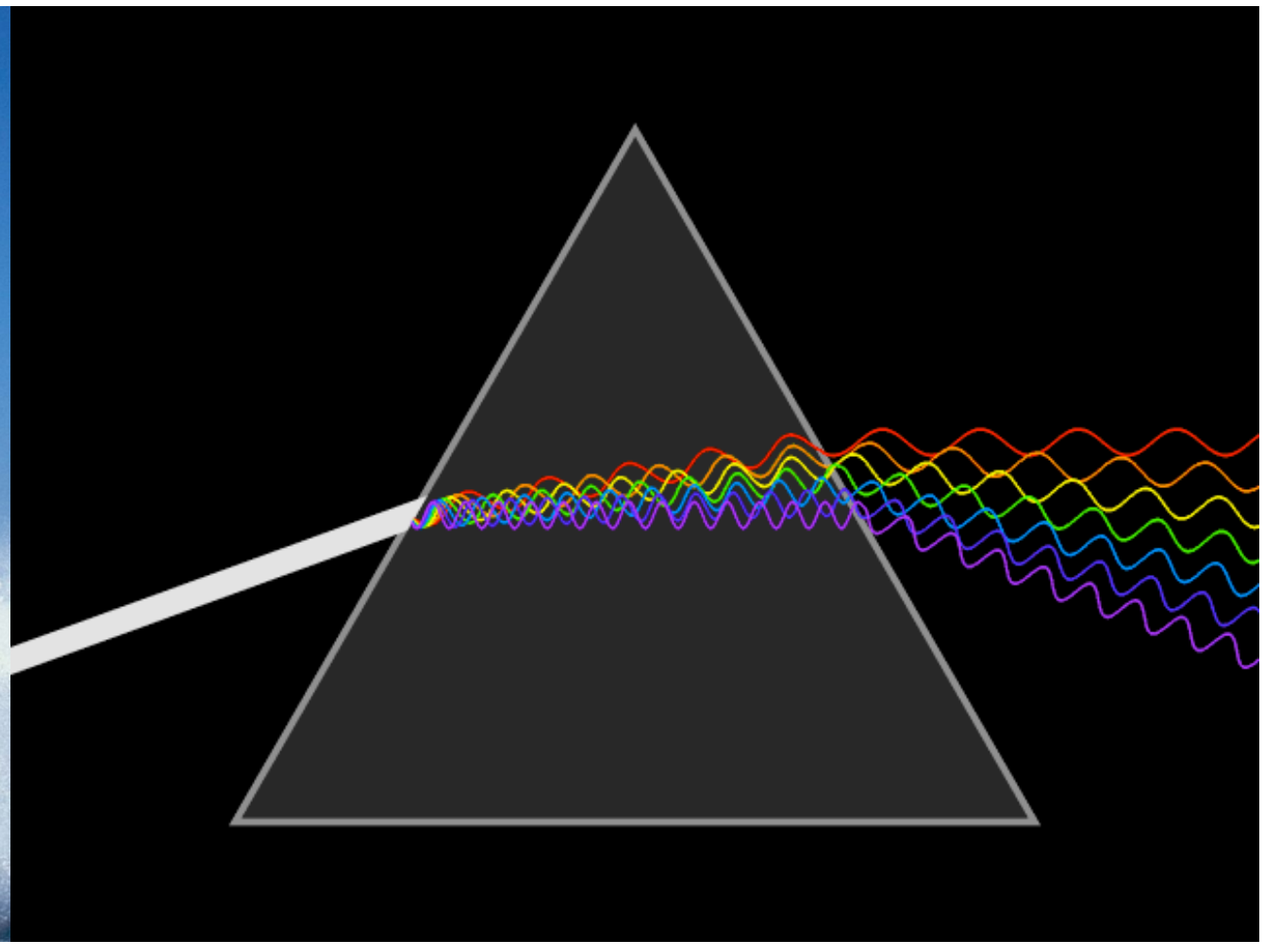
Speed of light = $3.0 \times 10^8$ m/s

Ole Rømer - 1676

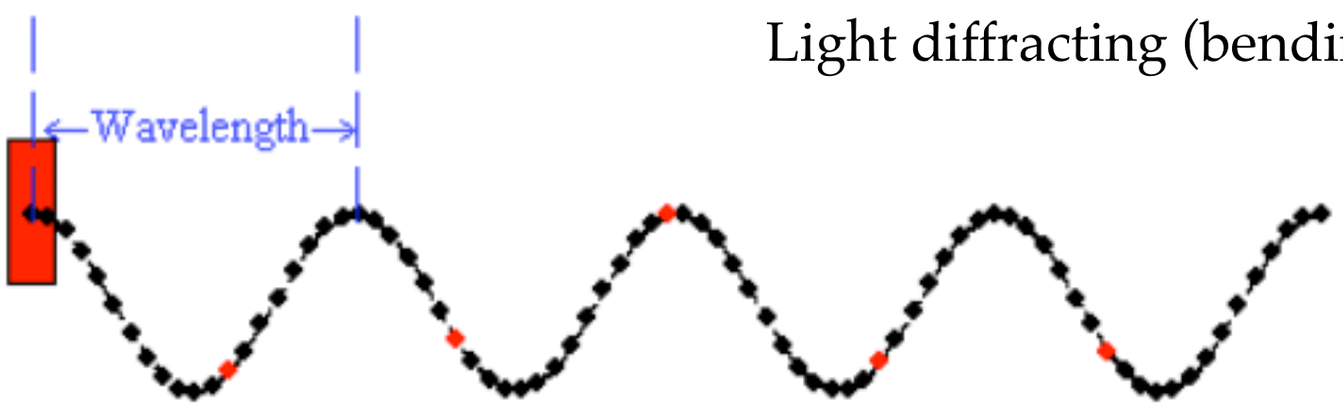



Eclipse duration of one of Jupiter's moons (Io), observed to vary throughout the year on Earth.

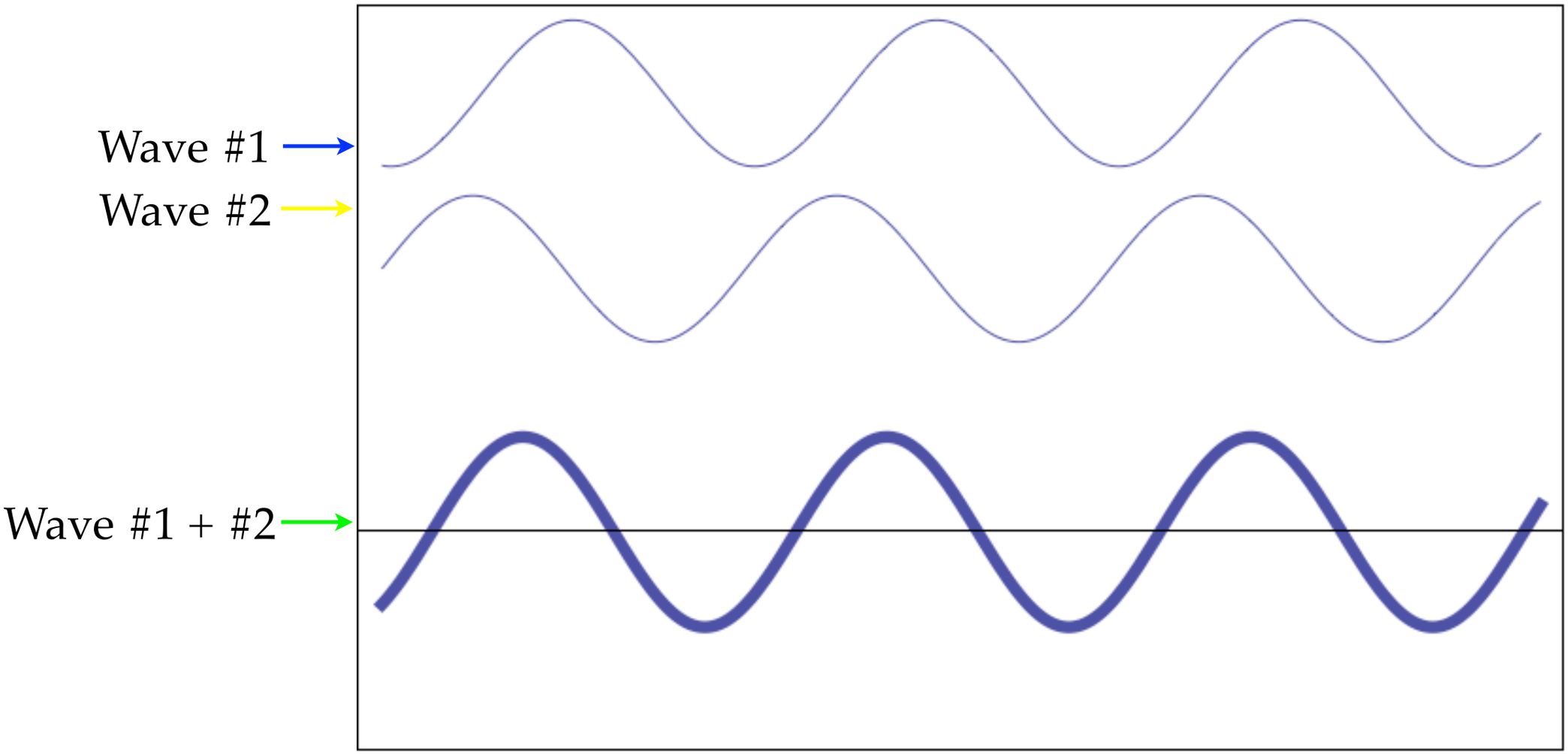
# What we know circa 1900:  Light is a wave.



Light diffracting (bending) through a prism

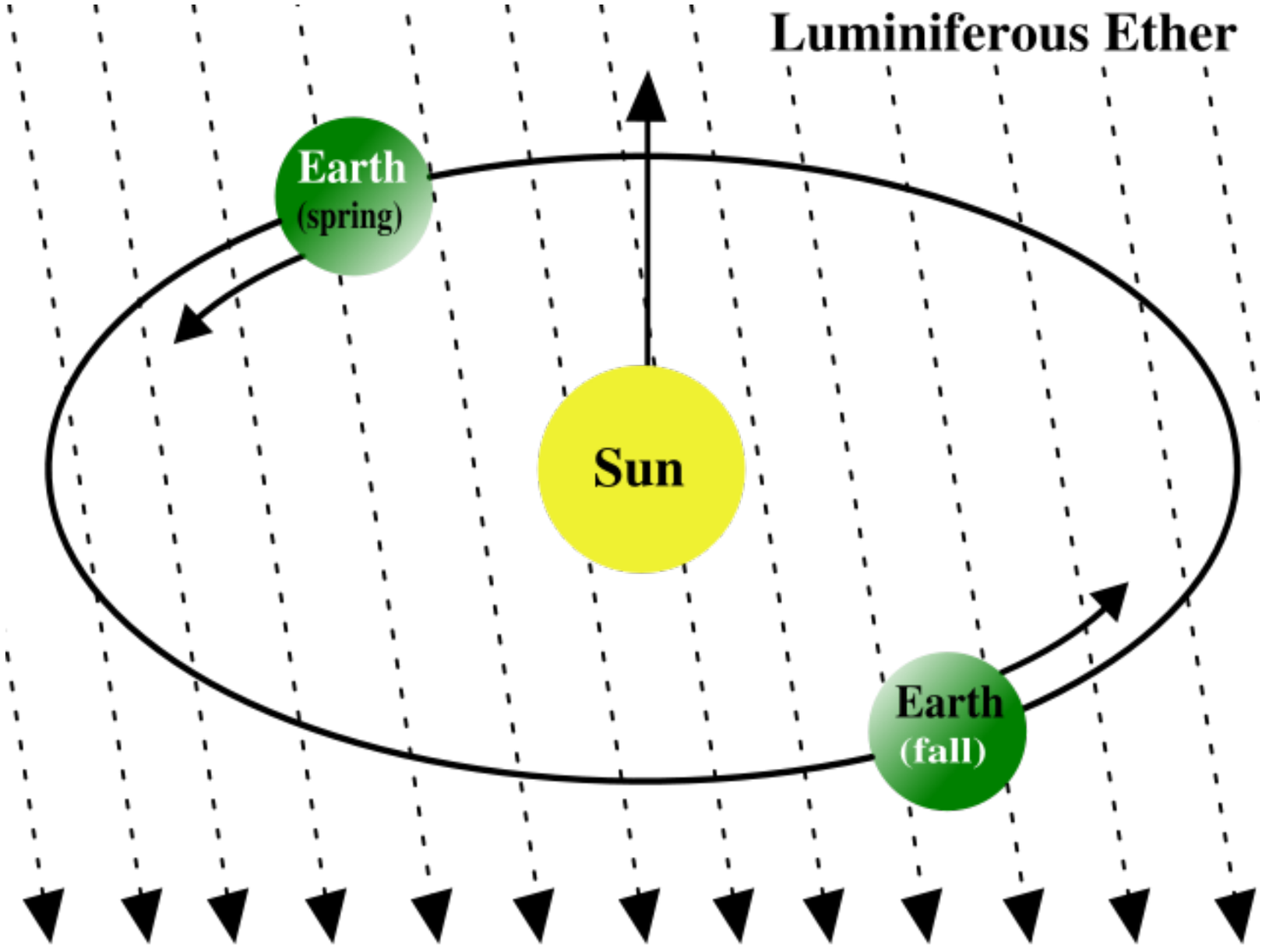


# Waves can Interfere.

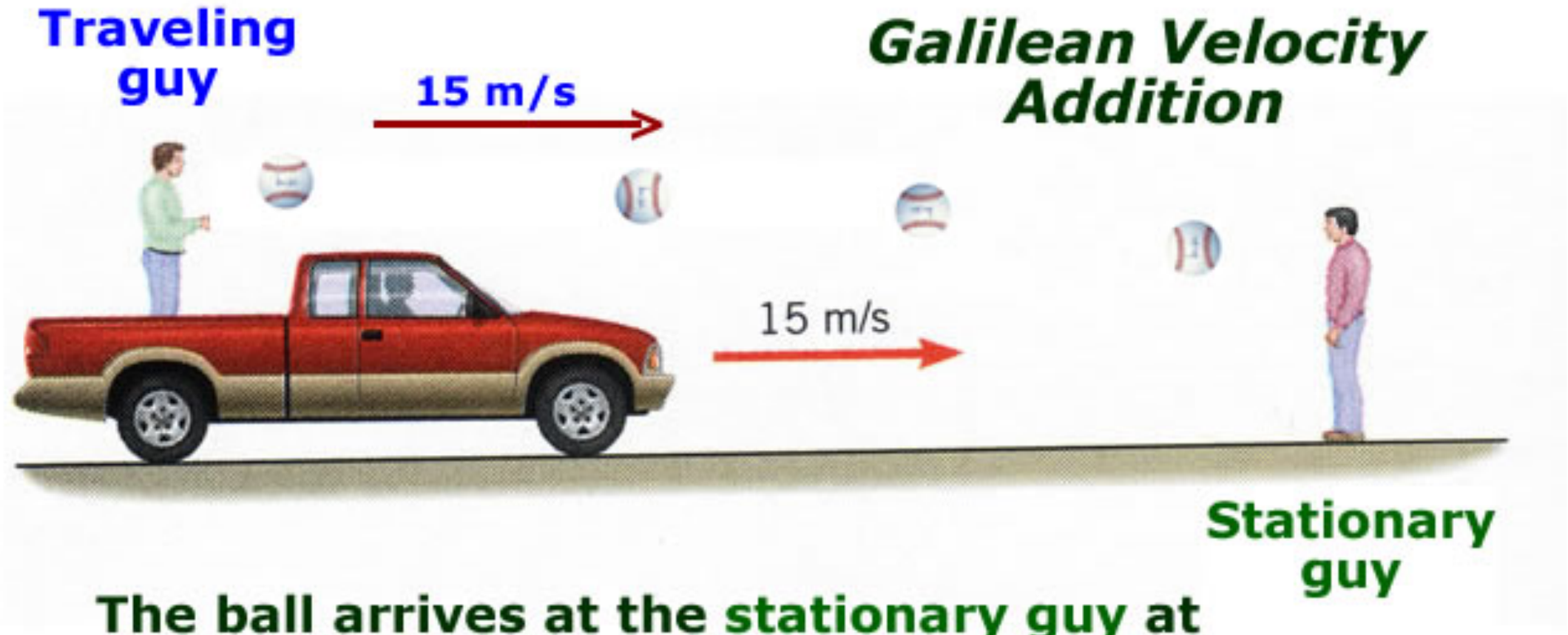



Relative alignment (phase) between waves can create constructive or destructive interference.

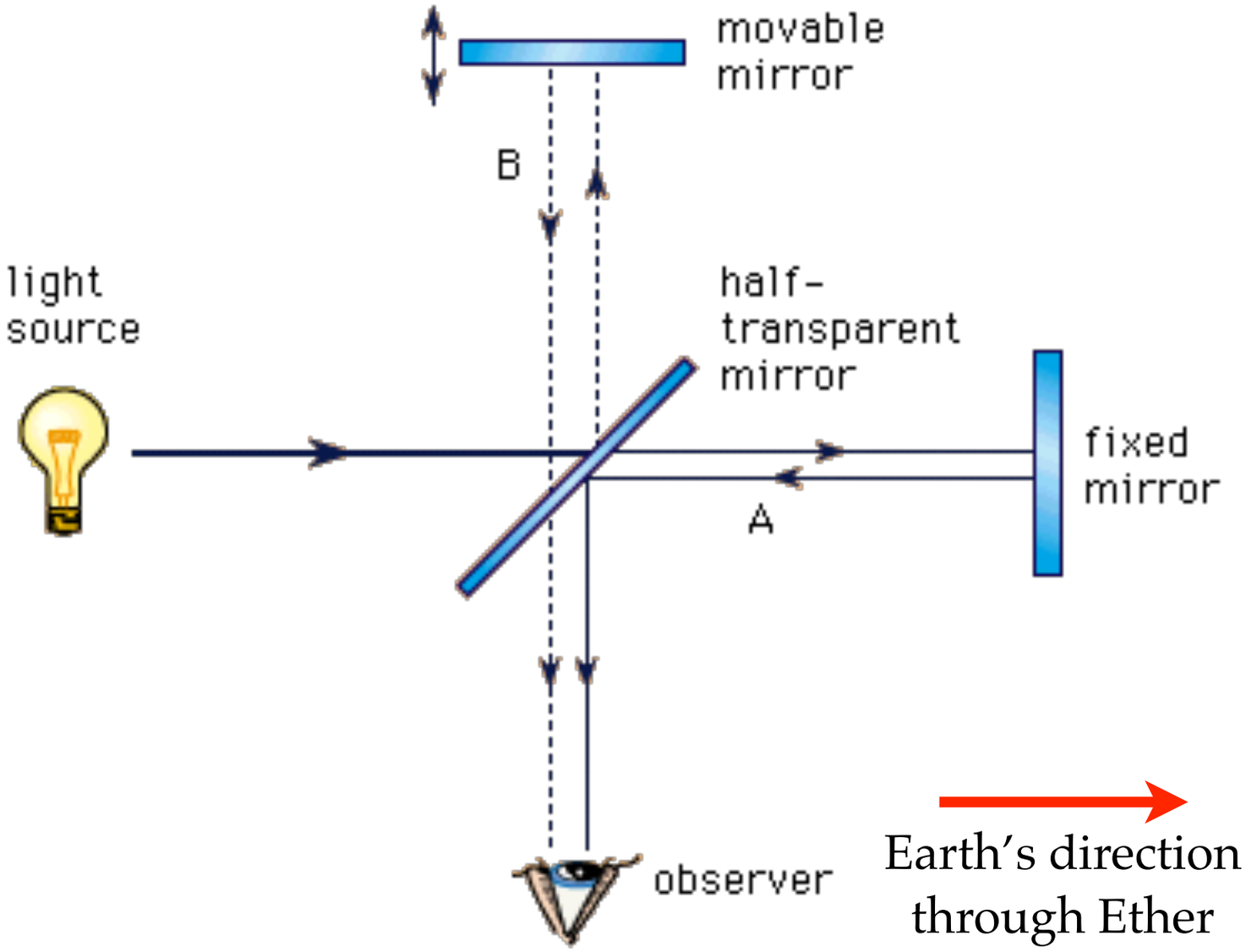
Light waves need something to propagate through -> Luminiferous Ether must pervade space.



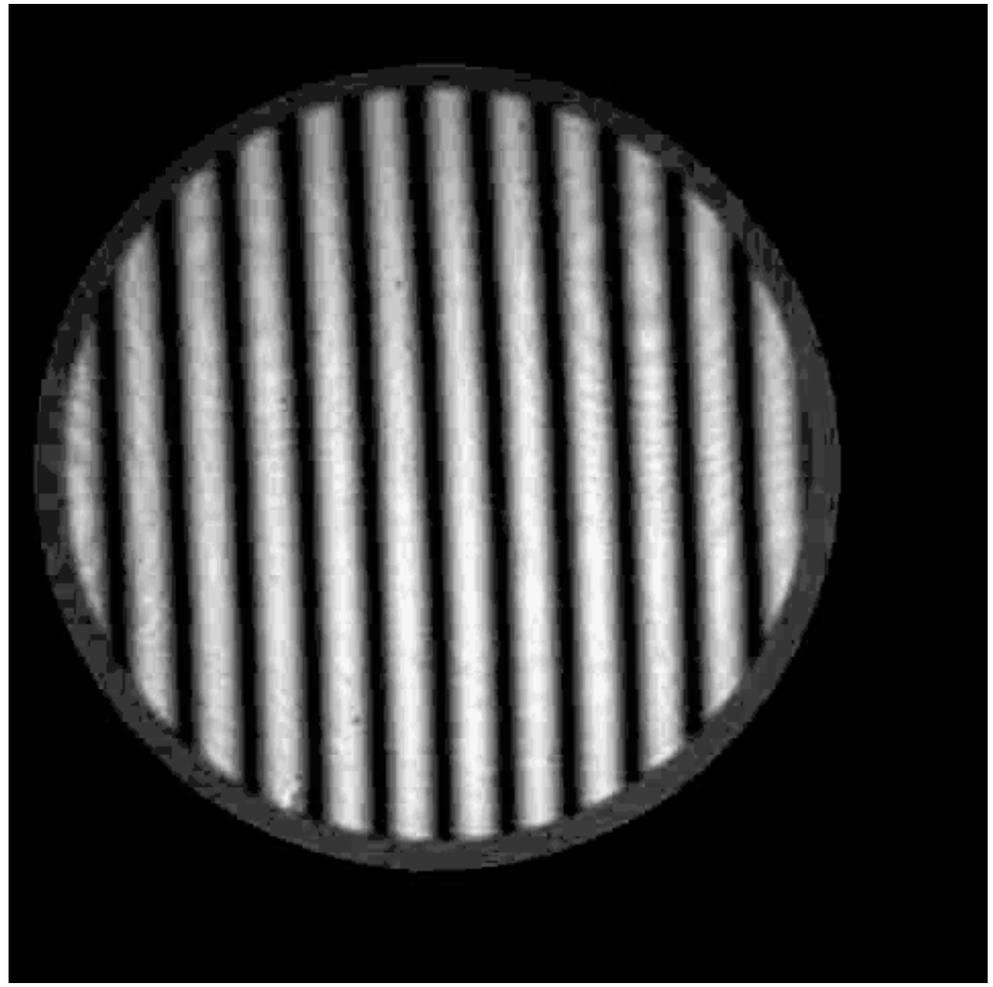
Since Earth is moving through the Ether, we should be able to "detect" the Ether by its influence on light.



# Detecting the Ether: Michelson-Morley Experiment




Earth's direction through Ether



Interference fringes will shift as we rotate apparatus relative to the Ether.

Depending on Earth's motion through the Ether, light in one path should have a little more/less velocity.

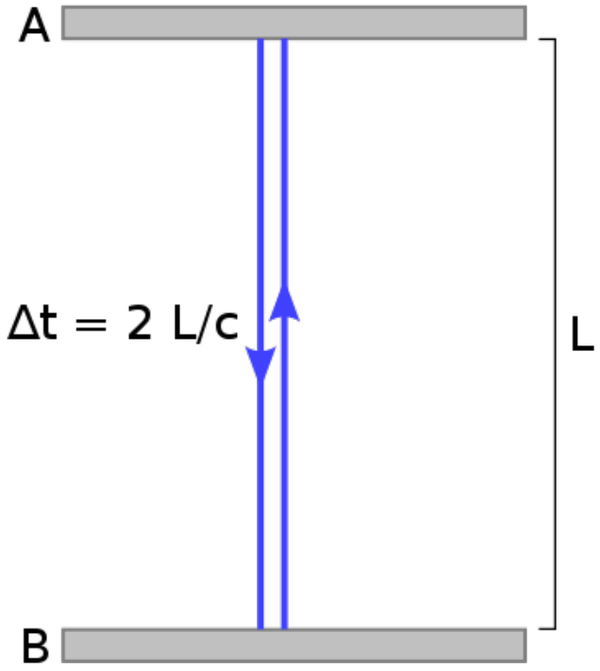
# Einstein: 1905

## Special Relativity Postulates:

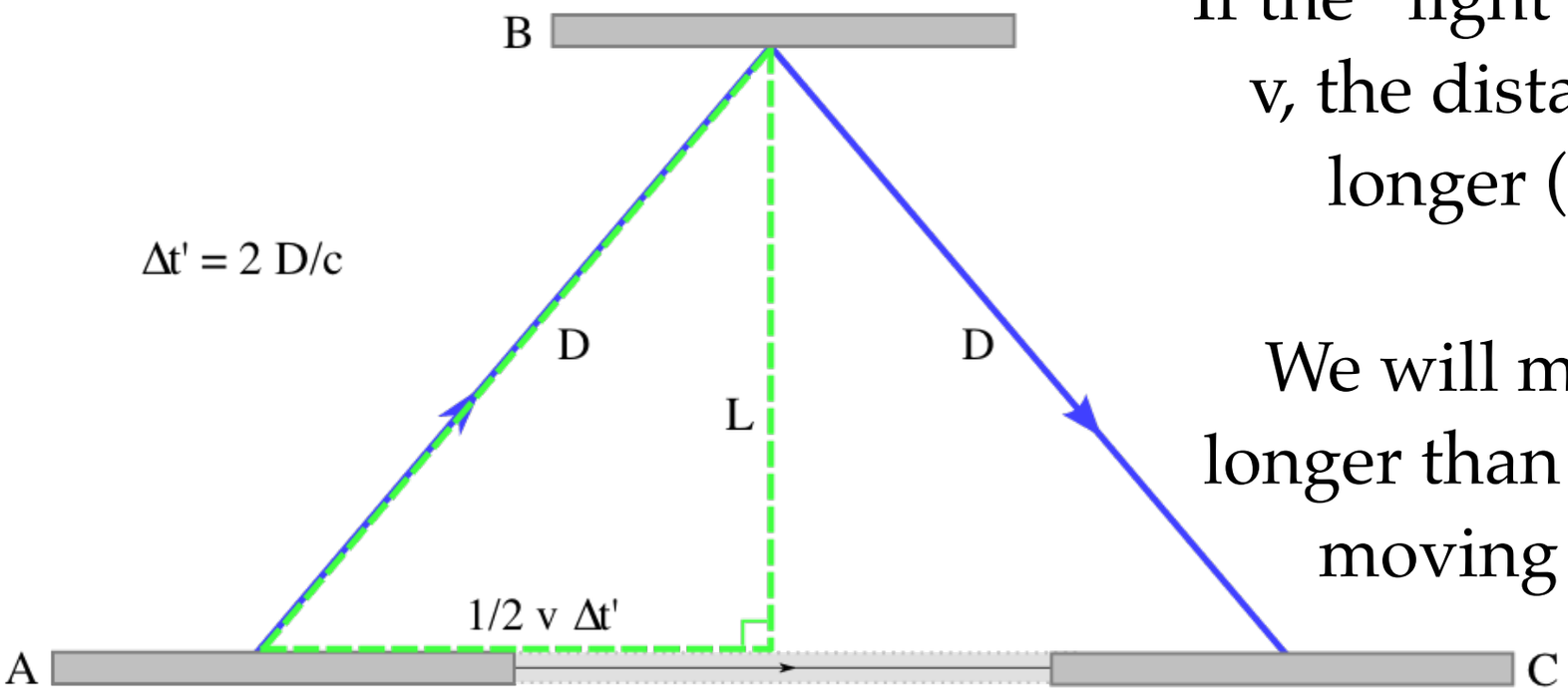
1. Laws of Physics are the same for all observers in **inertial** frames, and no one frame is preferred over others.
2. The speed of light in vacuum has the same value in all **inertial** frames.

Inertial = Non-Accelerating

# Time Dilation




A "light clock" has a beam of light bouncing between two mirrors. Transit time determined by mirror separation (L), and speed of light (c).

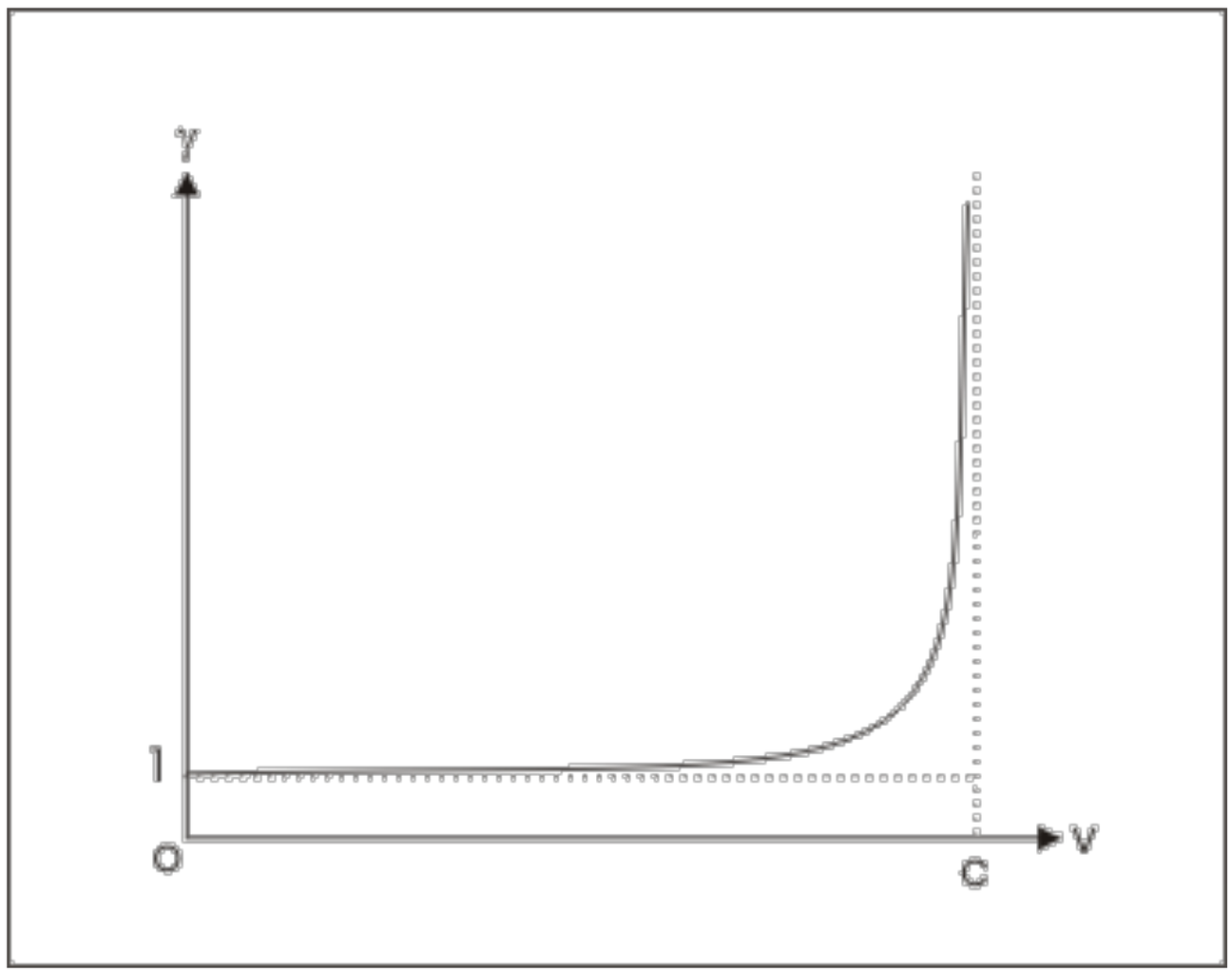



If the "light clock" moves by us at velocity v, the distance it travels in one "tick" is longer (D>L). Since D>L, and c is constant, $\Delta t' > \Delta t$.

We will measure the transit time to be longer than that measured by an observer moving along with the light clock!

**Proper time** = Time interval measured by clock at rest relative to observer.

Proper time related to frame-dependent time by Lorentz factor, $\gamma$




Proper Time

$$\Delta t' = \gamma \cdot \Delta t$$

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

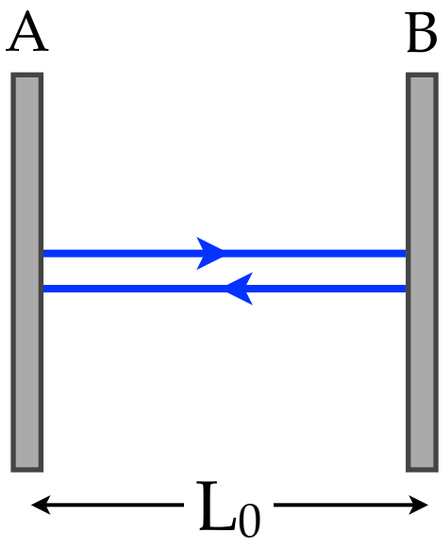
# Time Dilation: Hafele and Keating Experiment (1971)

Synchronized two cesium clocks, then flew one around the world...did it with both directions of travel. Compared resulting time differences to predictions of Relativity (Special+General).

Question: Explain the difference between East and West trips.

| | Predicted | Measured |
|---|---|---|
| Eastward Trip | -40±23 ns | -59±10 ns |
| Westward Trip | 275±21 ns | 273±7 ns |

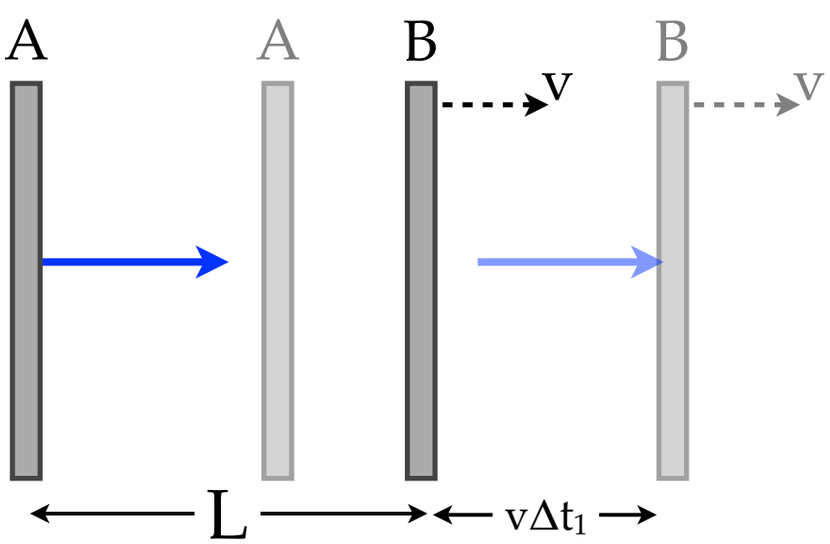
# Length Contraction

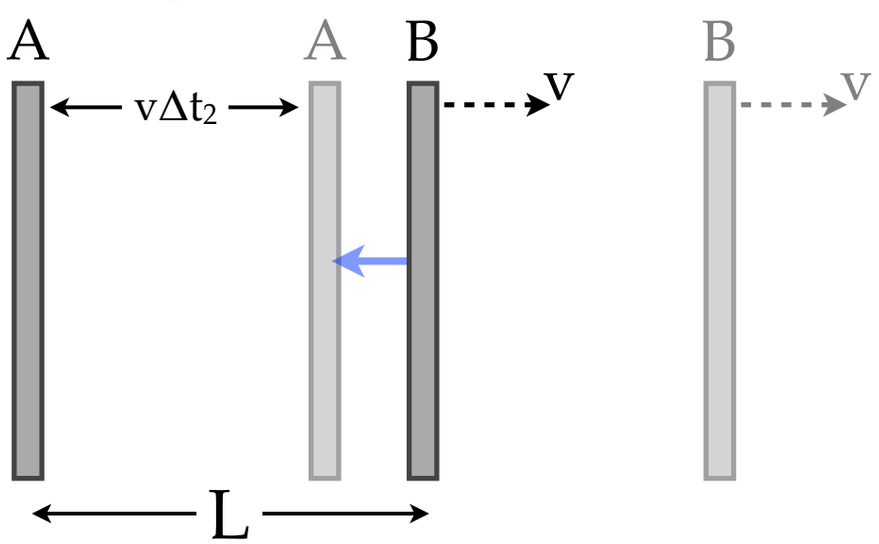



$$\Delta t = 2\frac{L_0}{c}$$

A "light clock" at rest.

A "light clock" moving along direction of light beam.




$d_1 = c\Delta t_1 = L + v\Delta t_1$

$\Delta t_1 = L/(c\text{-}v)$

$d_2 = c\Delta t_2 = L - v\Delta t_2$

$\Delta t_2 = L/(c+v)$

$$\Delta t' = \Delta t_1 + \Delta t_2 = \frac{L}{c-v} + \frac{L}{c+v}$$

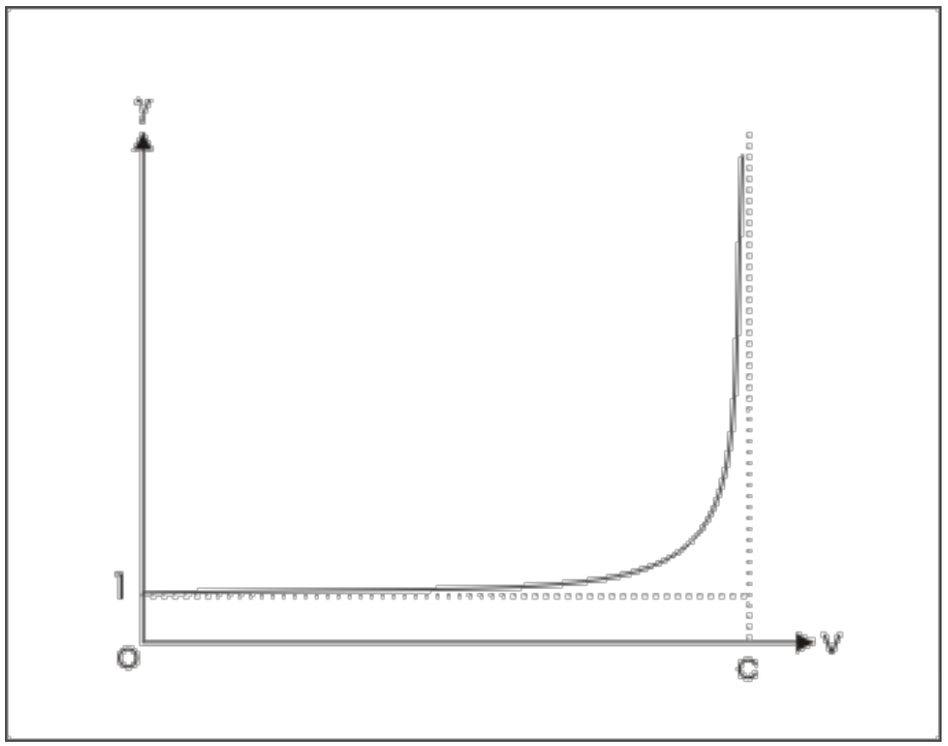
**Proper length** = Distance between two events, as measured in frame in which events are simultaneous.

$$\Delta t' = \gamma \cdot \Delta t$$

$$\Delta t' = \Delta t_1 + \Delta t_2 = \frac{L}{c-v} + \frac{L}{c+v}$$

$$\Delta t = 2\frac{L_0}{c}$$

**HW Problem**:
Show that combining these equations yields length contraction formula.



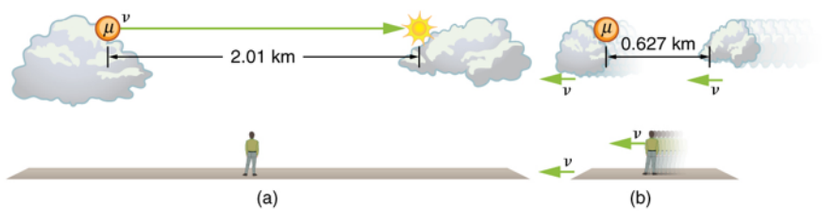

Proper Length

$$L = \frac{L_0}{\gamma}$$

$L \leq L_0$ since $\gamma \geq 1$

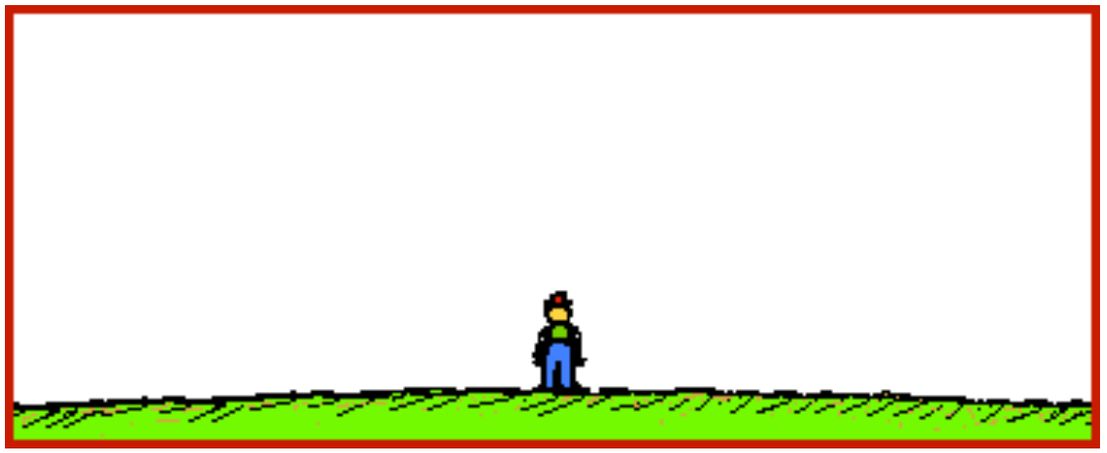
Consider a Rocket Ship at Rest:

$L_0$=200ft

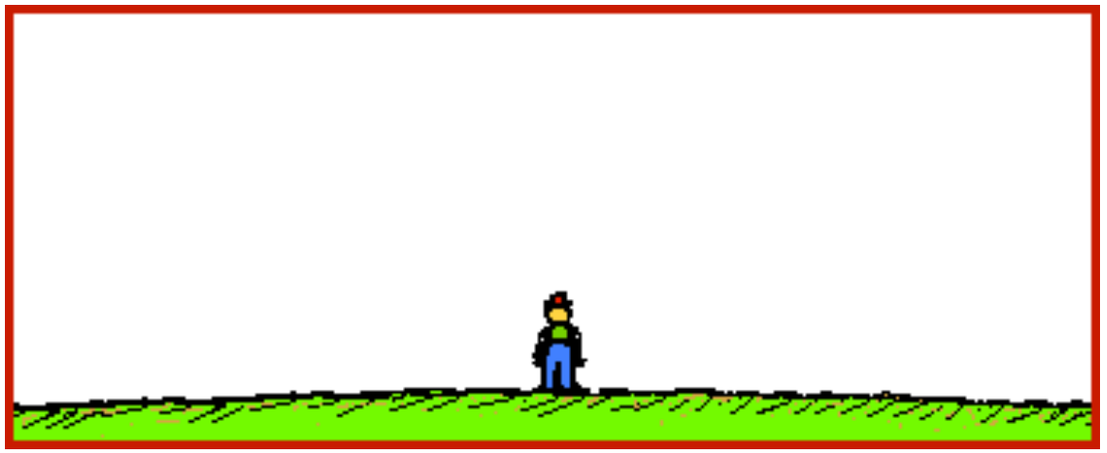



Related HW Problem: How do muons, with lifetime of 2.2$\mu$s, produced in the upper atmosphere ever reach the Earth's surface?

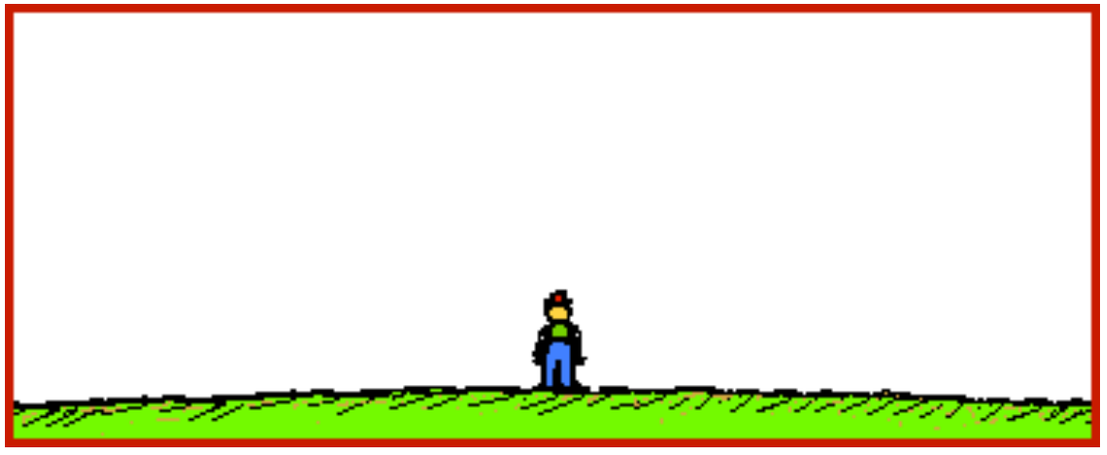
10% Speed of Light
L=199ft



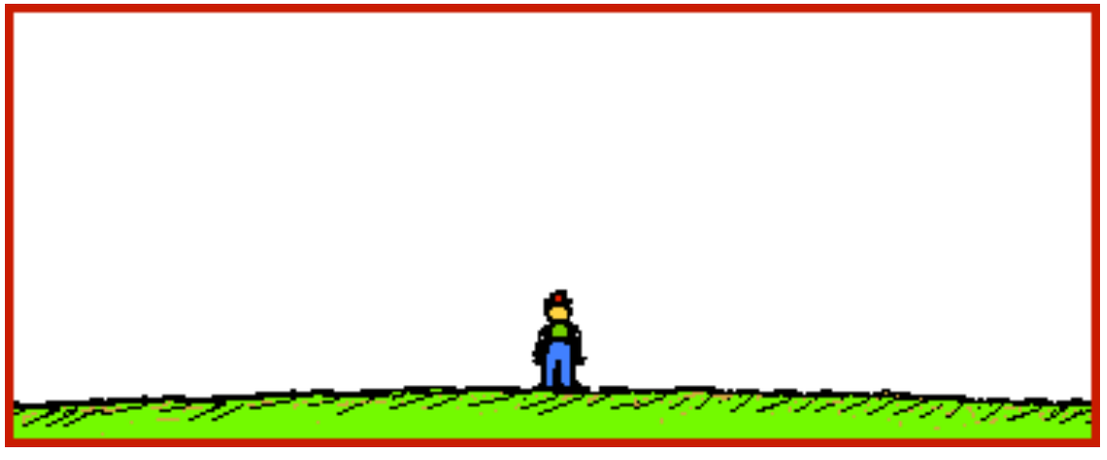
86.5% Speed of Light
L=100ft



99% Speed of Light
L=28ft

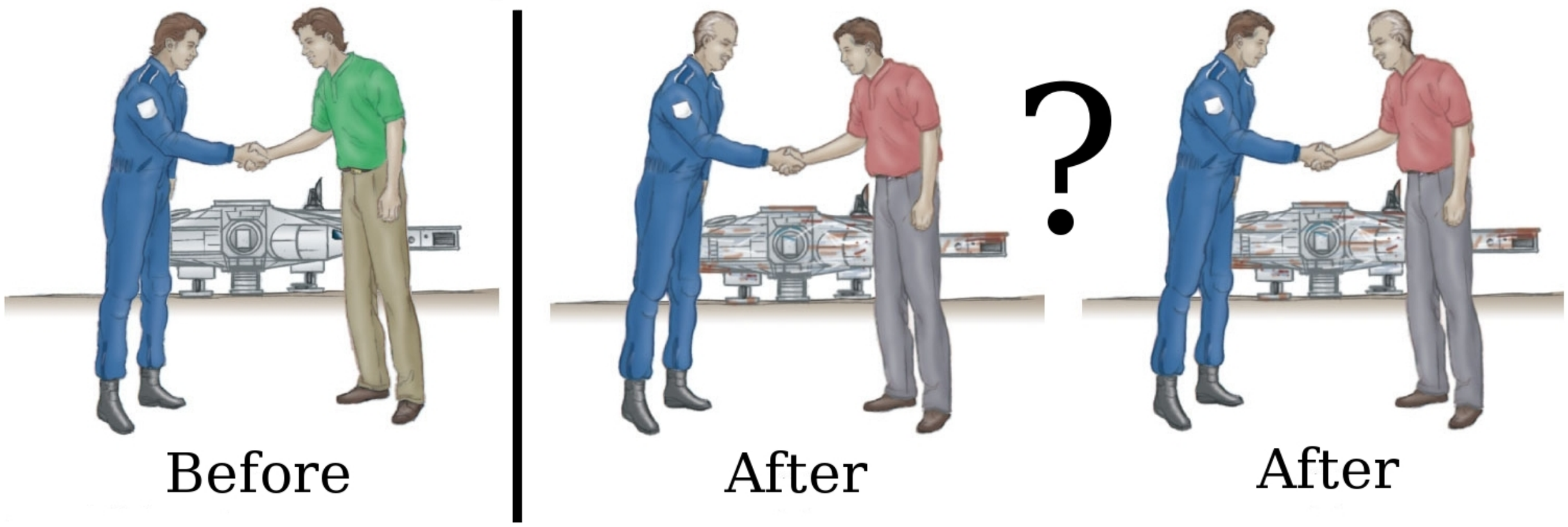


99.99% Speed of Light
L=3ft



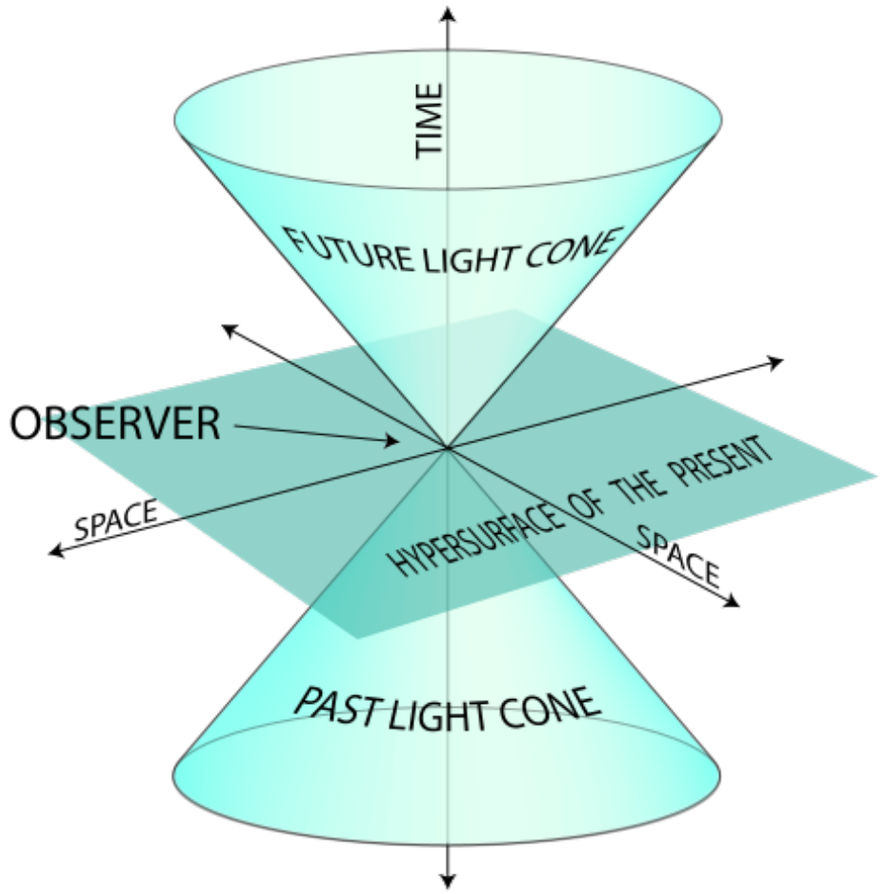
# Does Relativity Create Paradoxes?

One twin enters a windowless rocket ship for a round trip to a distant planet, another stays on Earth. Years later, the two reconvene. Who is older if they both claim they are the one who was stationary while the other travelled?



# SpaceTime

- Space and time can no longer be considered separate. **No absolute space or time.**
- Sequence of events is a function of your reference frame.
- Observers in different inertial frames will not necessarily agree on event locations/times/energies/momentums.
- We use a new metric (Minkowski) for defining measurements that observers in different frames can make, and transformations (Lorentz) between frames so information can be compared.




$$c^2t_1^2 - x_1^2 - y_1^2 - z_1^2 = c^2t_2^2 - x_2^2 - y_2^2 - z_2^2$$

# Equivalence of Mass and Energy


Question: Why can't massive objects travel at the speed of light?

Perhaps the most famous product of Special relativity is the simple relation between energy and mass, which indicates mass and energy are interchangeable.

"*E*" stands for **total energy** of object with relativistic mass, *m*, and rest mass $m_0$.

$$E = mc^2 = \gamma m_0 c^2$$

# Then Don't Massless Particles Have Zero Energy?

**Need to be very careful**...what happens to $\gamma$ for massless particles?


$$p = \gamma m_0 v$$

$$\downarrow$$

$$p \times \sqrt{1 - \frac{v^2}{c^2}} = m_0 v = 0 \quad \text{For massless particles}$$

$$\downarrow$$

$$v = c$$

$$\downarrow$$

$$\gamma = \infty$$

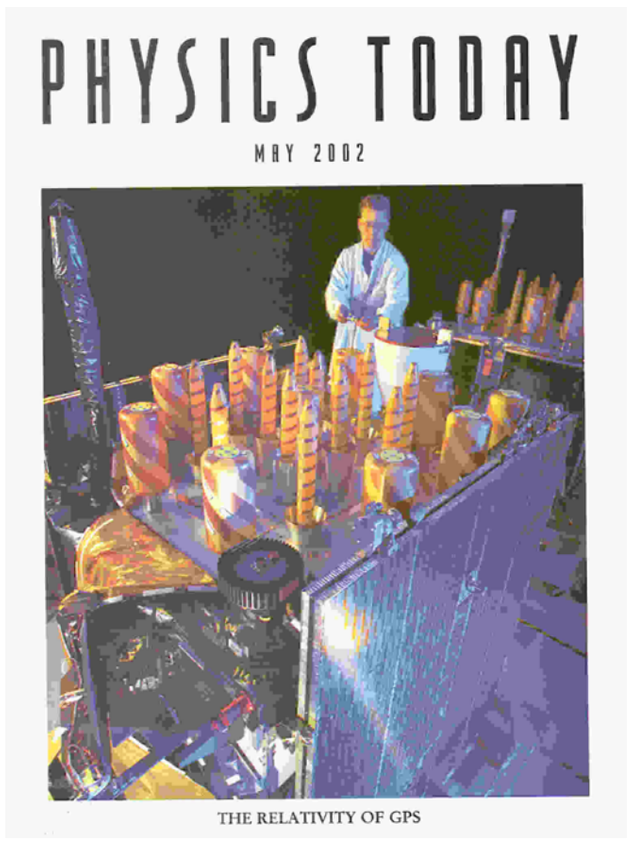
We can show (using invariance of Energy-Momentum "4-vector"), that total energy is also given by:

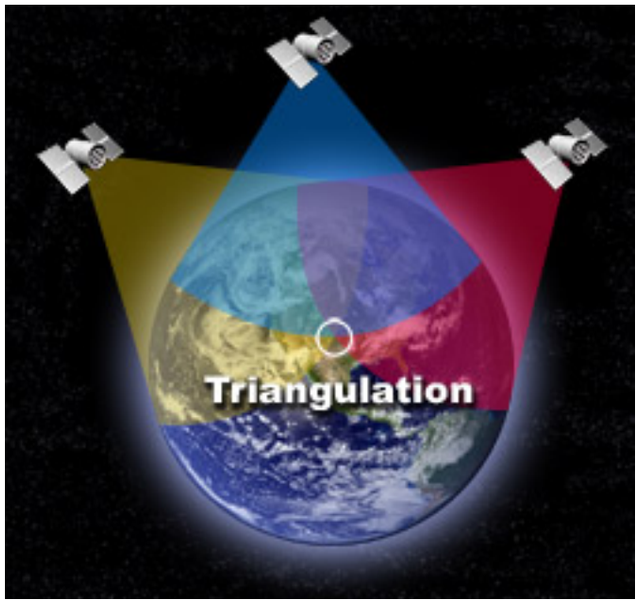
$$E = \sqrt{p^2 c^2 + m_0^2 c^4}$$

$$E = pc \quad \longleftarrow \text{Energy of massless particle}$$

# Applications: GPS

- GPS satellite sends out timestamped signal.
- GPS receiver gets that signal, and calculates how far away satellite is based on transit time.
- 3 Satellites is enough to determine position on surface of Earth...4th gives you altitude.
- Relativistic effects need to be included to get precise coordinates.



# Relevance: Nuclear Power & Weapons

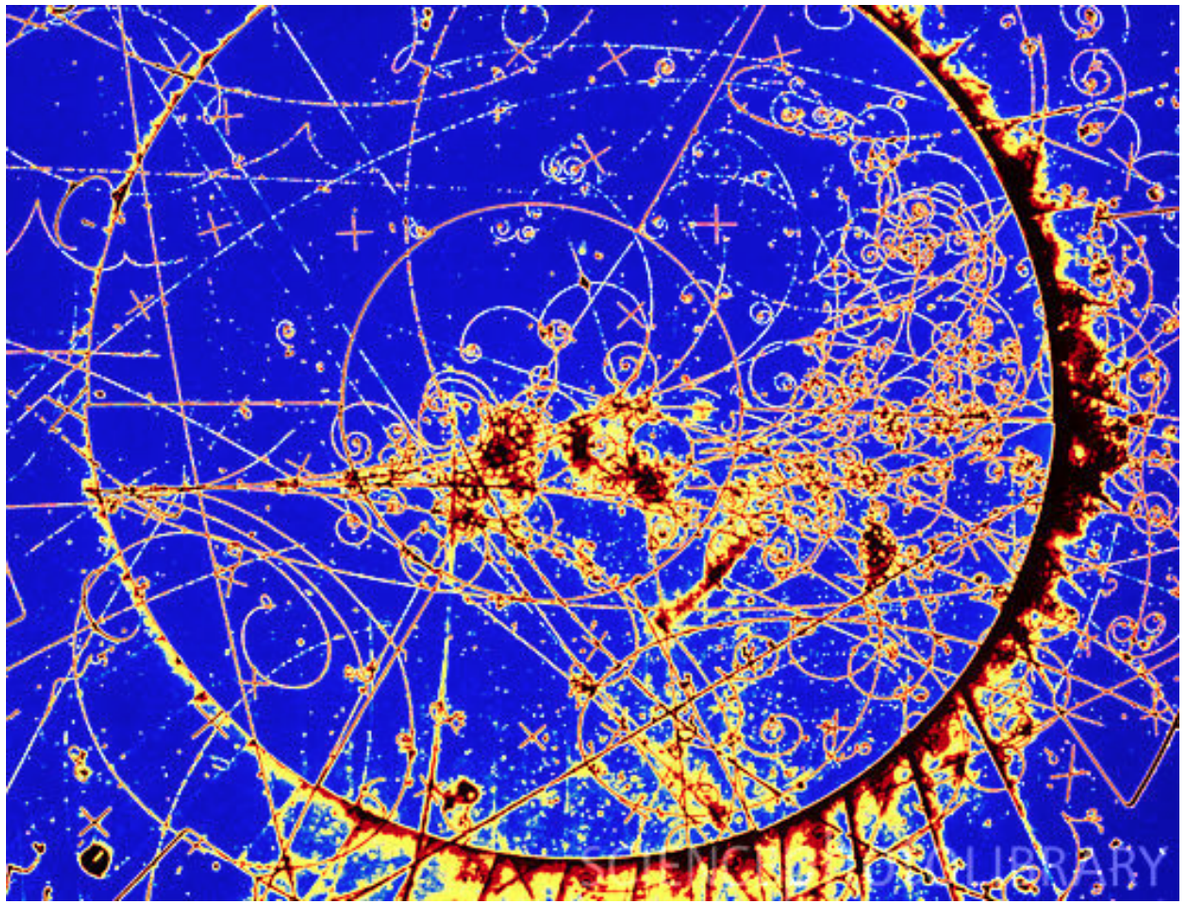
- $E=mc^2$ equation tells us there is an enormous amount of energy stored within the nuclei of atoms.

Hydrogen Bomb Explosion

Nine Mile Point Reactor in Oswego

# Relativity and High Energy Physics

We routinely accelerate particles to 99.9999...% the speed of light, so relativistic corrections are inherent in timing of accelerators.



The equivalence of mass and energies allows transformations, such as turning the energy of a light particle into the mass of a heavier particle.

# Faster than Light?


Published online 22 September 2011 | Nature | doi:10.1038/news.2011.554
**Updated** online: 23 September 2011

News

## Particles break light-speed limit

**Neutrino results challenge cornerstone of modern physics.**

**Geoff Brumfiel**

An Italian experiment has unveiled evidence that fundamental particles known as neutrinos can travel faster than light. Other researchers are cautious about the result, but if it stands further scrutiny, the finding would overturn the most fundamental rule of modern physics — that nothing travels faster than 299,792,458 metres per second.

Has OPERA found super-speedy neutrinos? *CERN*

The experiment is called OPERA (Oscillation Project with Emulsion-tRacking Apparatus), and lies 1,400 metres underground in the Gran Sasso National Laboratory in Italy. It is designed to study a beam of neutrinos coming from CERN, Europe's premier high-energy physics laboratory located 730 kilometres away near Geneva, Switzerland. Neutrinos are fundamental particles that are electrically neutral, rarely interact with other matter, and have a vanishingly small mass. But they are all around us — the Sun produces so many neutrinos as a by-product of nuclear reactions that many billions pass through your eye every second.

The 1,800-tonne OPERA detector is a complex array of electronics and photographic emulsion plates, but the new result is simple — the neutrinos are arriving 60 nanoseconds faster than the speed of light allows. "We are shocked," says Antonio Ereditato, a physicist at the University of Bern in Switzerland and OPERA's spokesman.

## Flaws found in faster-than-light neutrino measurement

**Two possible sources of error uncovered.**

**Eugenie Samuel Reich**

22 February 2012

The OPERA collaboration, which made headlines in September with the revolutionary claim that it had clocked neutrinos travelling faster than the speed of light, has identified two possible sources of error in its experiment. If true, its initial result would have violated Einstein's special theory of relativity, a cornerstone of modern physics.

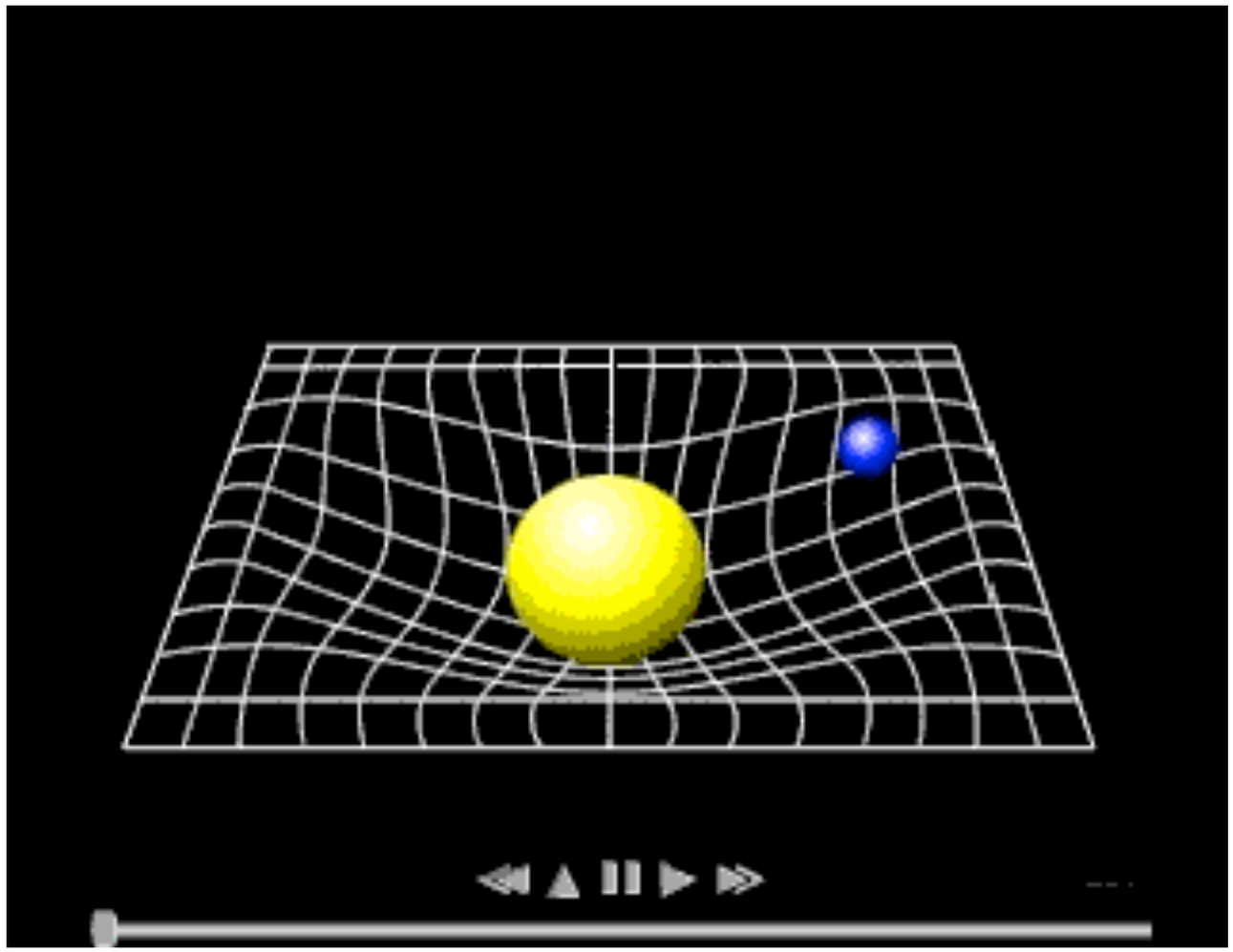
A possible faulty connection in the OPERA experiment may account for neutrinos appearing to travel faster than light.

*CERN*

OPERA had collected data suggesting that neutrinos generated at CERN near Geneva in Switzerland and sent 730 kilometres to its detector at Gran Sasso National Laboratory in Italy were arriving 60 nanoseconds faster than a light beam would take to travel the same distance. Many physicists were sceptical, but the measurement seemed to have been done carefully and reached a statistically significant level.

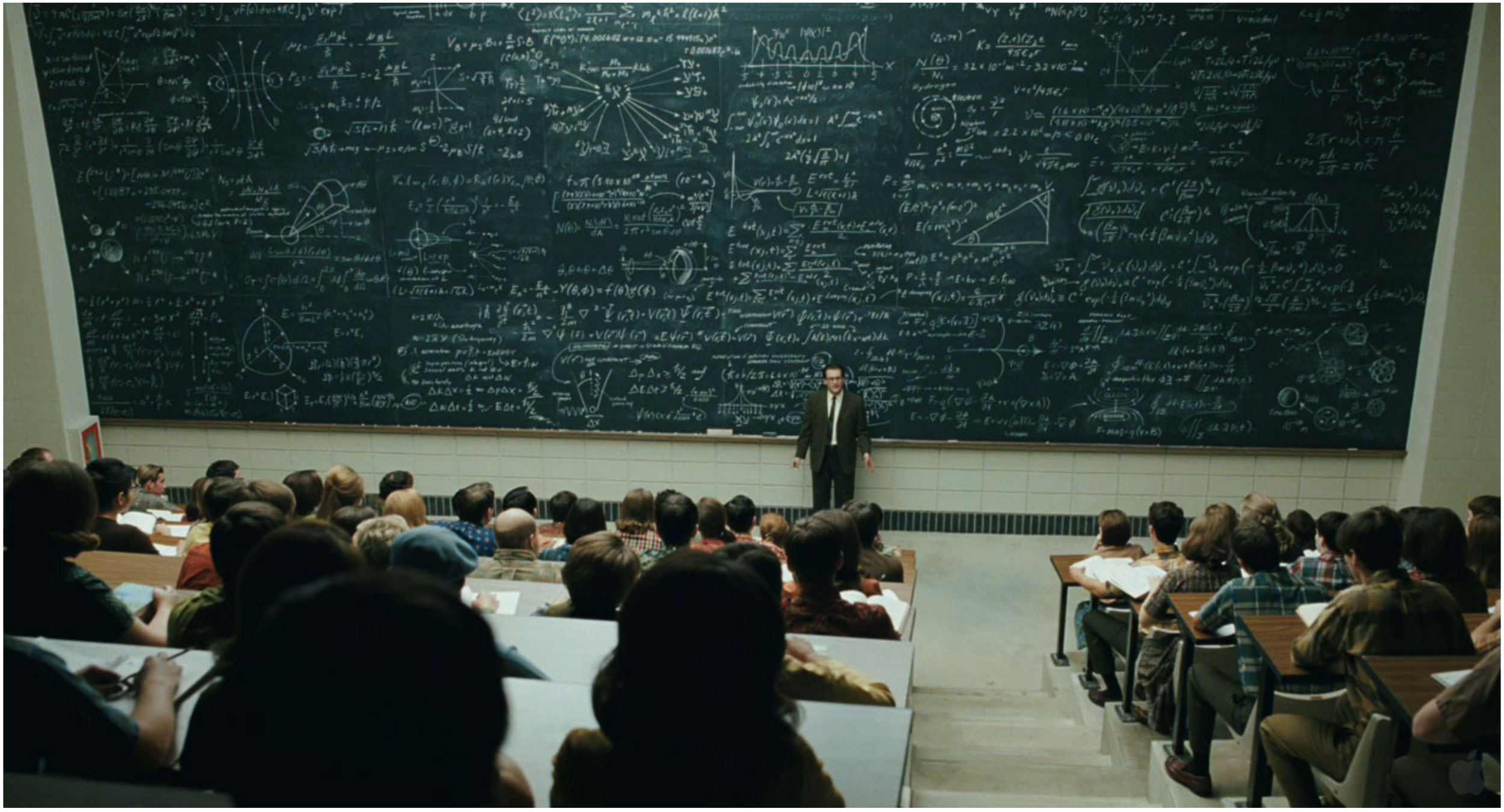
But according to a statement OPERA began circulating today, two possible problems have now been found with its set-up. As many physicists had speculated might be the case, both are related to the experiment's pioneering use of Global Positioning System (GPS) signals to synchronize atomic clocks at each end of its neutrino beam. First, the passage of time on the clocks between the arrival of the synchronizing signal has to be interpolated and OPERA now says this may not have been done correctly. Second, there was a possible faulty connection between the GPS signal and the OPERA master clock.

# General Relativity



Special relativity is applicable for inertial frames...General Relativity includes non-inertial frames.

Many consequences...interplay of mass and space.



# Questions?