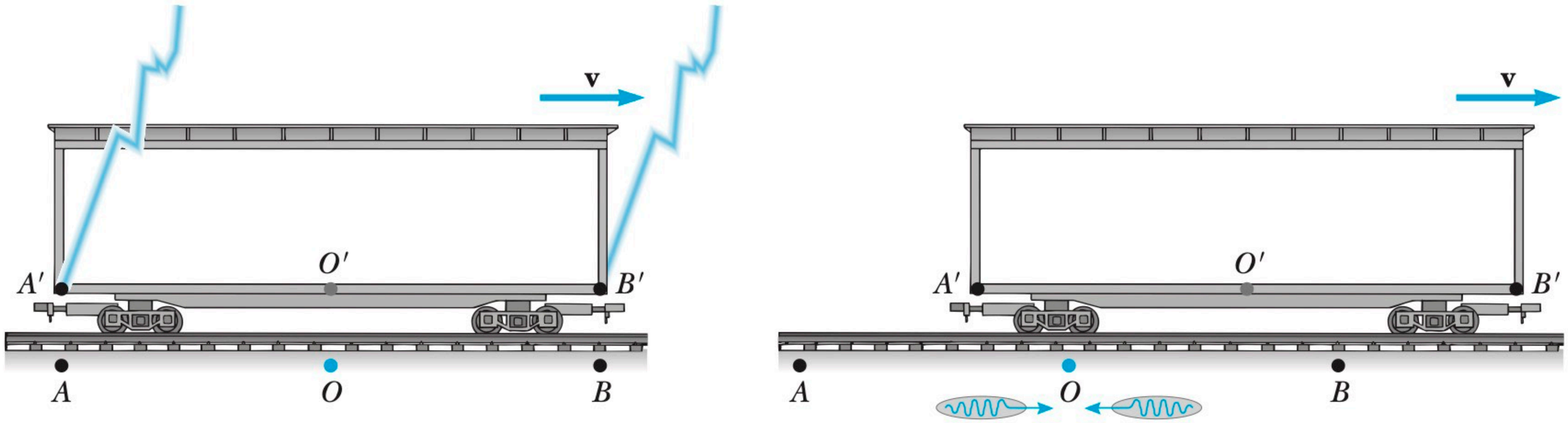
Simultaneity and the relativity of time

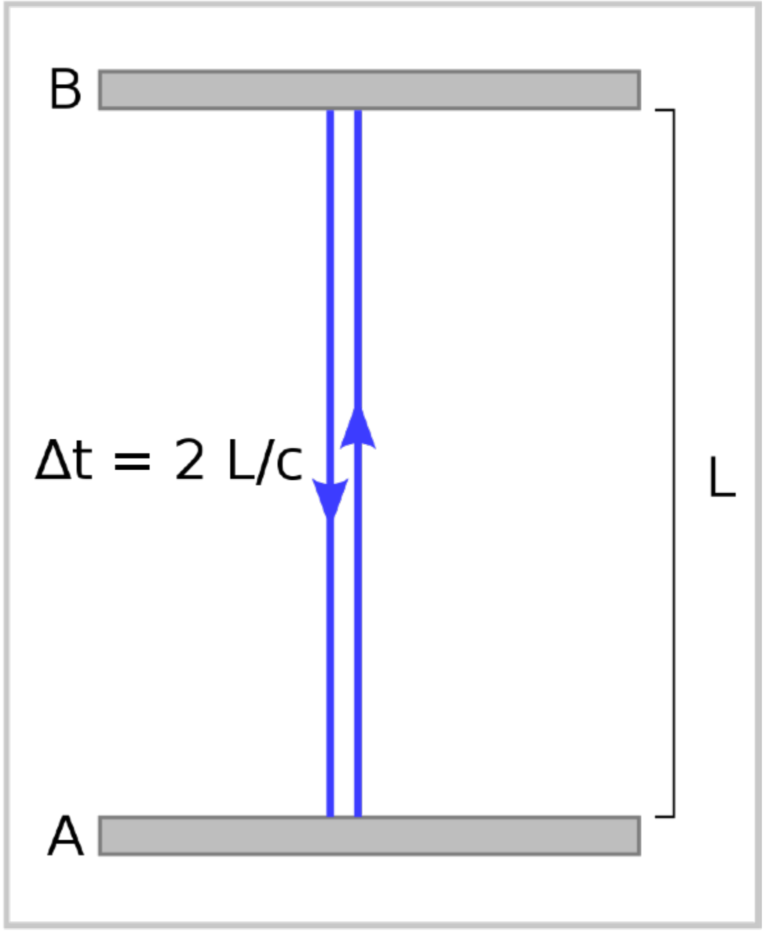


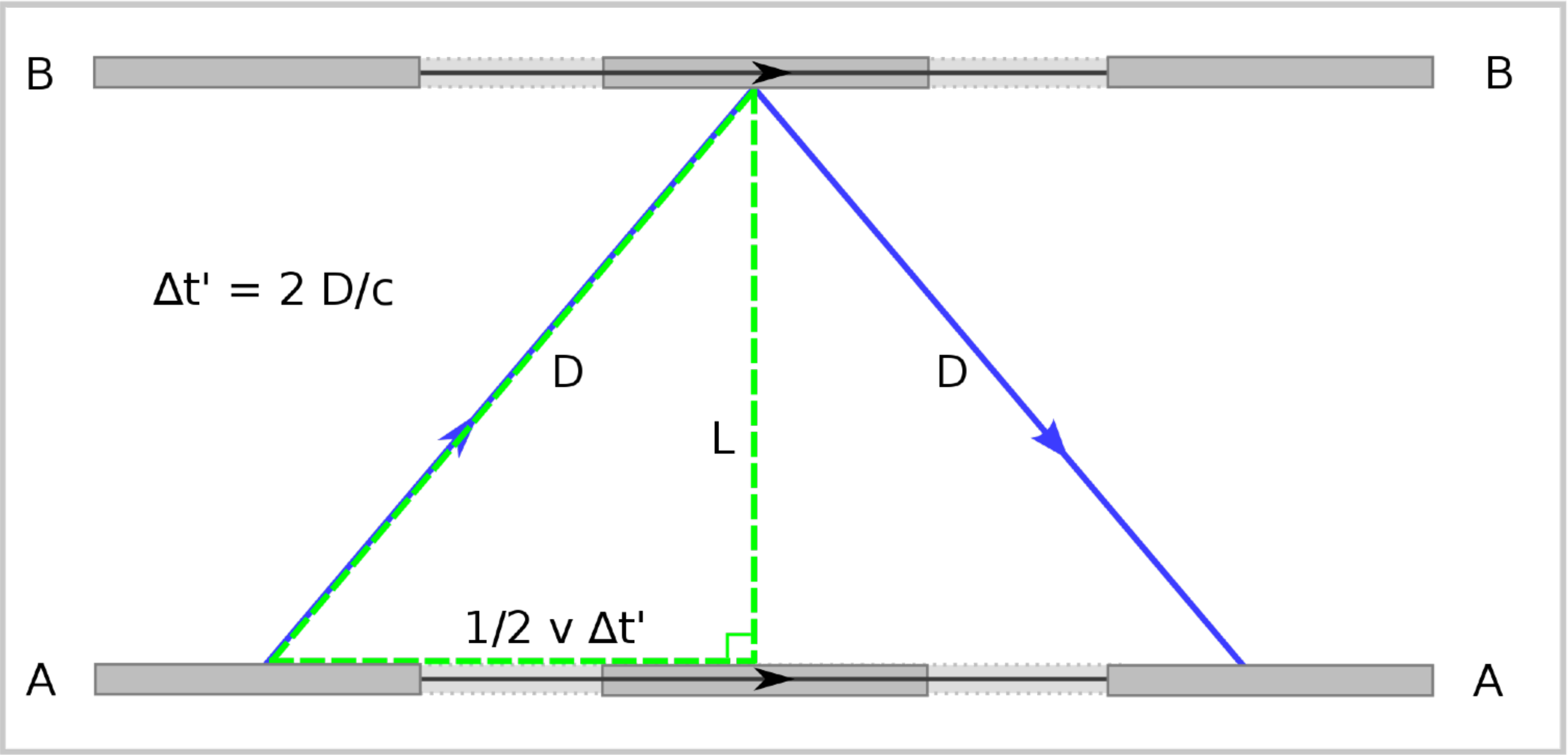
Two events that are simultaneous in one frame are in general not simultaneous in a second frame moving with respect to the first. That is, simultaneity is not an absolute concept, but one that depends on the state of motion of the observer.

Time dilation

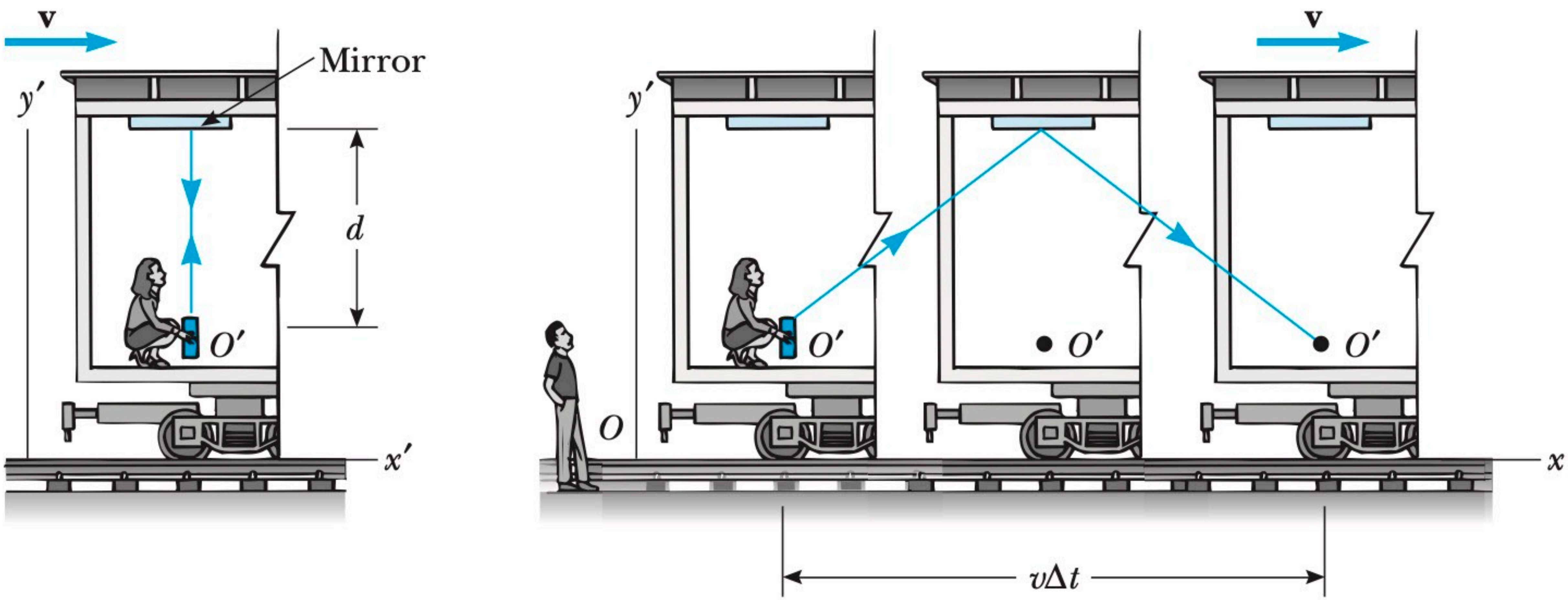
Observer at rest

Observer is moving to the left

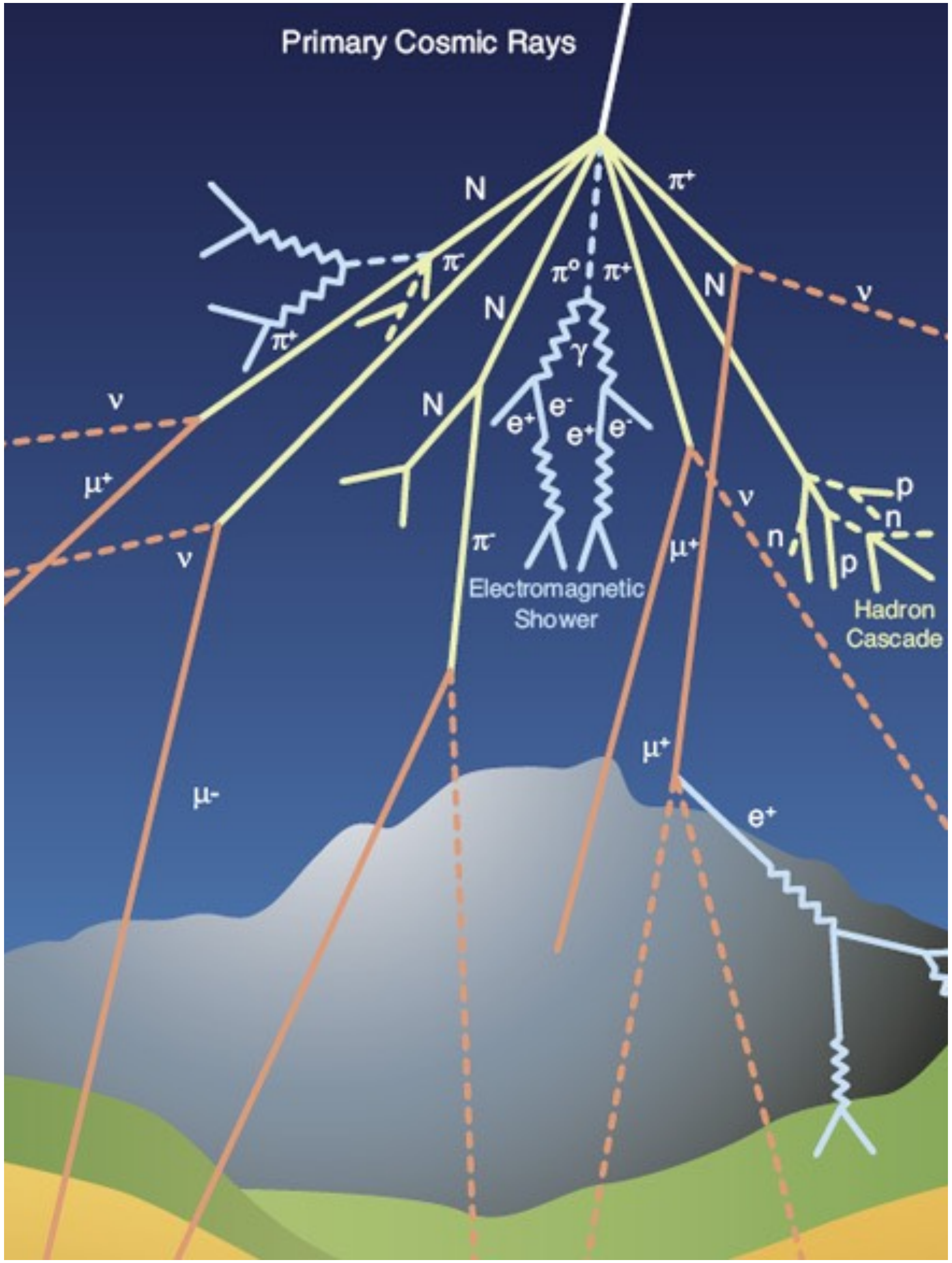




Time dilation: Which clock are we talking about?

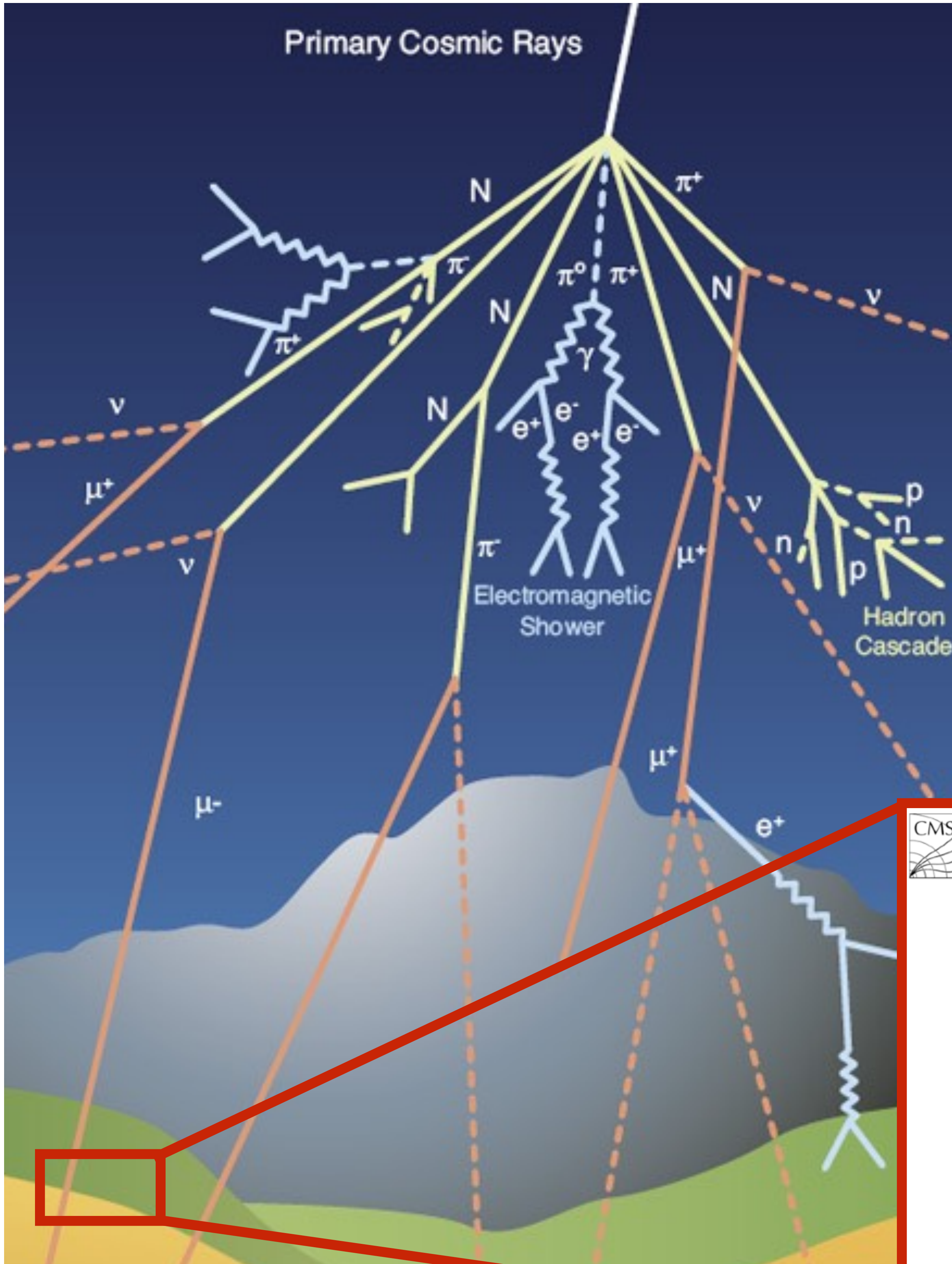


Muons

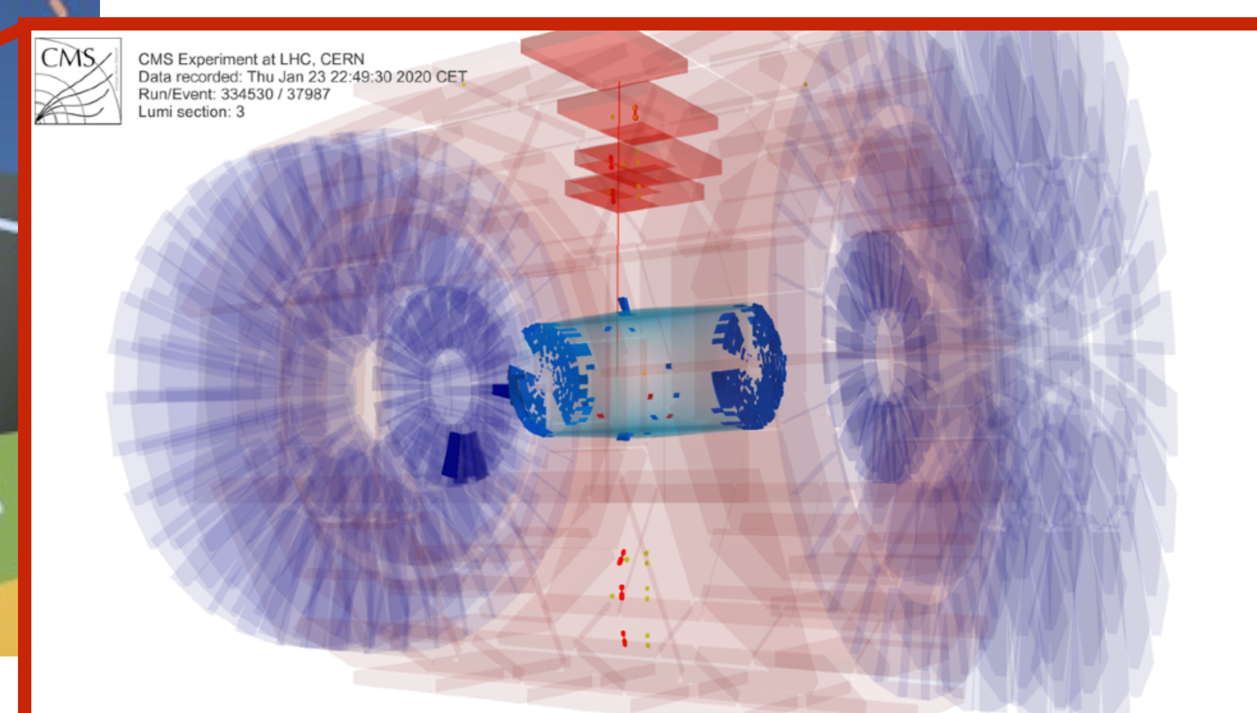


- Unstable elementary particles that have a charge equal to that of an electron and a mass 207 times that of the electron.
- Produced by the collision of cosmic radiation with atoms at a height of several thousand meters above the surface of the Earth
- A lifetime of only 2.2 μs when measured in a reference frame at rest with respect to them.

Muons

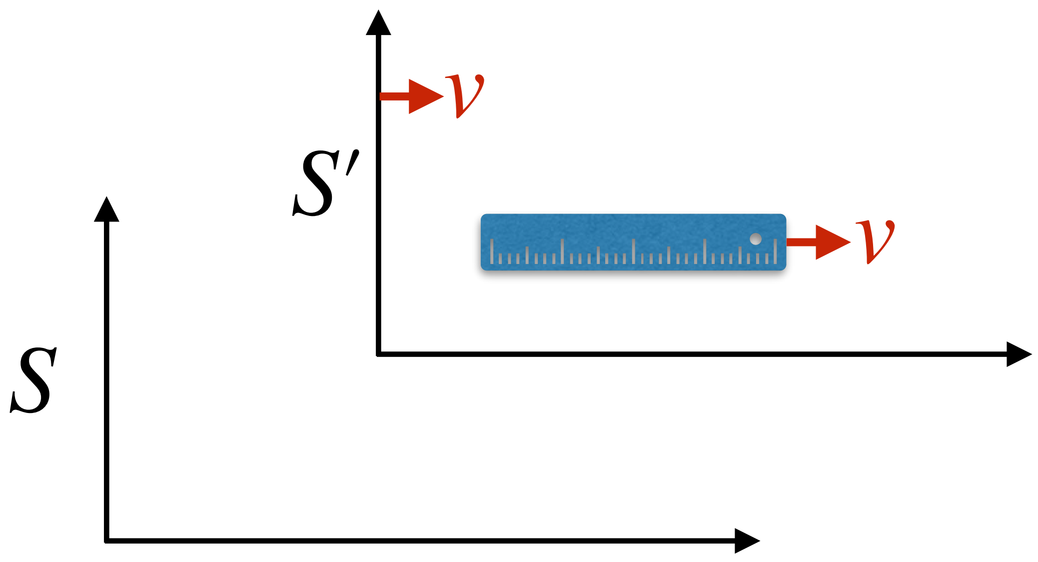


However, we can detect muon on Earth, e.g. 100 m underground at the CMS experiment at CERN. **How?**

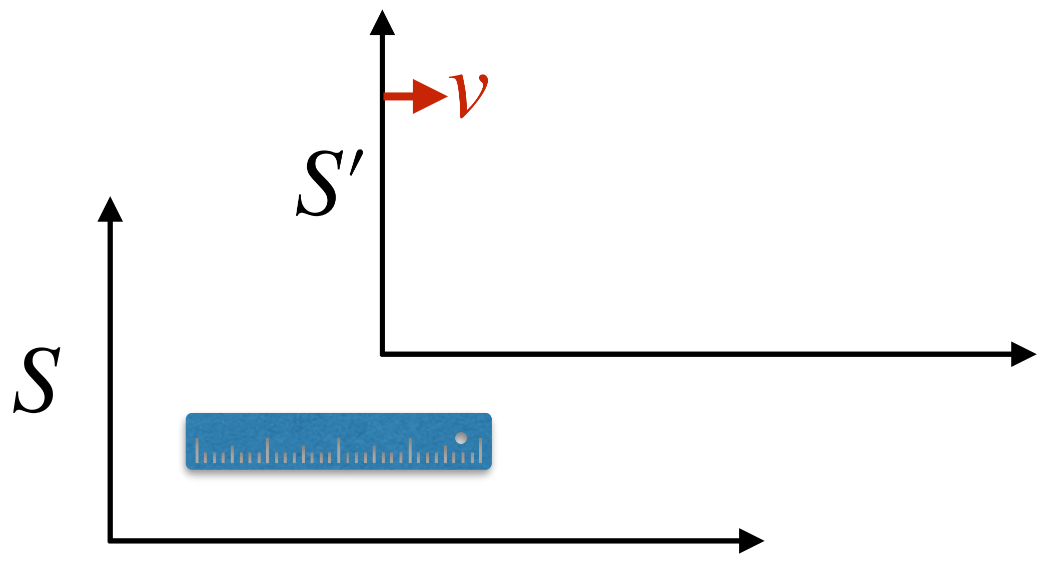


Length contraction

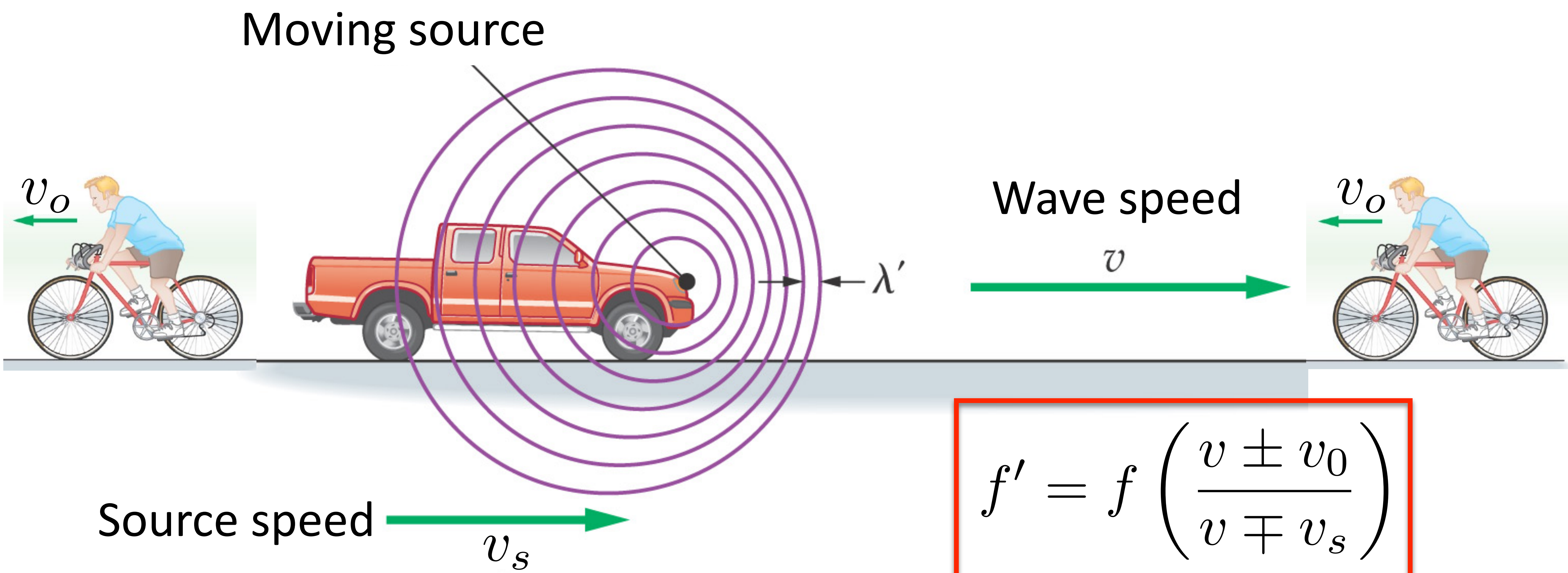
length in S' is known



length in S is known



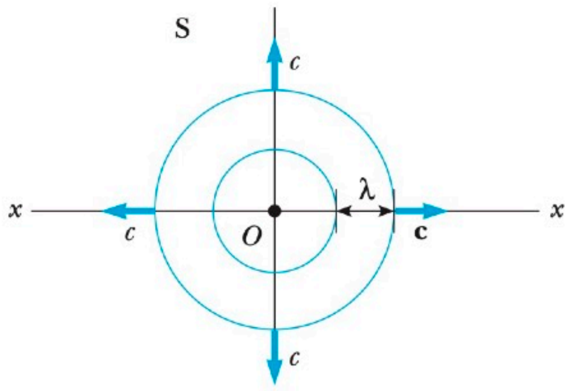
Review: Doppler effect



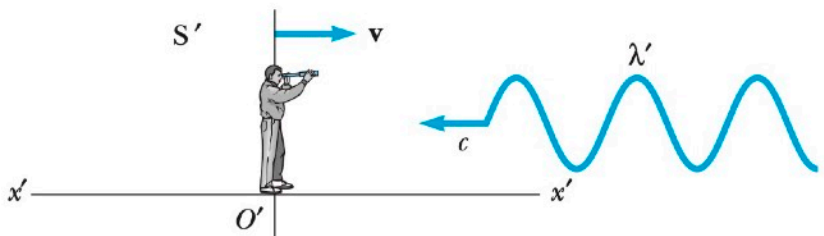
$$f' = f\left(\frac{v \pm v_0}{v \mp v_s}\right)$$

- v is the propagation speed of waves in the medium;
- v_o is the speed of the receiver relative to the medium,
  - ➡added to v if the receiver is moving towards the source,
  - ➡subtracted if the receiver is moving away from the source;
- v_s is the speed of the source relative to the medium,
  - ➡added to v if the source is moving away from the receiver,
  - ➡subtracted if the source is moving towards the receiver.

The relativistic doppler shift



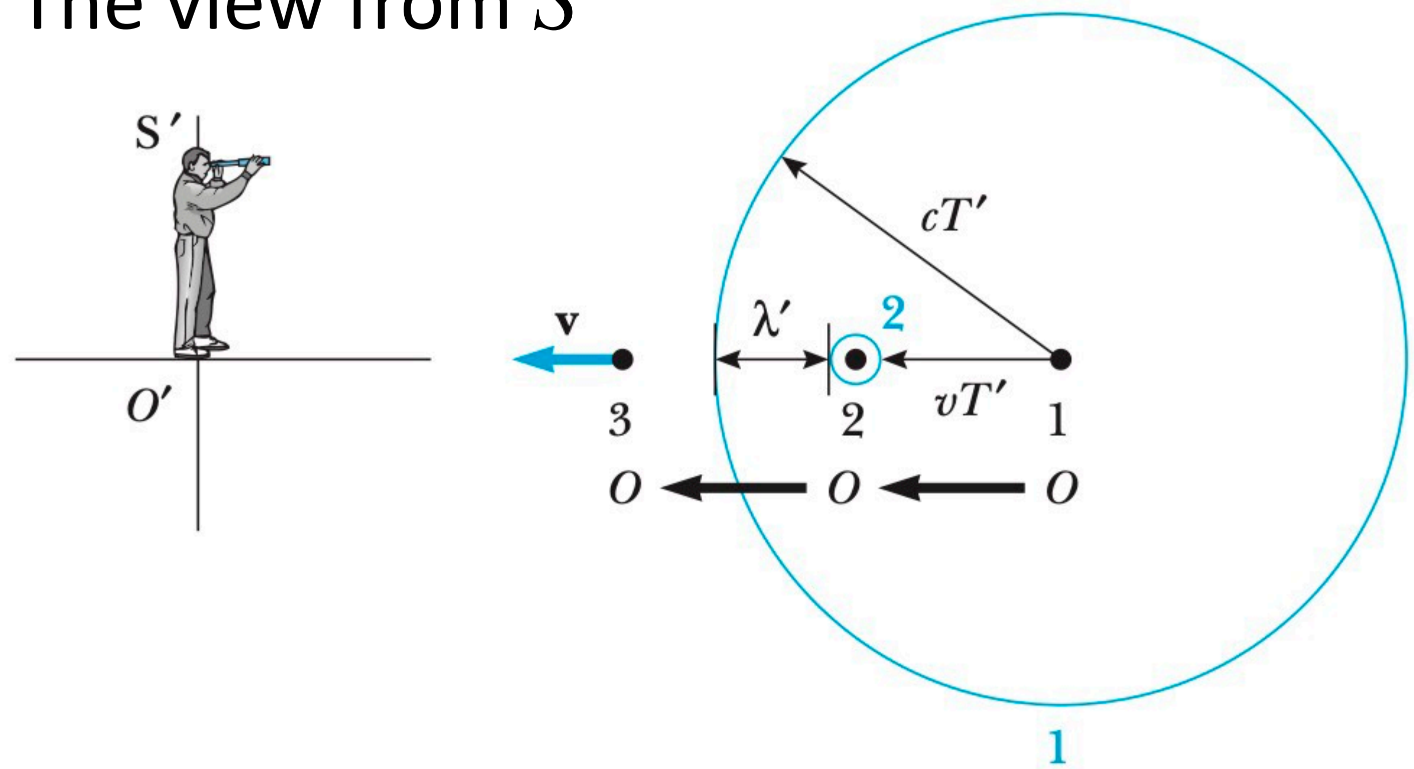
(a)



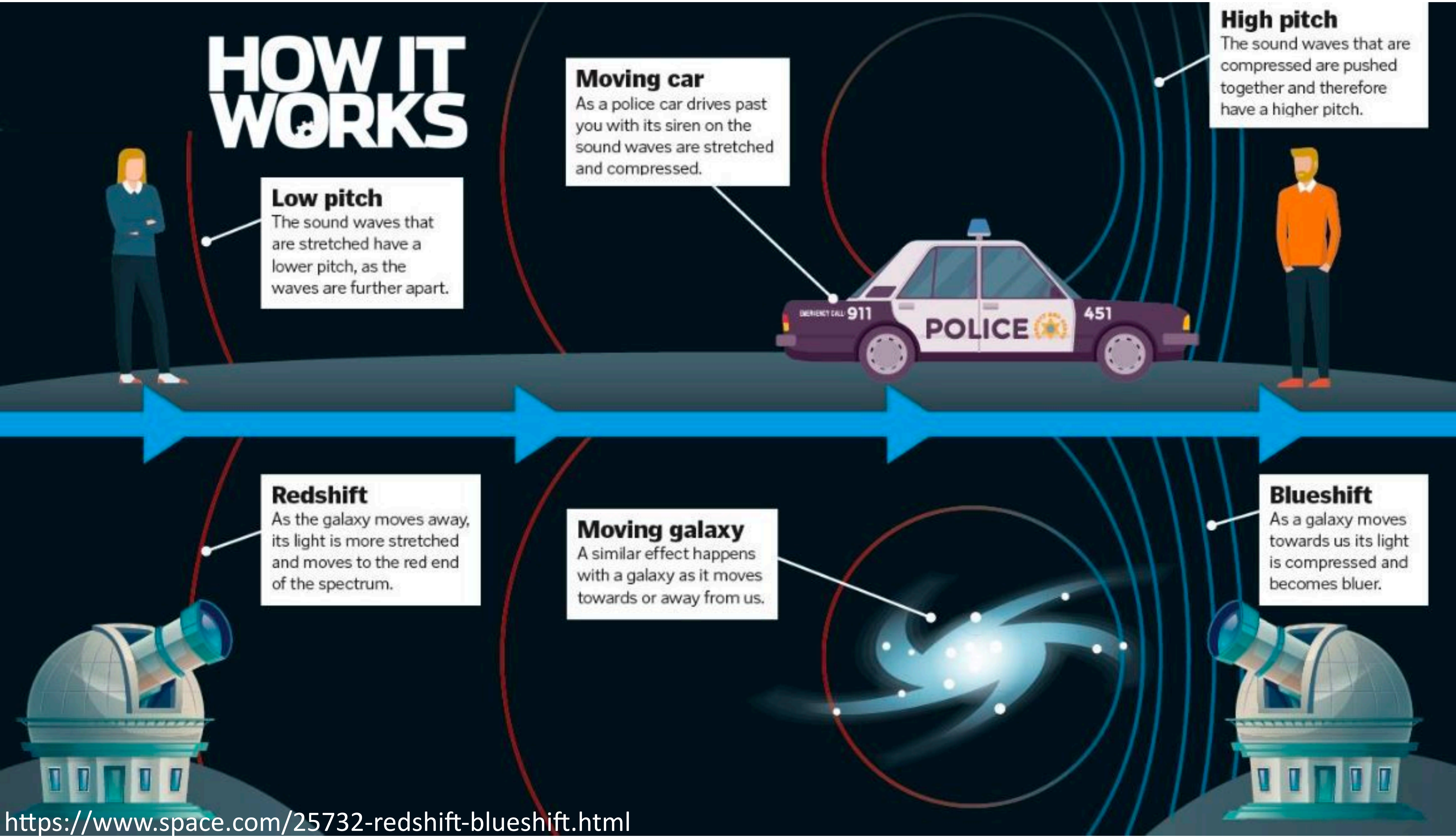
The view from S

(b)

The view from S'



The relativistic doppler shift



https://www.space.com/25732-redshift-blueshift.html

Summary: consequences of the special theory of relativity and paradoxes

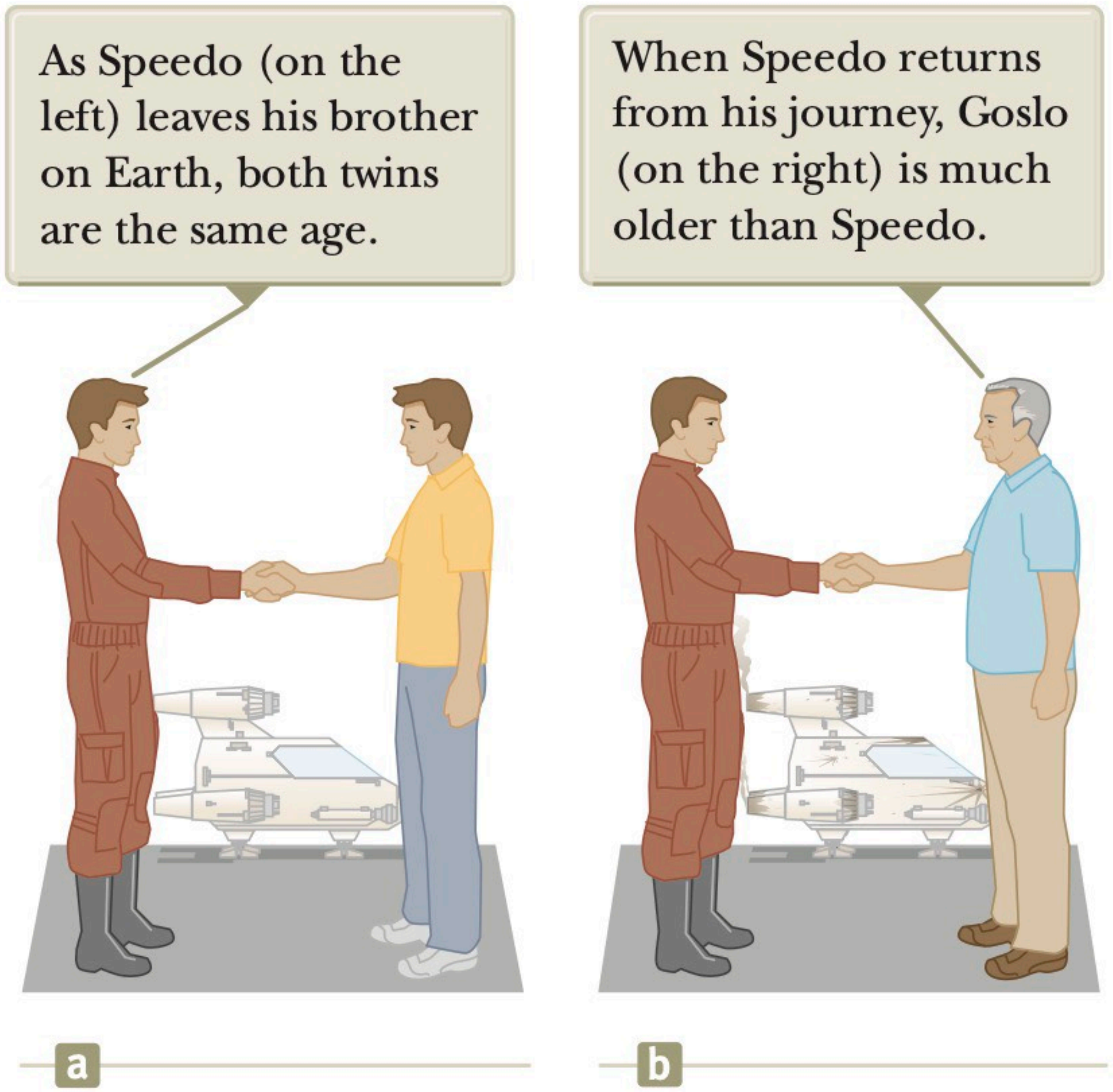
Paradoxes are just apparent paradoxes, they are not true.

There is always only one truth!

The twin paradox

Suppose that one of two identical twin brothers flies off into space at nearly the speed of light. According to relativity, time runs more slowly on his spacecraft than it does on Earth; therefore, when he returns to Earth, he will be younger than his Earth-bound brother.

But in relativity, what one observer sees as happening to a second one, the second one sees as happening to the first one. To the space-going brother, time moves more slowly on Earth than it does in his spacecraft; when he returns, his Earth-bound brother is the one who is younger.



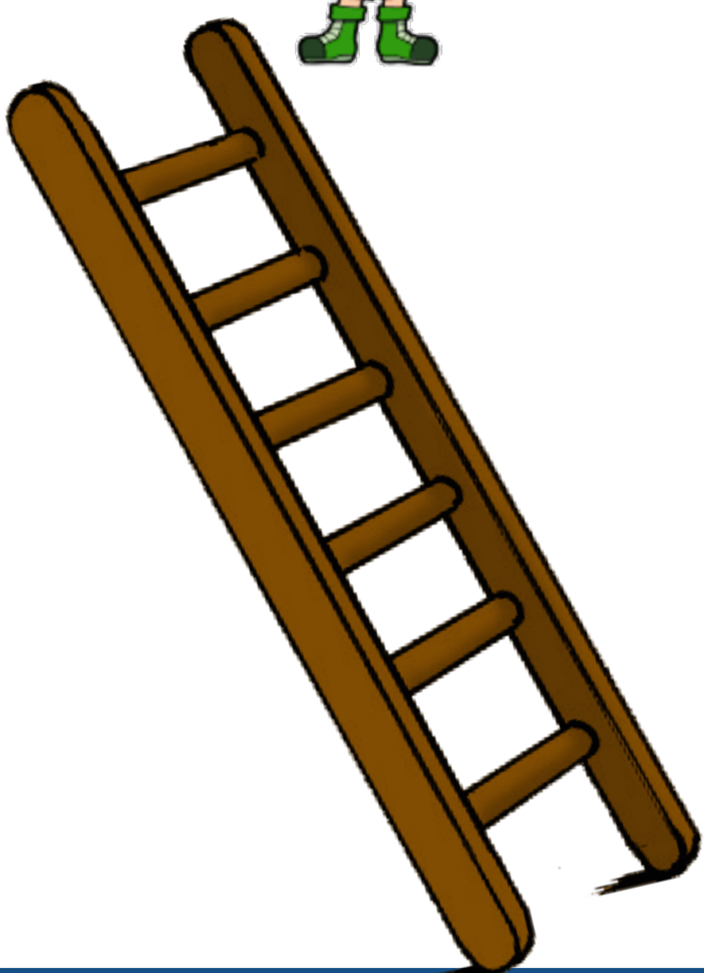
How can the space-going twin be both younger and older than his Earth-bound brother?

Ladder paradox (or barn-pole paradox)

In a Hunter exam, Gon has to carry the ladder through the barn. The ladder is much longer than the barn. The barn has a front door and a back door. The catch is this: both doors close for a brief time, to demonstrate that the ladder fits.

How can I do this, Killua?

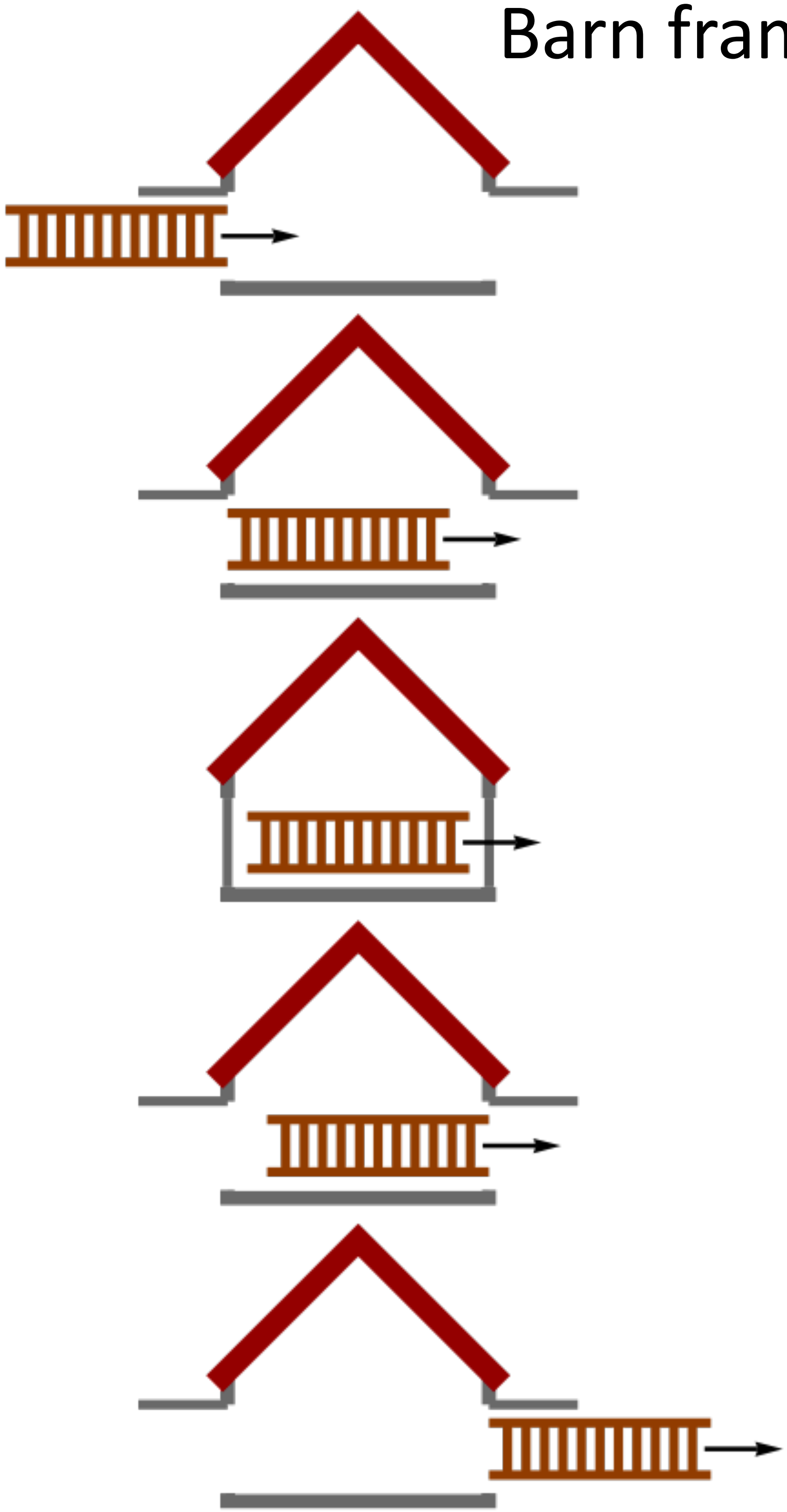
Run fast ... SR will help you.



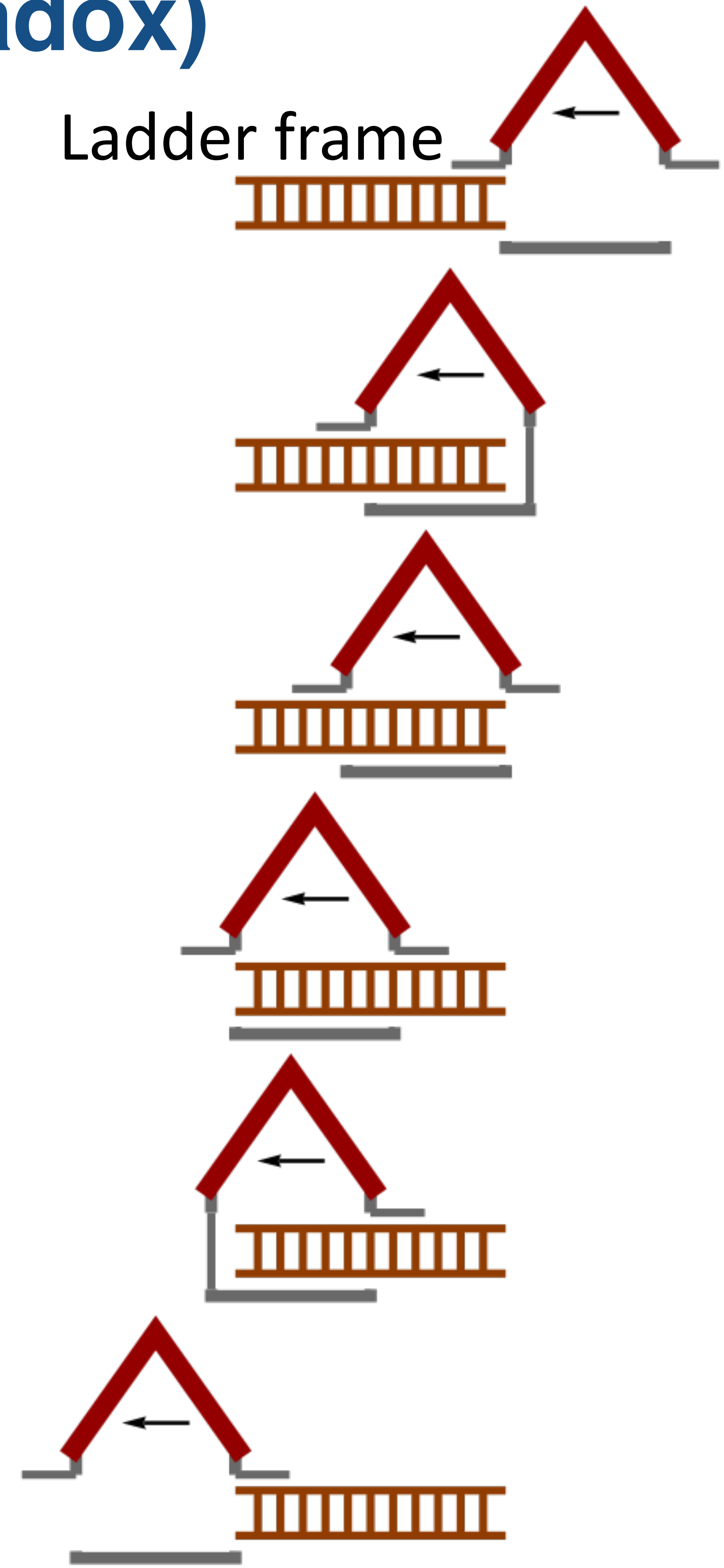
What is the key to the paradox?

Ladder paradox (or barn-pole paradox)

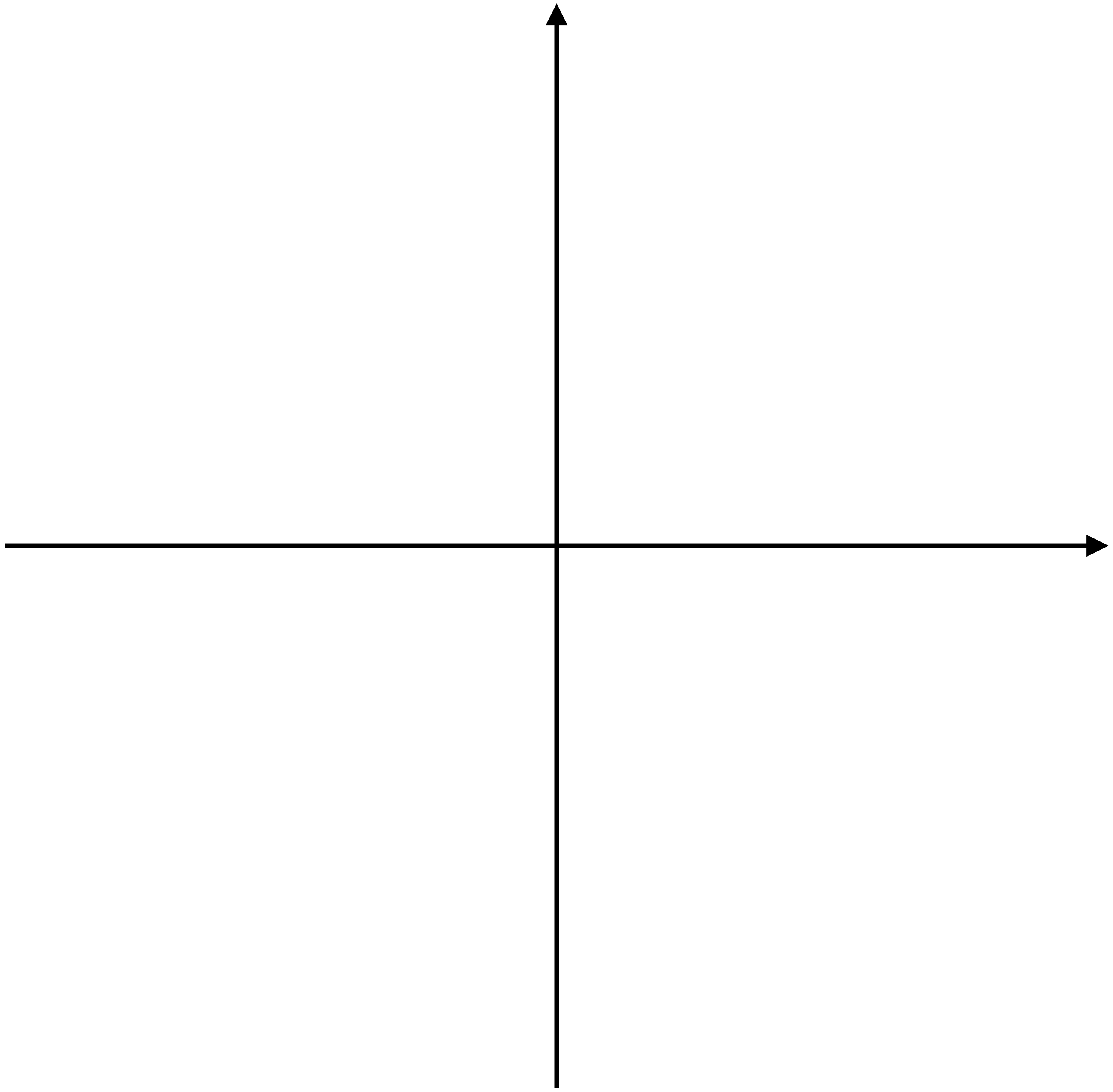
Barn frame



Ladder frame



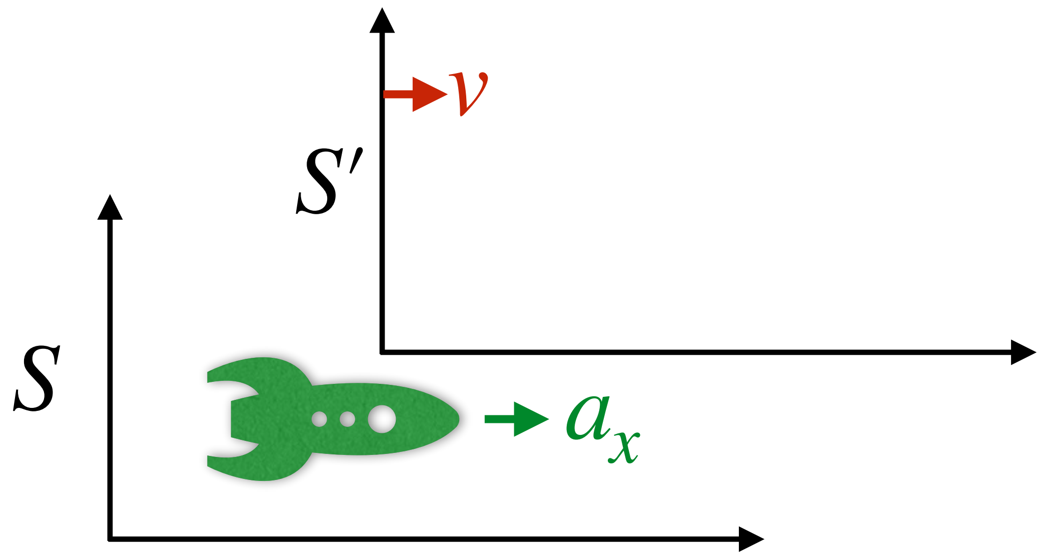
Spacetime and causality



Again, starting from the Lorentz transformation, we try to understand the connection between 2 events.

Acceleration in special theory of relativity

Let's discuss about how different initial observers will see an object under constant acceleration.



Space-Time interval

A single particle and four-momentum

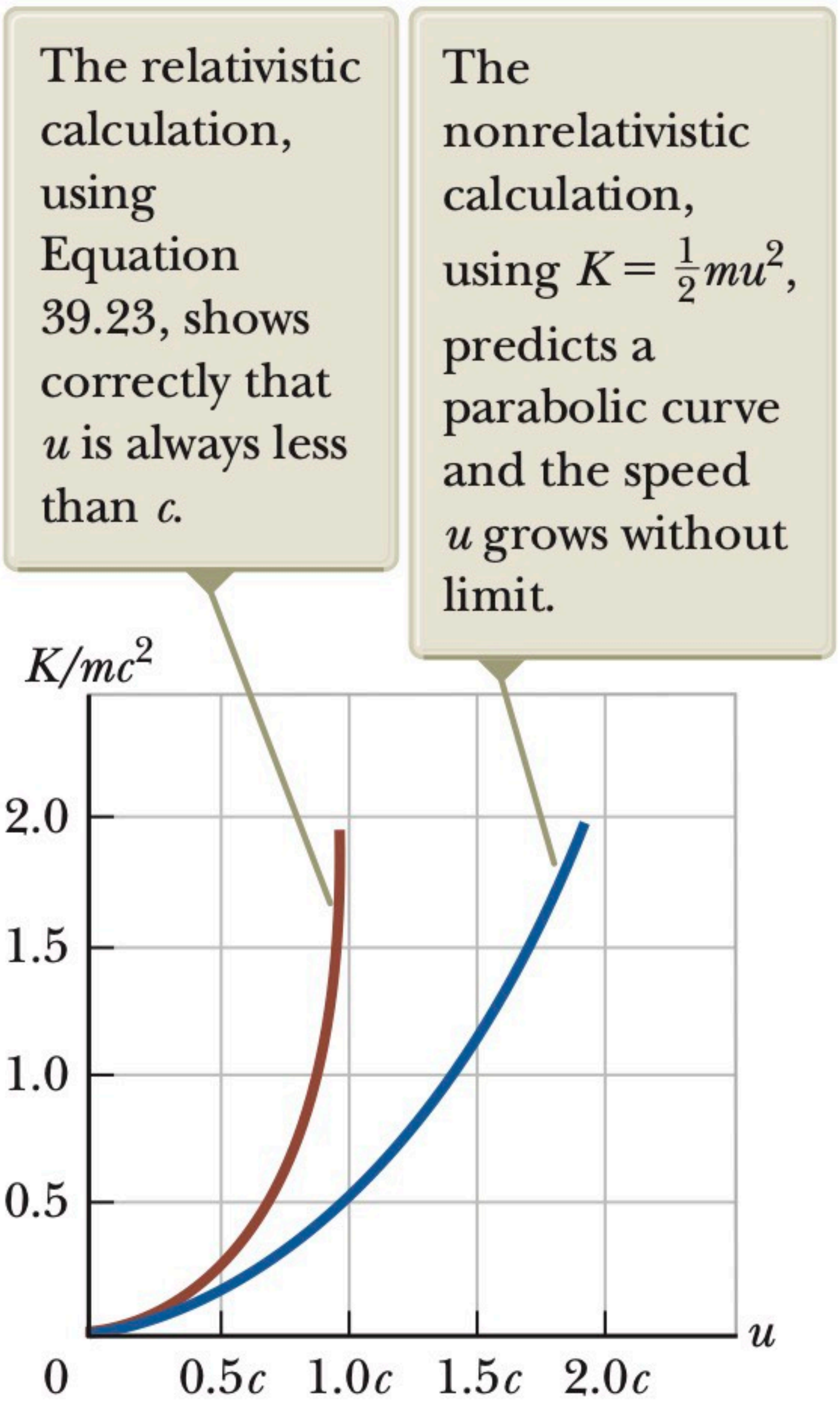
Relativistic linear momentum

Try: Show that under relativistic conditions, the acceleration $\overrightarrow{a}$ of a particle decreases under the action of the constant force, in which case $a \propto (1 - u^2/c^2)^{3/2}$. (See challenge question in Serway)

Relativistic linear momentum: Example

An electron, which has a mass of 9.11×10^{-31} kg, moves with a speed of $0.750c$. Find its relativistic momentum and compare this with the momentum calculated from the classical expression.

Relativistic energy



Electron volt

When dealing with subatomic particles, it is convenient to express their energy in electron volts because the particles are usually given this energy by acceleration through a potential difference.

The conversion factor is

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

For example, the mass of an electron is 9.11×10^{-31} kg. Hence, the rest energy of the electron is

Relativistic energy: Example

The total energy of a proton is three times its rest energy:

(a) Find the proton's rest energy in electron volts.

(b) What is the speed of the proton?

(c) Determine the kinetic energy of the proton in units of electron volts.

(d) What is the proton's momentum?

Mass as a measure of energy

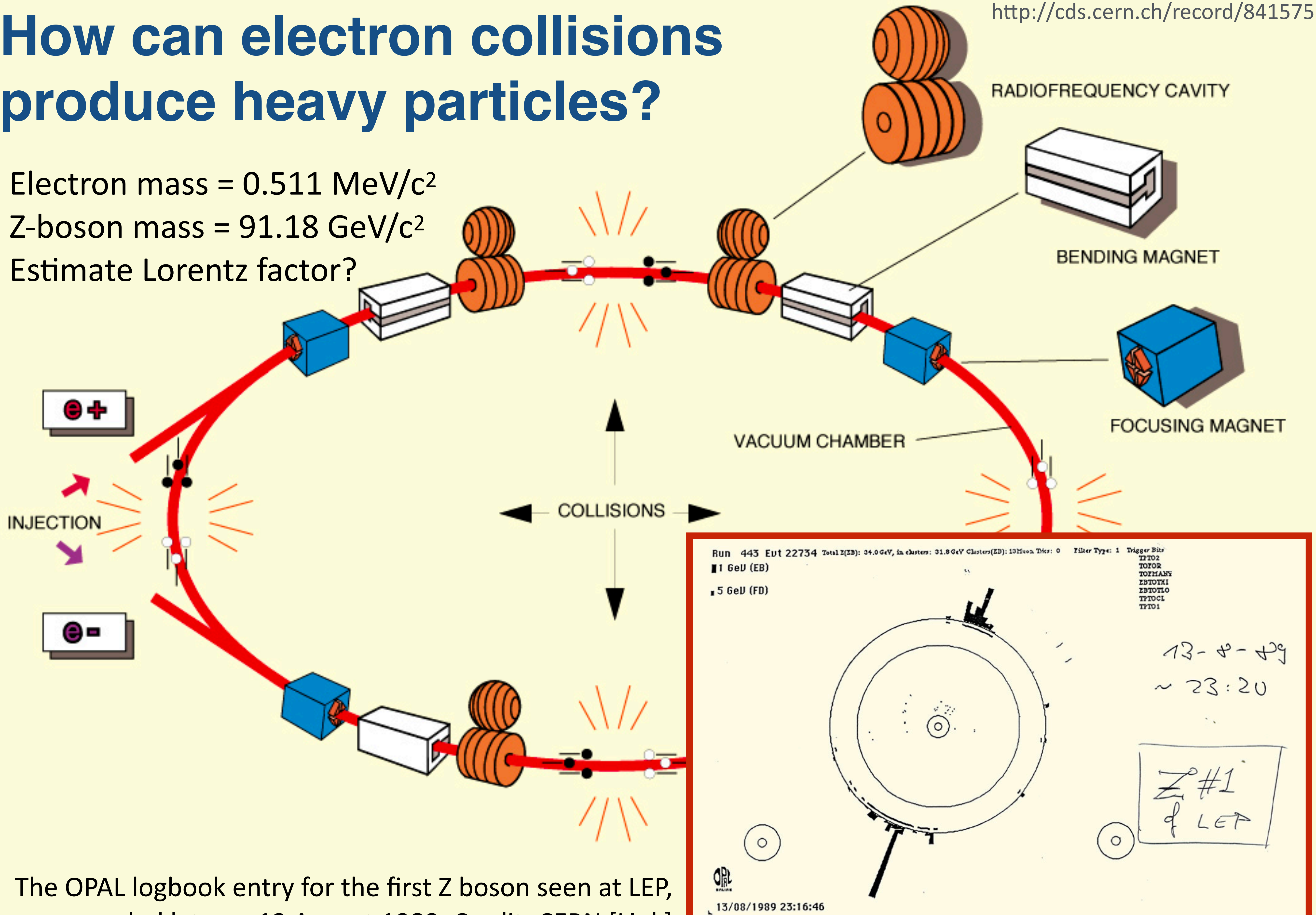
The equation $E = \gamma mc^2$ as applied to a particle suggests that even when a particle is at rest ($\gamma = 1$) it still possesses enormous energy through its mass.

The conservation of mass–energy: the sum of the mass–energy of a system of particles before interaction must equal the sum of the mass–energy of the system after interaction where the mass – energy of the ith particle is defined as the total relativistic energy $E_i = \gamma_i m_i c^2$.

How can electron collisions produce heavy particles?

http://cds.cern.ch/record/841575

Electron mass = 0.511 MeV/c^2
Z-boson mass = 91.18 GeV/c^2
Estimate Lorentz factor?



The OPAL logbook entry for the first Z boson seen at LEP, recorded late on 13 August 1989. Credit: CERN [Link]

CERN AC - E509

Fission

A nucleus of mass M undergoing fission into particles with masses M_1, M_2, and M_3 and having speeds u_1, u_2, and u_3, conservation of total relativistic energy requires

$$MC^2 = \frac{M_1c^2}{\sqrt{1-u_1^2/c^2}} + \frac{M_2c^2}{\sqrt{1-u_2^2/c^2}} + \frac{M_3c^2}{\sqrt{1-u_3^2/c^2}}$$

What do you get from this?