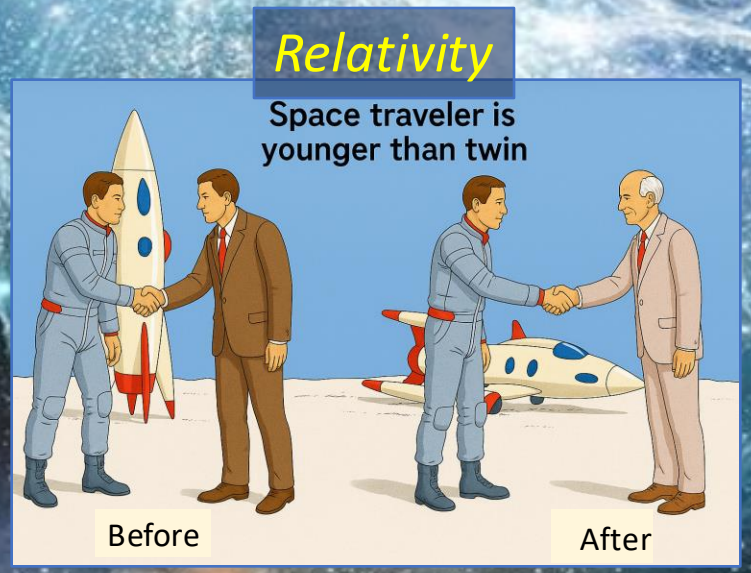
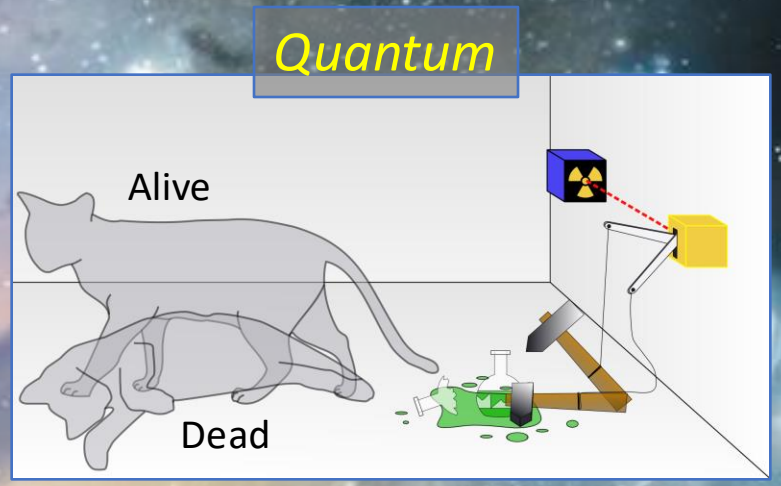
The Relativistic Quantum World

A lecture series on
Relativity Theory and Quantum Mechanics

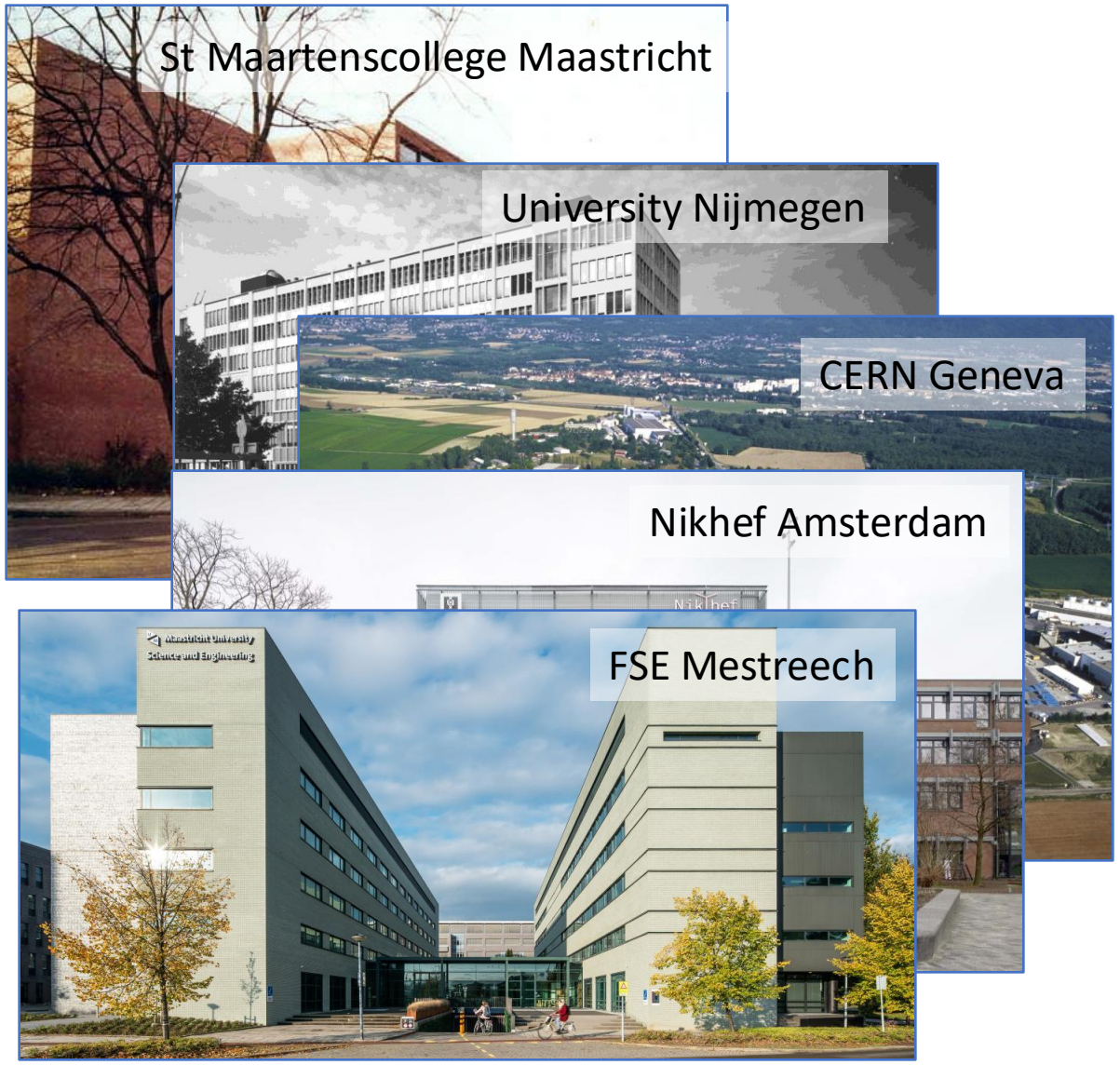




Marcel Merk
Studium Generale Maastricht
Sep 10 – Oct 8, 2025

Who am I?

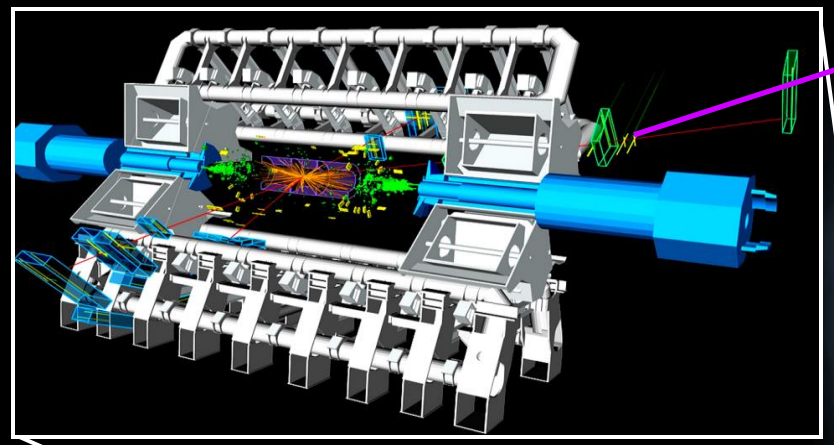
Working career

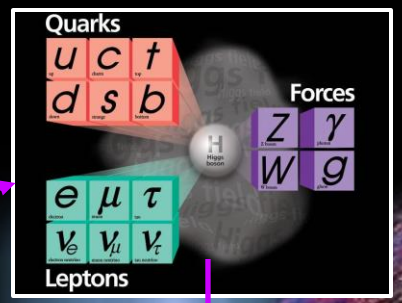


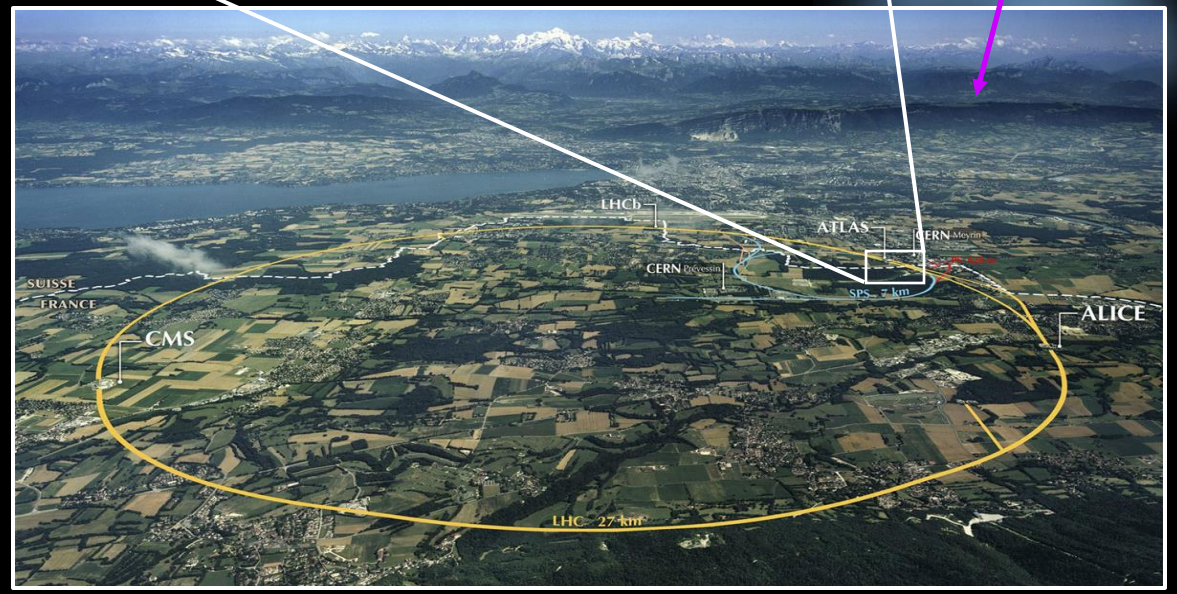
Personal career

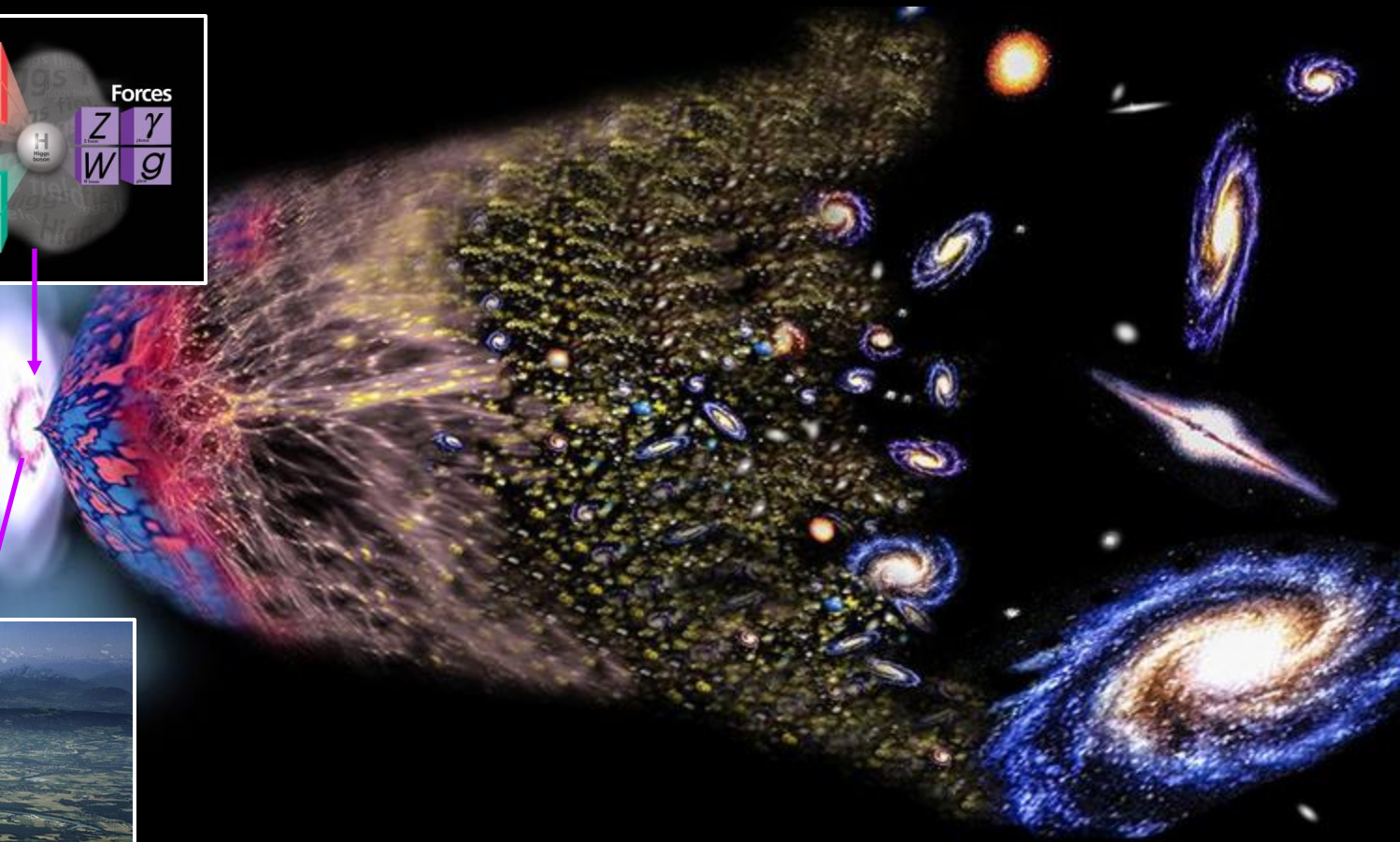
What do I do?

Website: www.nikhef.nl/~i93 Email: marcel.merk@nikhef.nl









Why is there something rather then nothing?

(More in the last lecture of the series)

Research with the Large Hadron Collider at CERN
Study the *matter-vs-antimatter asymmetry* in nature

The Relativistic Quantum World

Relativity	Sep. 10:	Lecture 1: The Principle of Relativity and the Speed of Light Lecture 2: Time Dilation and Lorentz Contraction
	Sep. 17:	Lecture 3: The Lorentz Transformation and Paradoxes Lecture 4: General Relativity and Gravitational Waves
Quantum Mechanics	Sep. 24:	Lecture 5: The Early Quantum Theory Lecture 6: Feynman's Double Slit Experiment
	Oct. 1 :	Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat Lecture 8: Quantum Reality and the EPR Paradox
Standard Model	Oct. 8:	Lecture 9: The Standard Model and Antimatter Lecture 10: Why is there something rather than nothing?

Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

The Relativistic Quantum World

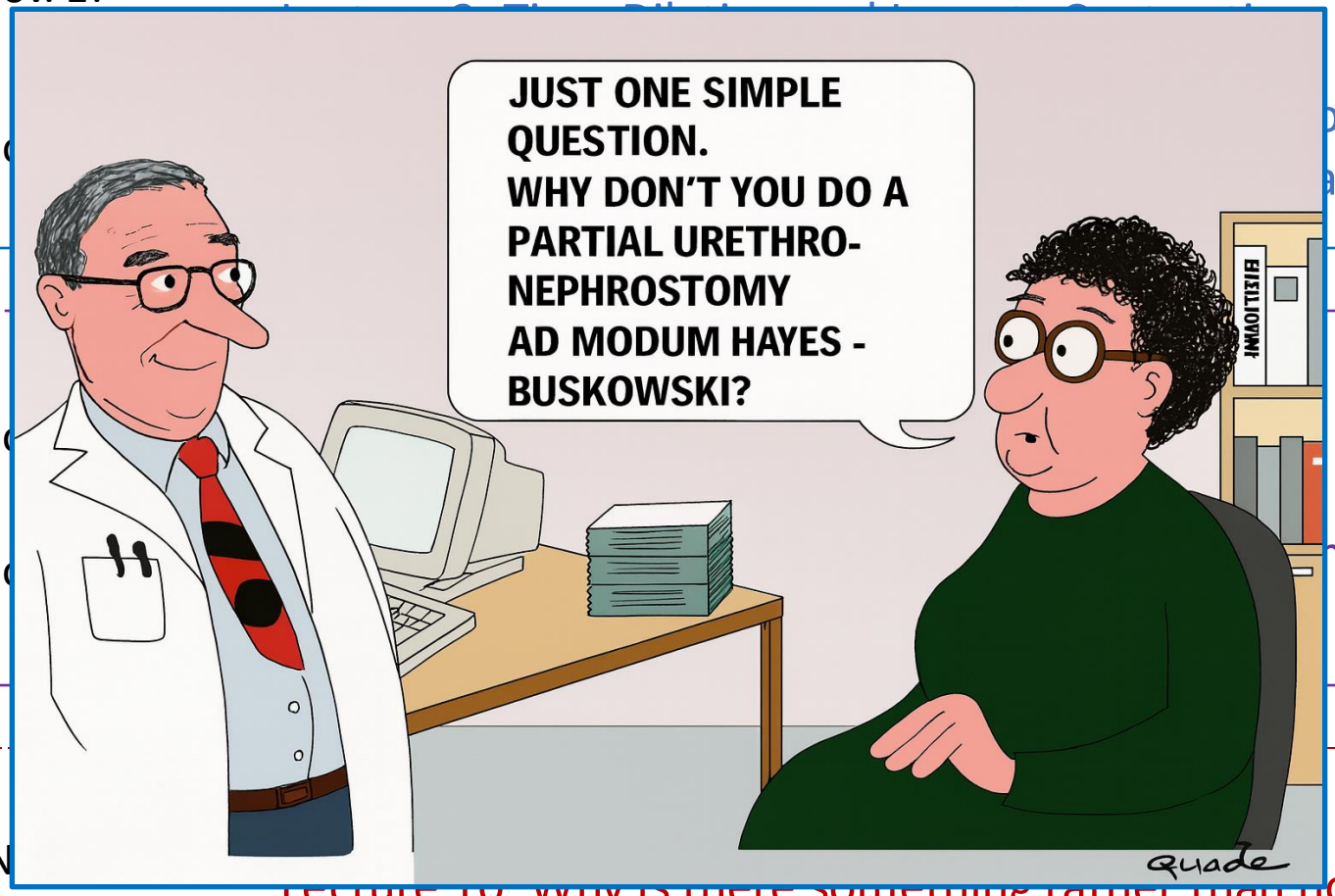
Relativity

Quantum Mechanics

Standard Model

Nov. 1:

Lecture 1: The Principle of Relativity and the Speed of Light



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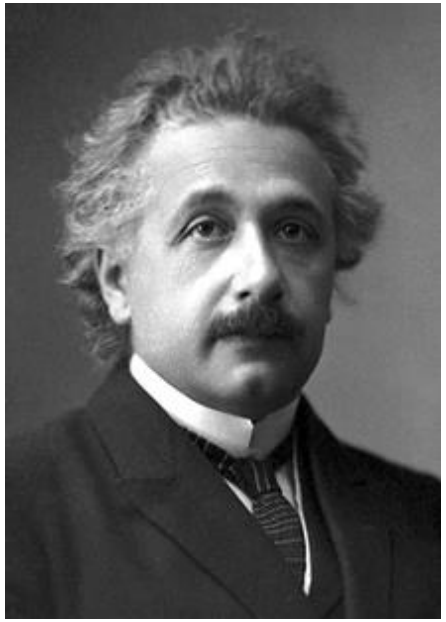
Relativity and Quantum Mechanics

"There is nothing new to be discovered in physics now. All that remains is more precise measurements."
- Lord Kelvin on Physics in 1900

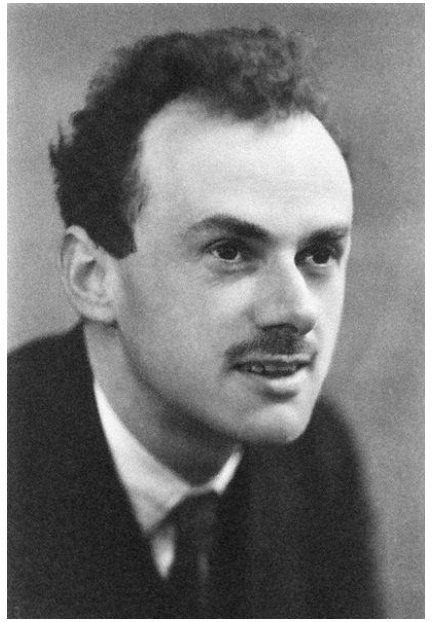
However, there were two unsolved issues:
1. The existence of the mysterious ether ➔ Relativity Theory
2. Black-body radiation and atom stability ➔ Quantum Mechanics


Albert Einstein

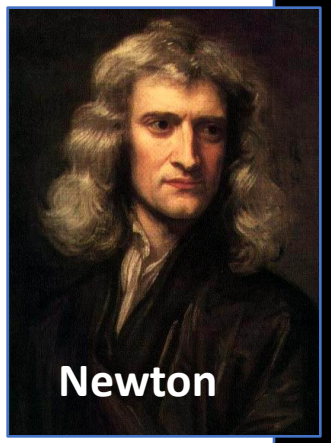

Niels Bohr


Werner Heisenberg


Erwin Schrödinger


Paul Dirac

Relativity and Quantum Mechanics

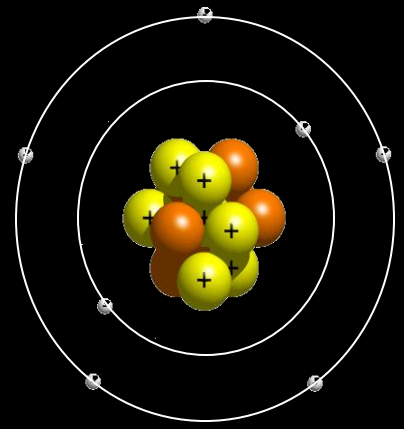


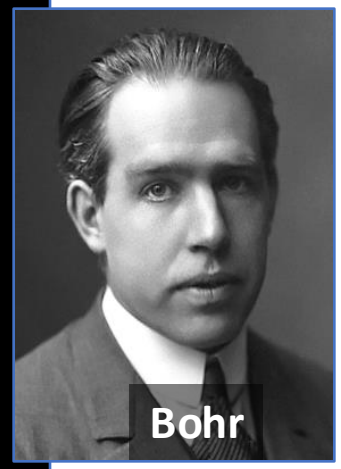
Classical Mechanics

Quantum Mechanics

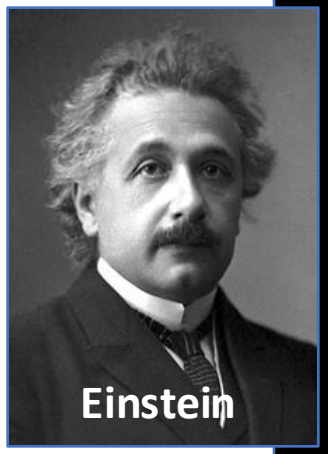
Smaller Sizes (ħ)

Higher Speed (c)

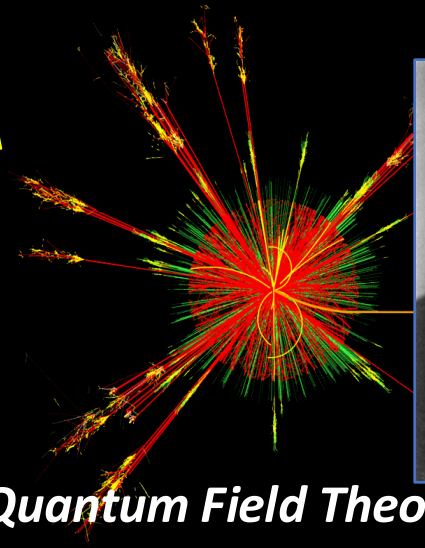




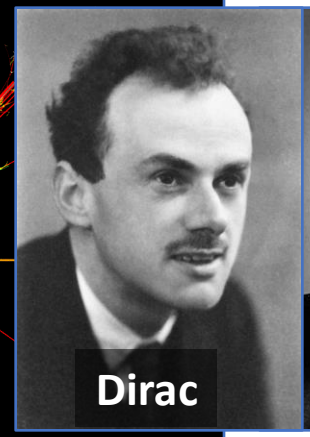
Classical mechanics is not “wrong”.
It is limited to macroscopic objects and moderate velocities.

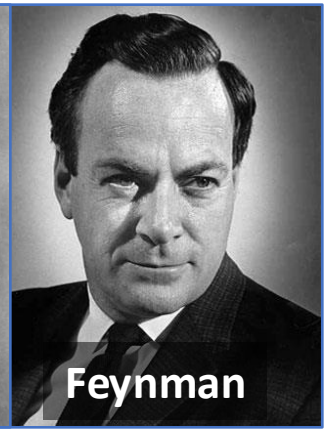


Relativity Theory

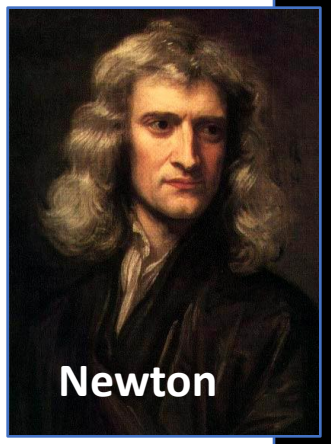


Quantum Field Theory





Relativity and Quantum Mechanics

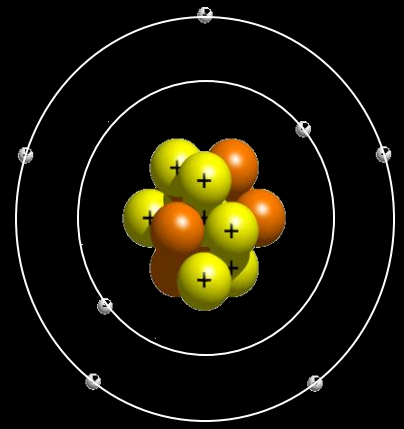


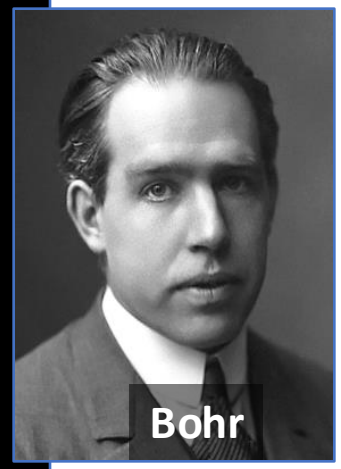
Classical Mechanics

Quantum Mechanics

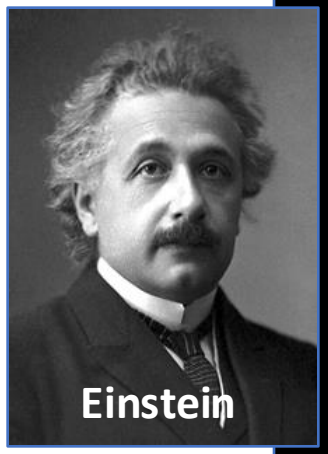
Smaller Sizes (ħ)

Higher Speed (c)

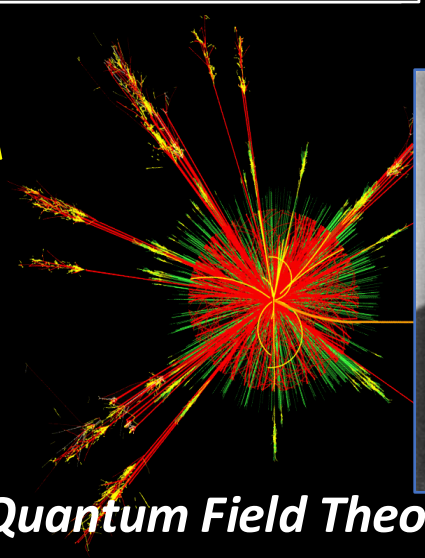




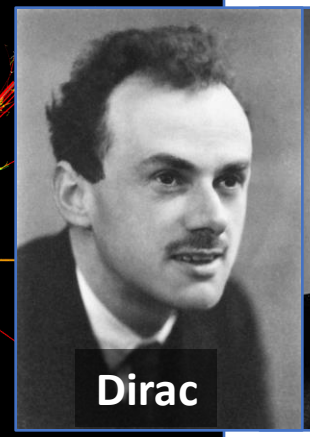
From our experience we are not used to relativistic and quantum mechanical phenomena. That's why we find it counterintuitive.

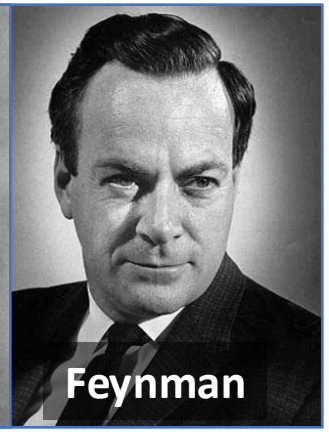


Relativity Theory



Quantum Field Theory



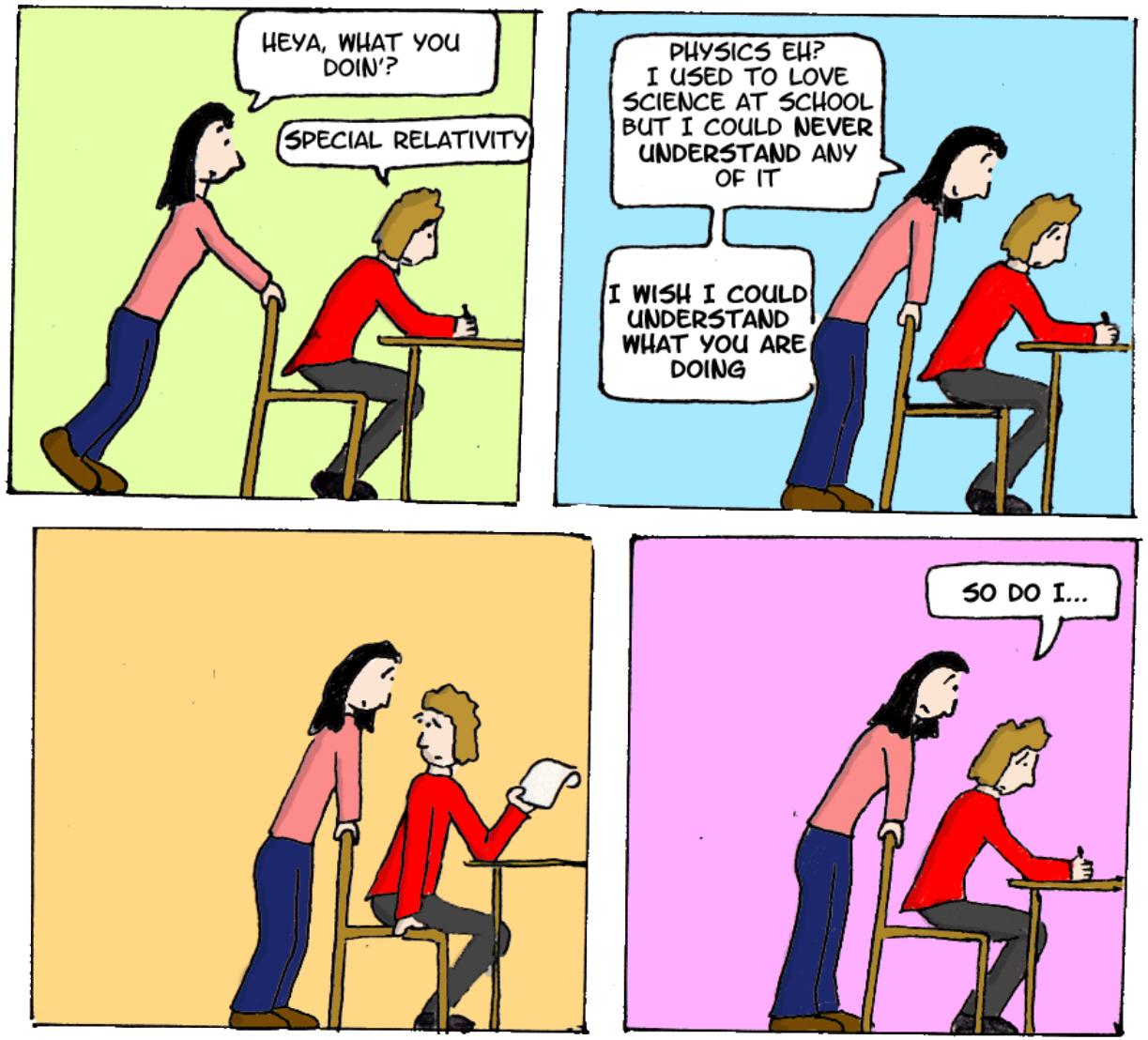


Lecture 1

The Principle of Relativity and the Speed of Light

"If you can't explain it simply you don't understand it well enough"
- Albert Einstein

“Everything should be made as simple as possible, but not simpler”
- Albert Einstein



Albert Einstein (1879 – 1955)

"Annus Mirabilis" 1905:

- Special theory of relativity
  - Fundamental change interpreting space and time
  - Equivalence of mass and energy: $E=mc^2$
- The photo electric effect → Nobel prize 1921
  - Quantum Mechanics: light consists of photon-quanta
- Brownian Motion
  - Demonstration of existence of atoms

Although these studies were motivated by curiosity, they eventually had a large impact on society: computing and communication technology, health-care technology, navigation, military, …

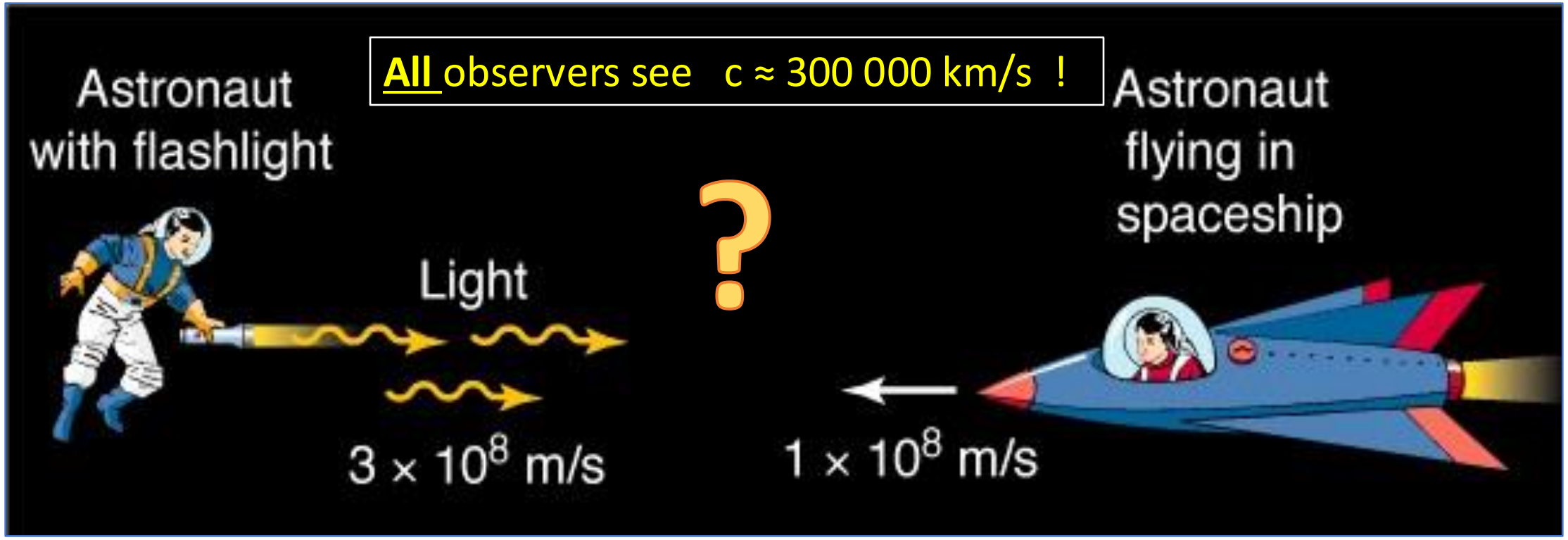
Relativity: “Nothing can move faster than the speed of light”

What is the speed of light? “300 000 km/s”

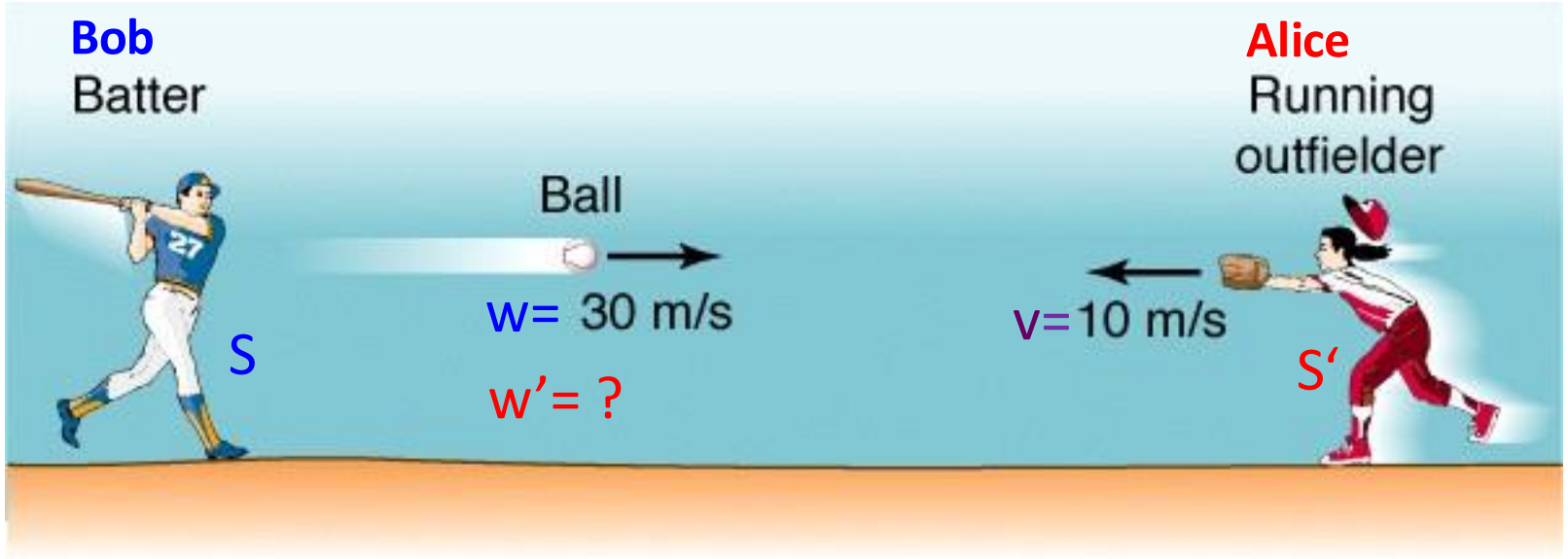
Relative to what? “to the vacuum” ??

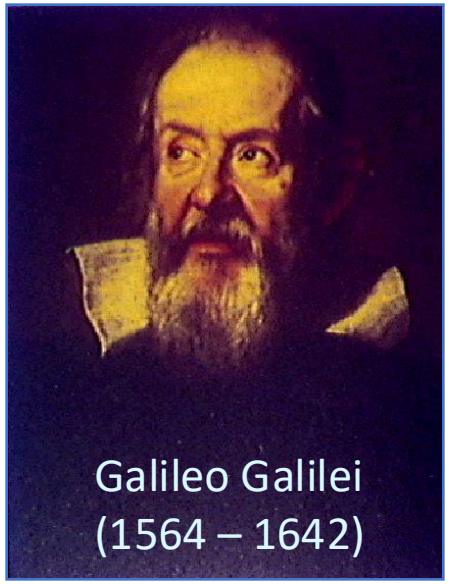
Einstein: “The speed of light in vacuum is always the same."

$c \approx 300\,000$ km/s



Galilei Transformation law





With which speed do Alice and the ball hit by Bob approach each other?
Intuitive law (daily experience): 30 m/s + 10 m/s = 40 m/s

More formal: Observer S (Bob) observes the ball with relative velocity: w

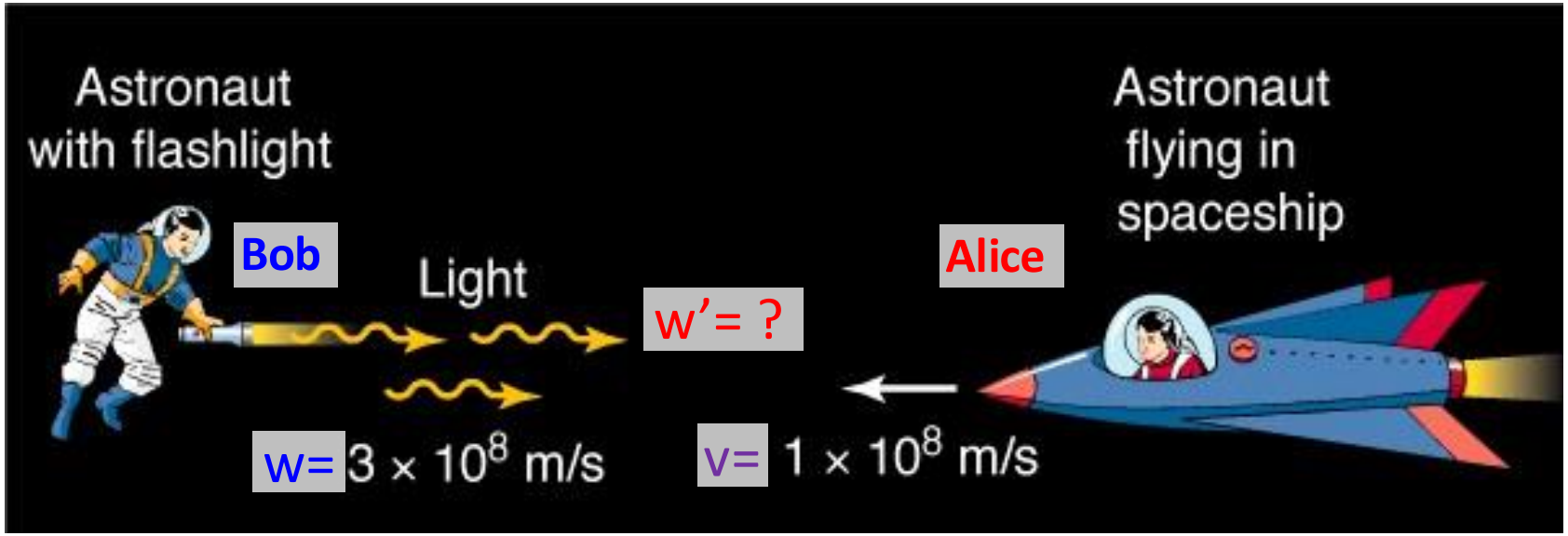
Observer S' (Alice) observes the ball with relative velocity: w'

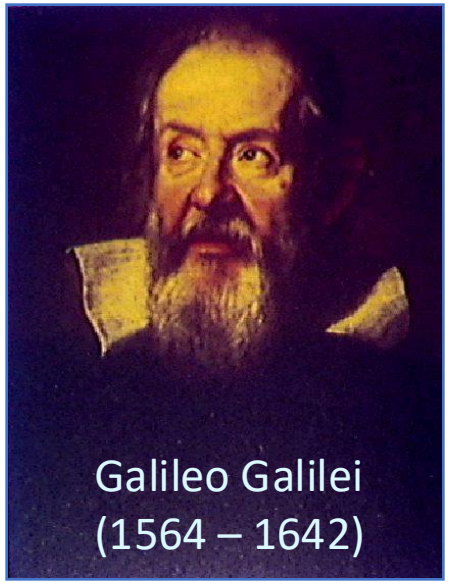
The velocity of S' with respect to S is: v

$$w' = w + v$$

This is the Galileian law for adding velocities.

Galilei Transformation law





With which speed do Alice and the light sent by Bob approach each other?

Intuitive law: 300 000 km/s + 100 000 km/s = 400 000 km/s ???

More formal: Observer S (Bob) observes the light with relative velocity: w

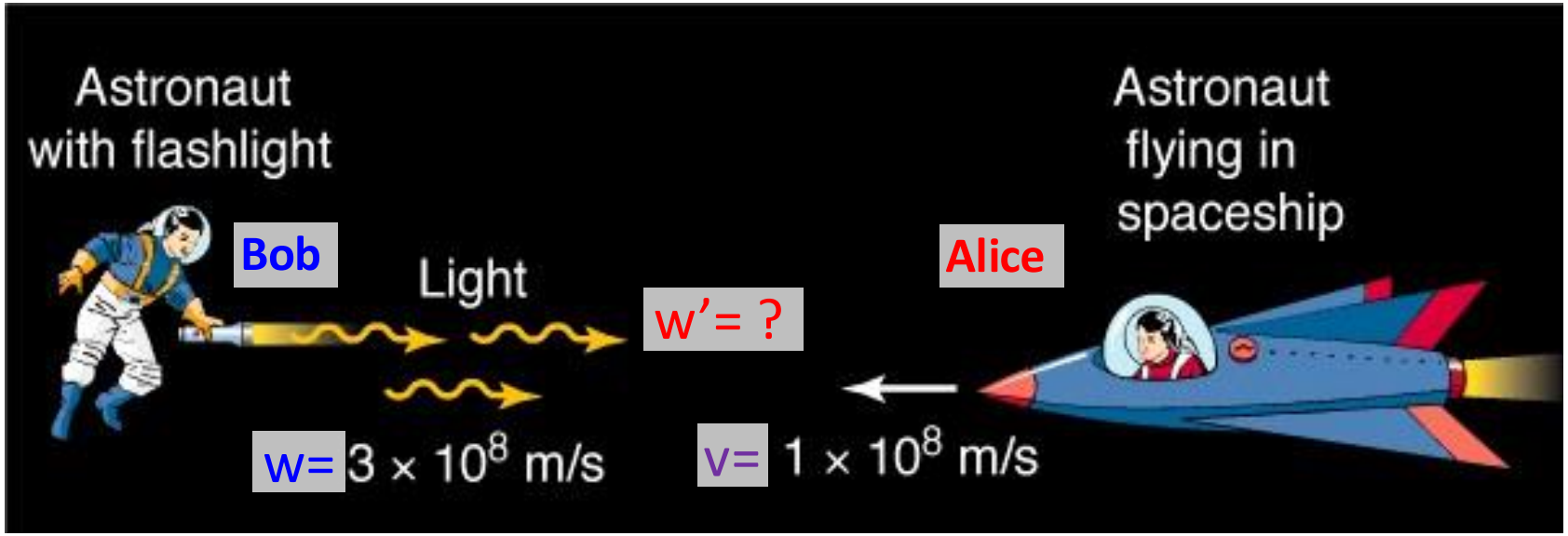
Observer S' (Alice) observes the light with relative velocity: w'

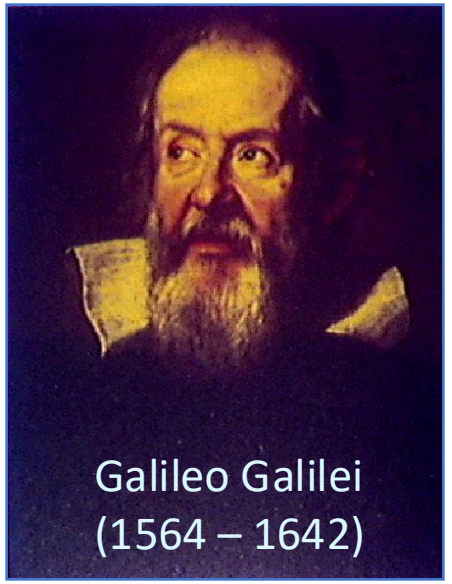
The velocity of S' with respect to S is: v

$$w' = w + v$$

This is the Galileian law for adding velocities.

Galilei Transformation law





With which speed do Alice and the light sent by Bob approach each other?
Intuitive law: 300 000 km/s + 100 000 km/s = 400 000 km/s ???

But nothing can move faster than the speed of light ?!

$$w' = w + v$$

This is the Galileian law for adding velocities.

Let’s do the experiment…

Experiments:

If it’s green and it wiggles,
… it’s biology,

If it stinks, … it’s chemistry,

If it doesn’t work…,
… it’s physics.

Measurement of the Speed of Light

James Clerk Maxwell

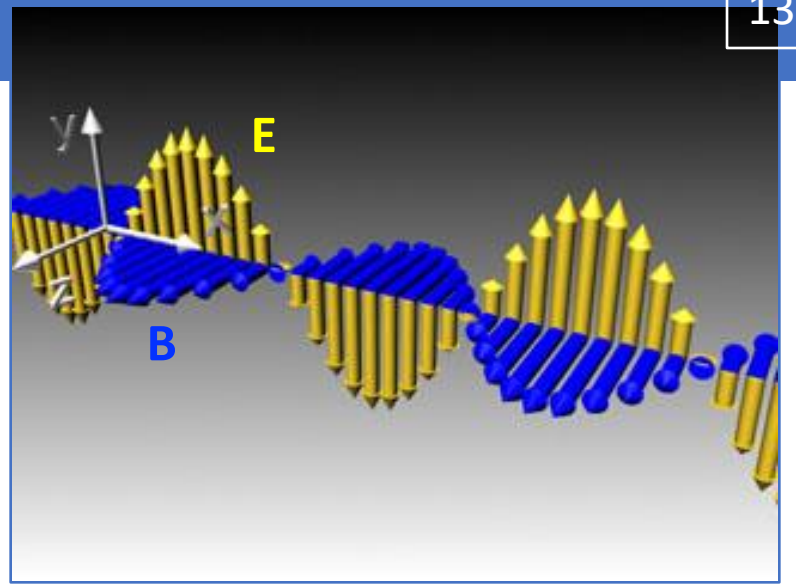
1831-1879

Electromagnetism:

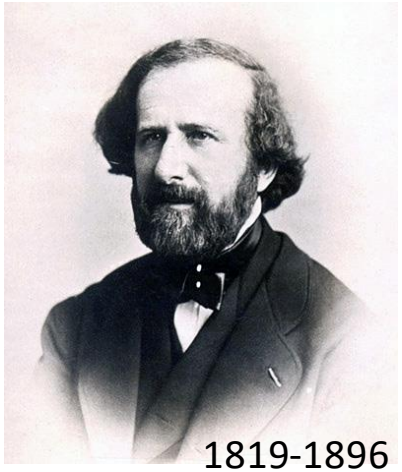
Light consists of propagating waves of perpendicular electric (E) and magnetic (B) fields

Propagation speed: $c = 1/\sqrt{\epsilon_0 \mu_0} = 299\ 792$ km/s

1865: "This velocity is so close to the speed of light, that it seems we have to conclude that light is an electromagnetic disturbance."

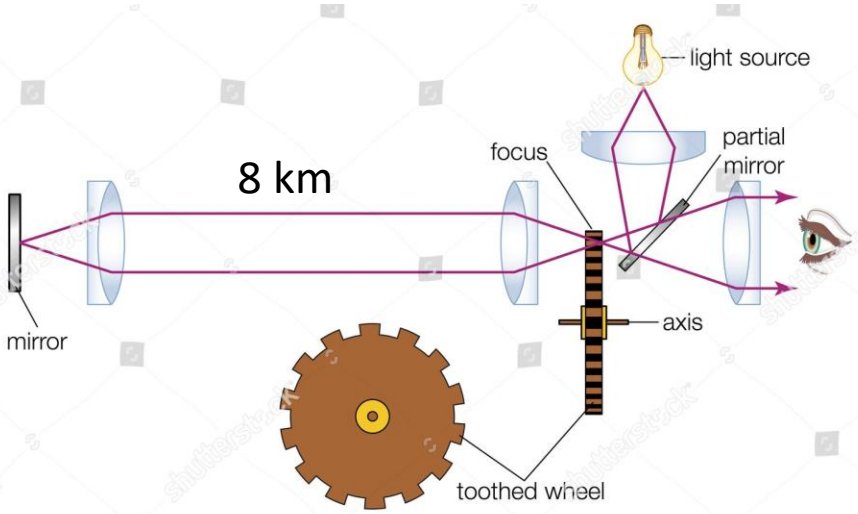


Measure the speed of light directly:



1819-1896

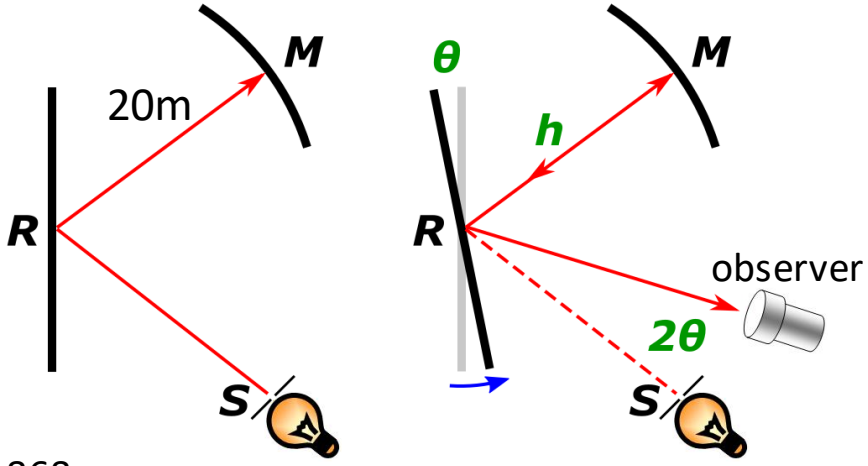
Armand Fizeau



1849: c = 315 000 km/s

1819-1868

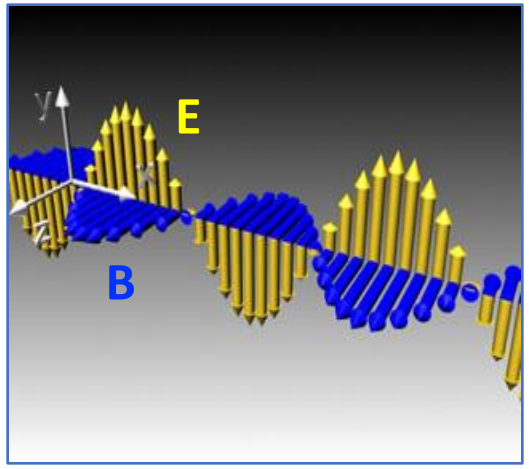
Leon Foucault

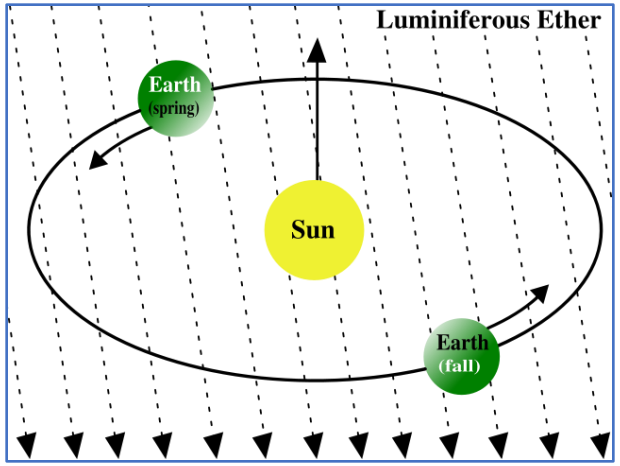


1862: c = 298 000 km/s

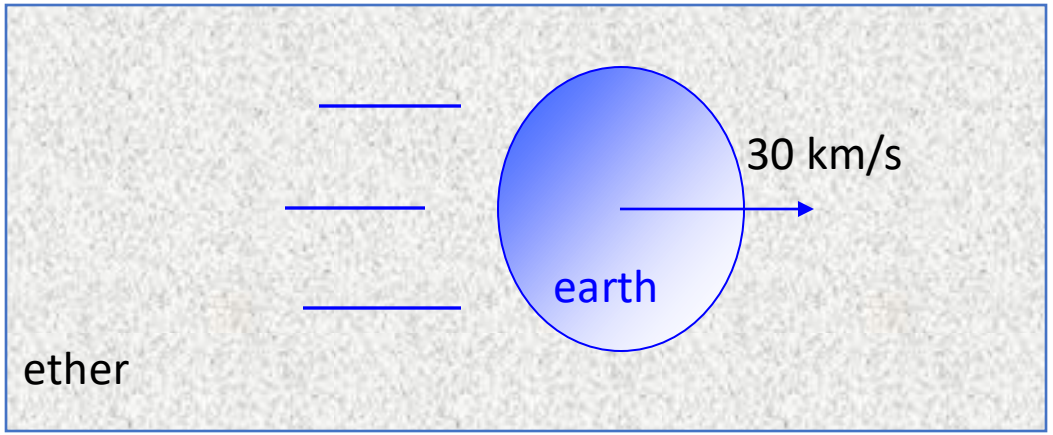
Measurement of the Speed of Light in ether

Light waves were believed to be carried by the "ether".

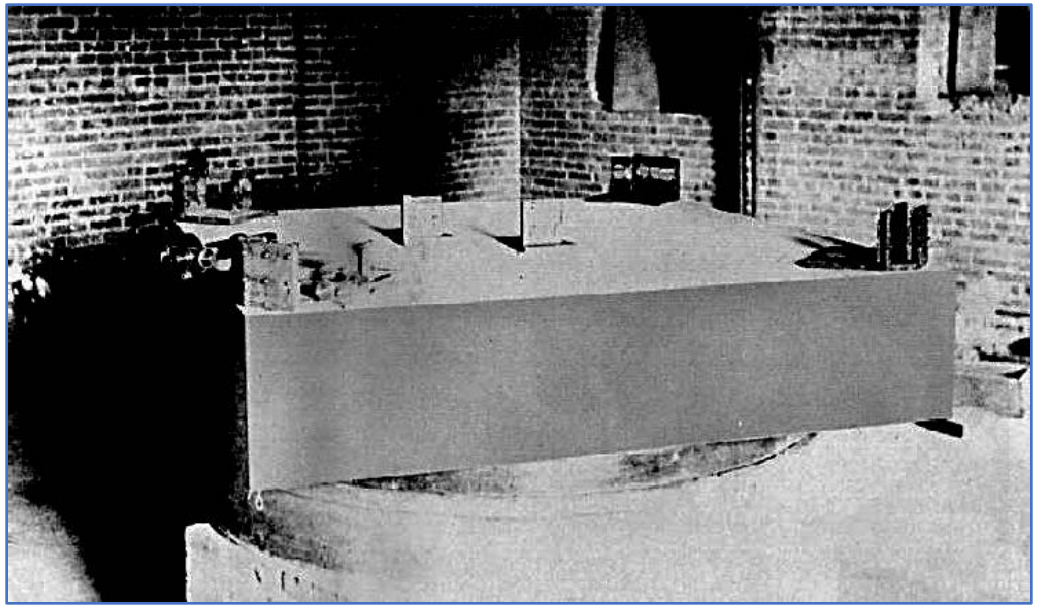


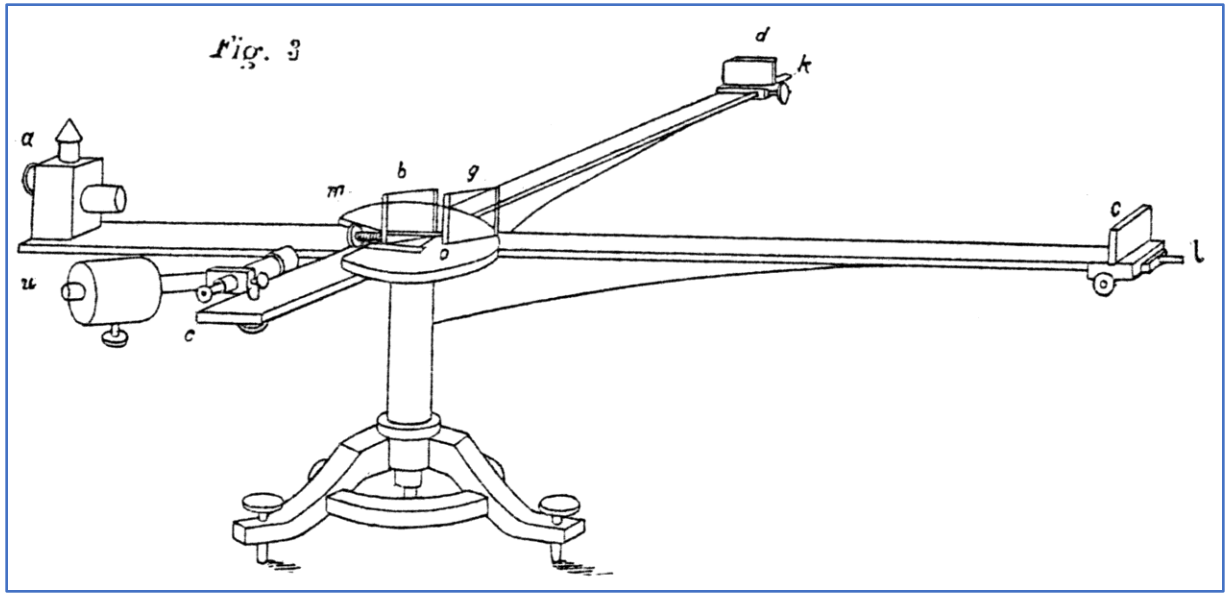


Earth moves through the ether around sun:



Measure light speed with interferometer along two perpendicular directions: *Michelson-Morley Experiment (1887)*





Measurement of the Speed of Light in ether

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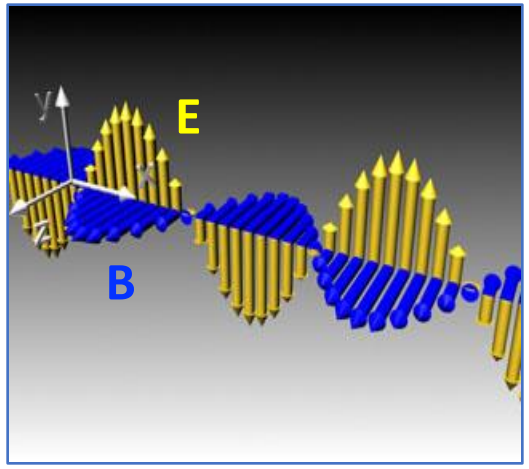
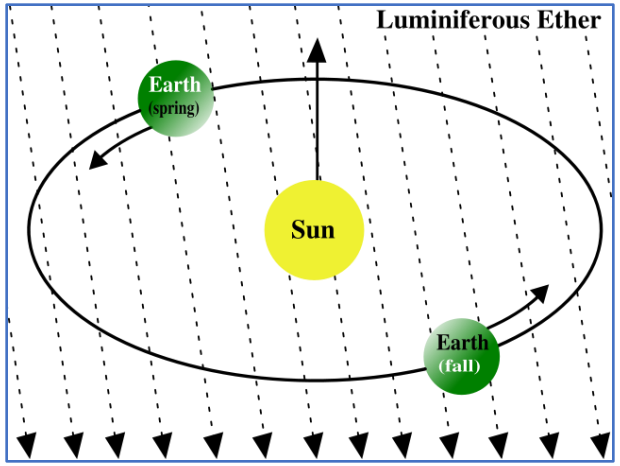
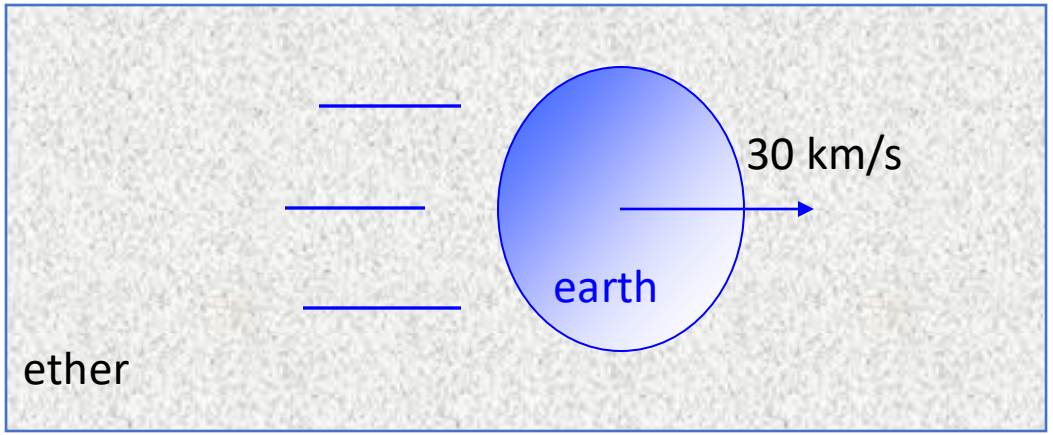


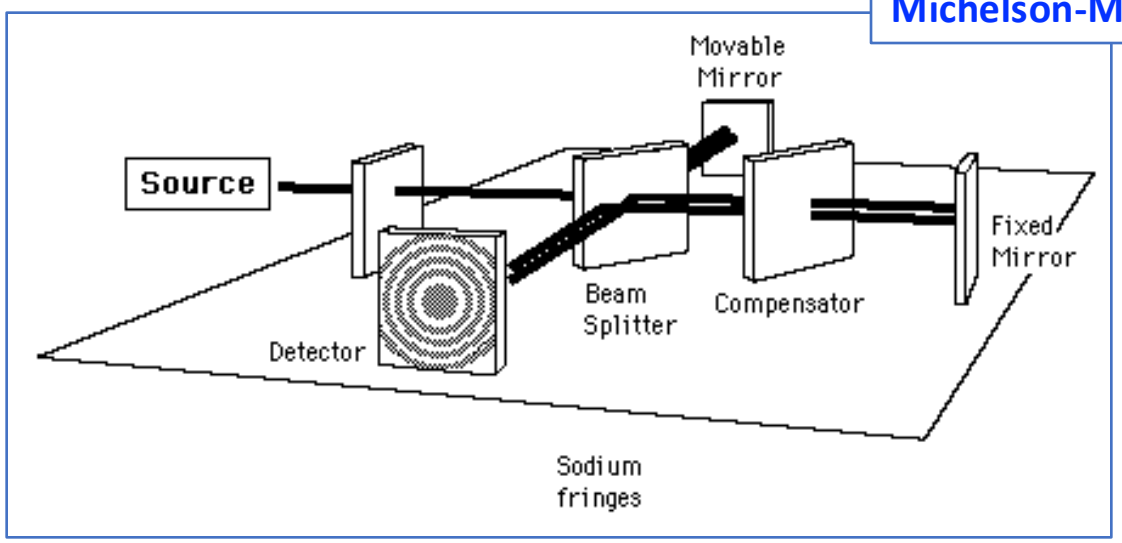


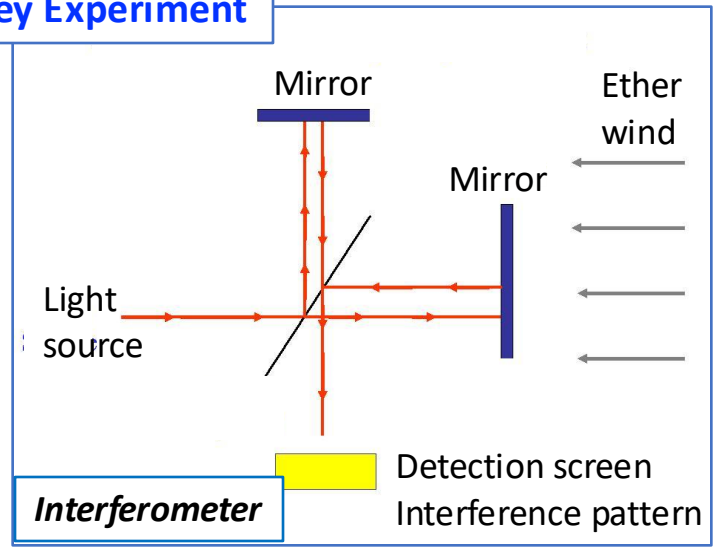
Earth moves through the ether around sun:



Measure light speed with interferometer along two perpendicular directions: *Michelson-Morley Experiment (1887)*

Michelson-Morley Experiment

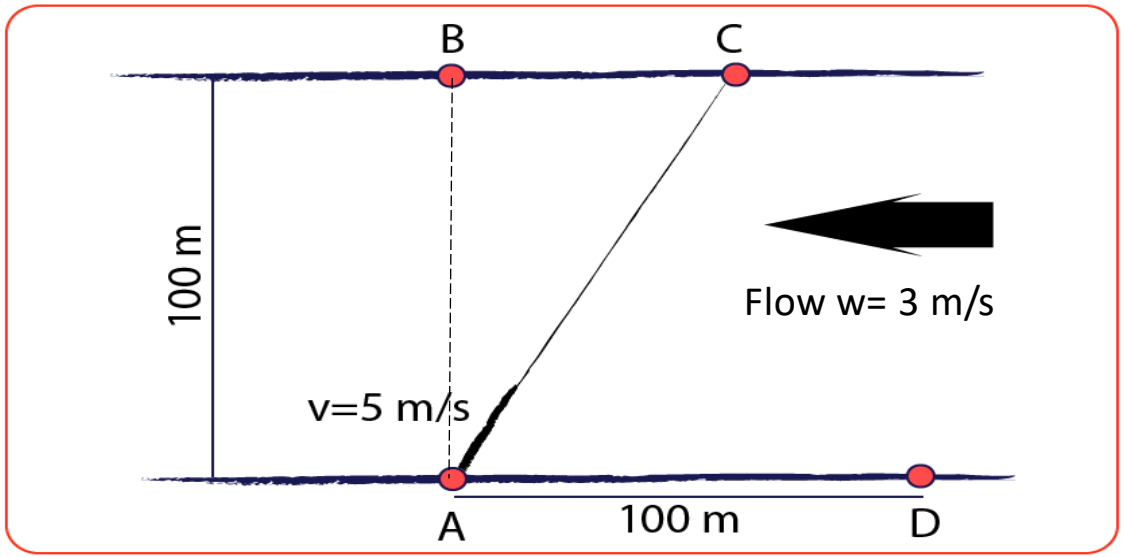




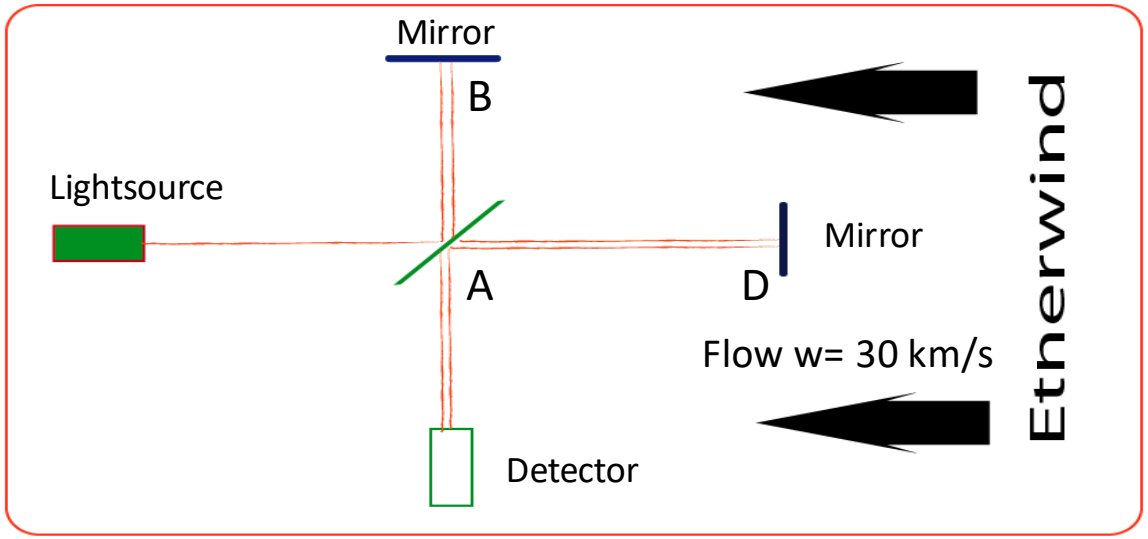
What do we expect to find for the travel times?

Comparison with water in a river

Swimmer crossing a river with flowing water



Light propagating through the ether wind



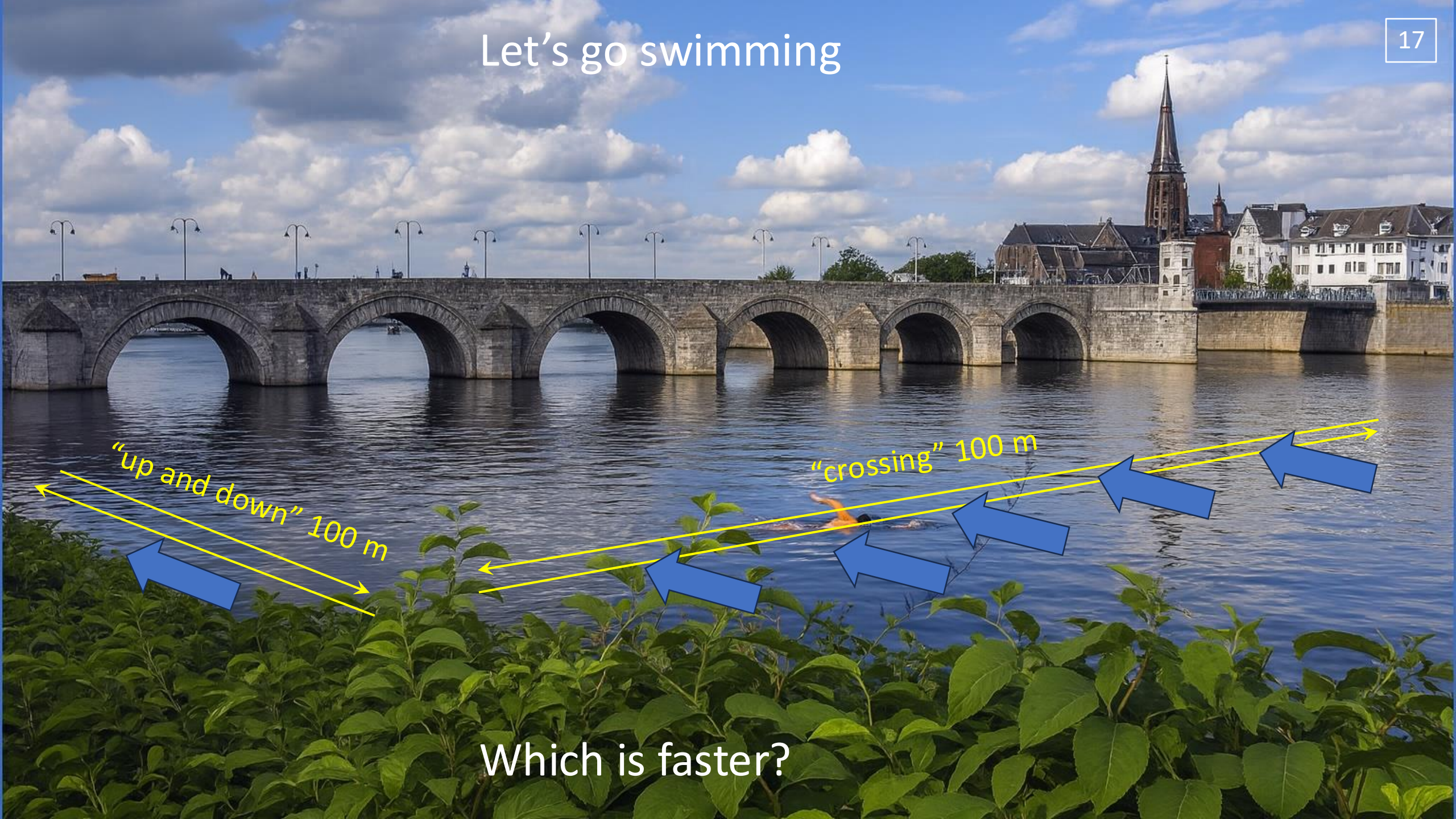
Compare swimming from A → B and back with swimming A → D and back.
Which one is faster?

Water flows from right to left: so swimmer needs to aim to C in order to reach B!

Lightbeam "swims" through the Ether from A → B and back, compared to A → D and back.
Which one is faster?

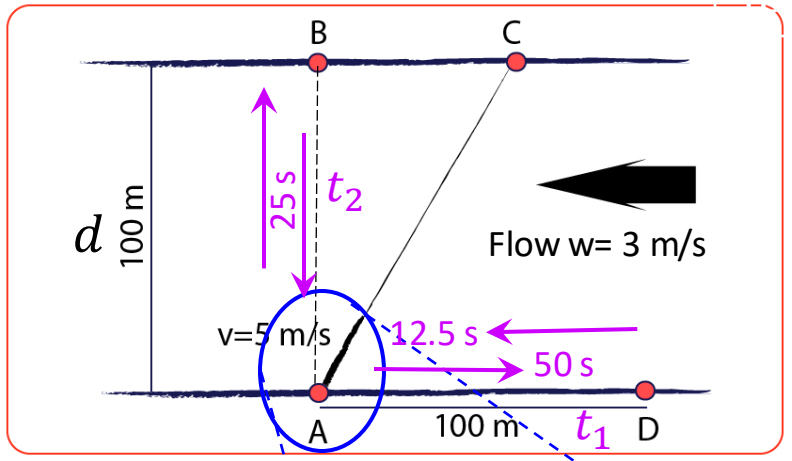
Suppose Ether flows from right to left.

Let’s go swimming



Which is faster?

Let's go: "Crossing" vs "Up-and-Down"



1. Swimming AD + DA: t_1 = time$_1$ + time$_2$=

v = 5 m/s
w = 3 m/s

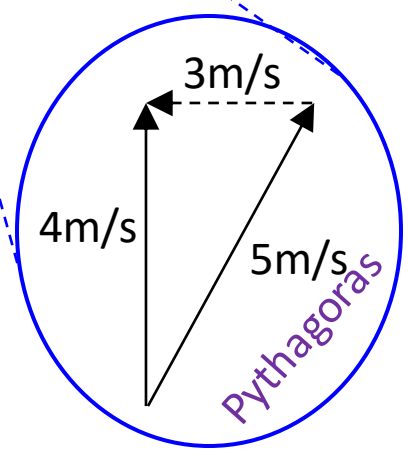
$= 100m/(5-3)m/s + 100m/(5+3)m/s$
$= 100m\ /\ (2m/s) + 100m\ /(8m/s)$
$= 50\ s + 12.5\ s = \mathbf{62.5\ s}$

2. Swimming AB + BA: Must swim under an angle A to C to compensate the flow w

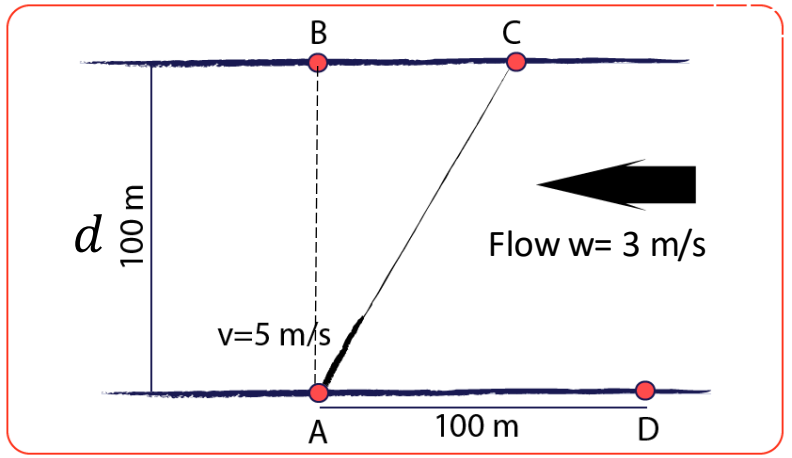
v = 5 m/s
w = 3 m/s

Effective crossing speed= $\sqrt{5^2 - 3^2}$= $\sqrt{25-9}$ =$\sqrt{16}$ = 4 m/s

t_2 = time$_1$ + time$_2$=
$= 100m\ /\ (4m/s) + 100m\ /\ (4\,m/s)$
$= 25\ s + 25\ s = \mathbf{50\ s}$



Let's go: "Crossing" vs "Up-and-Down"



1. Swimming AD + DA: t_1 = time$_1$ + time$_2$=

$= d/(v-w) + d/(v+w)$

$= d(v+w)/(v^2-w^2) + d(v-w)/(v^2-w^2)$

$= 2dv/\left(v^2(1-w^2/v^2)\right)$

$= \boxed{2\,d/v \;\times\; 1/(1-w^2/v^2)}$

2. Swimming AB + BA: Must swim under an angle A to C to compensate the flow w

Effective crossing speed= $\sqrt{v^2-w^2} = v\sqrt{(1-w^2/v^2)}$

t_2 = time$_1$ + time$_2$=

$= d/\sqrt{v^2-w^2} + d/\sqrt{v^2-w^2}$

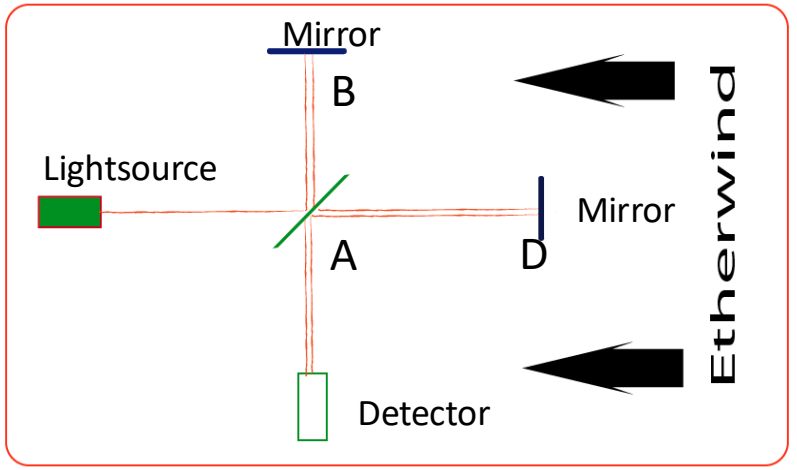
$= 2d/\left(v\sqrt{(1-w^2/v^2)}\right)$

$= \boxed{2d/v \times 1/\sqrt{(1-w^2/v^2)}}$

Translated to light, replace: $v \rightarrow c$ in ether wind w:

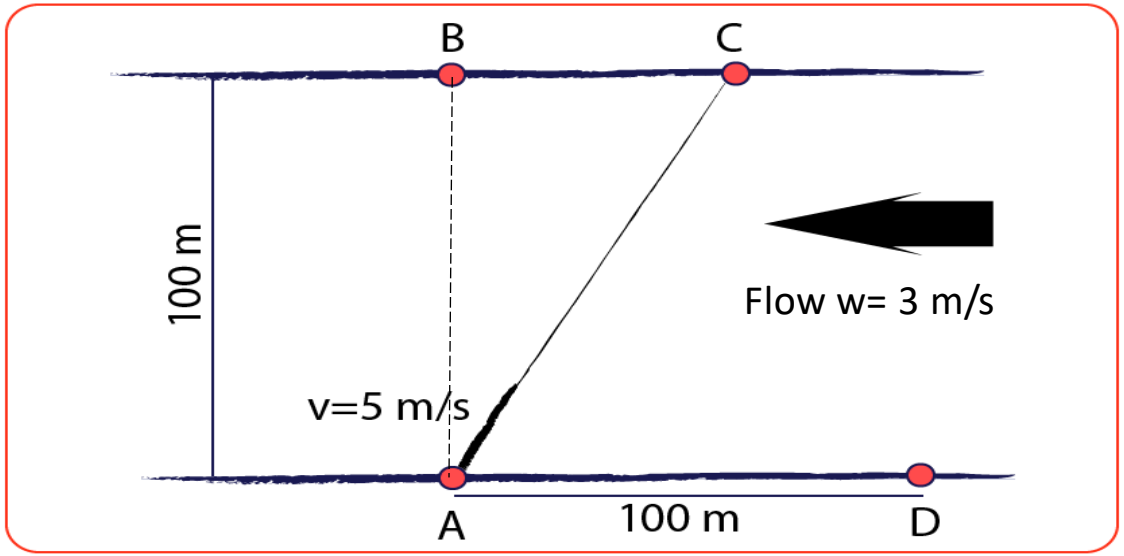
$$t_1 = 2d/c \;\times\; 1/\sqrt{(1-w^2/c^2)}$$
$$t_2 = 2d/c \;\times\; 1/(1-w^2/c^2)$$

Michelson-Morley measure:
Which is faster?

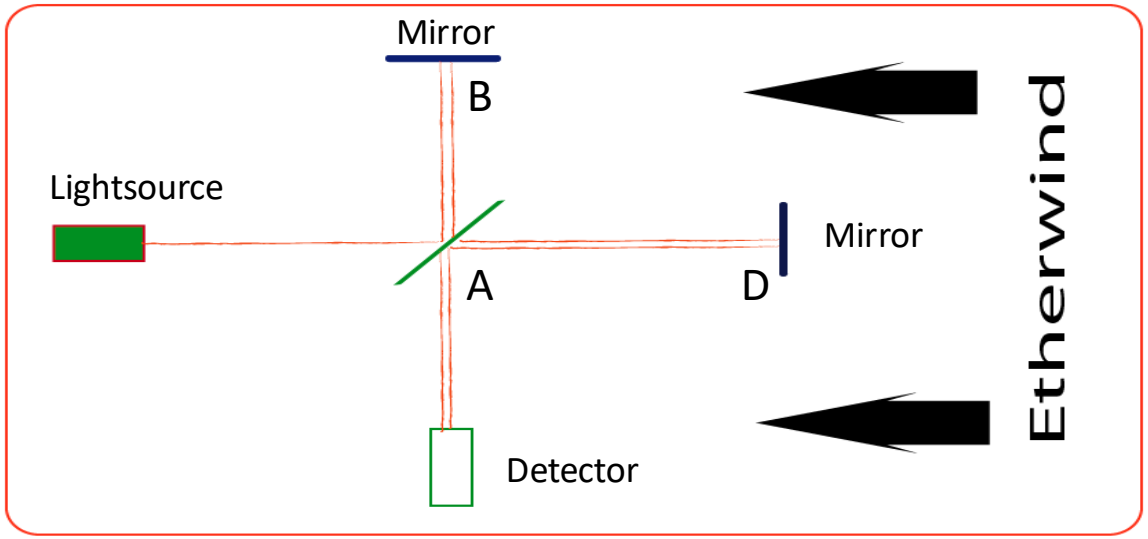


Comparison of two cases

Swimmer crossing a river with flowing water



Light propagating through the ether wind



The time *traversing* 100 meter is **shorter** than the time for 100 meter *up- and downstream*.

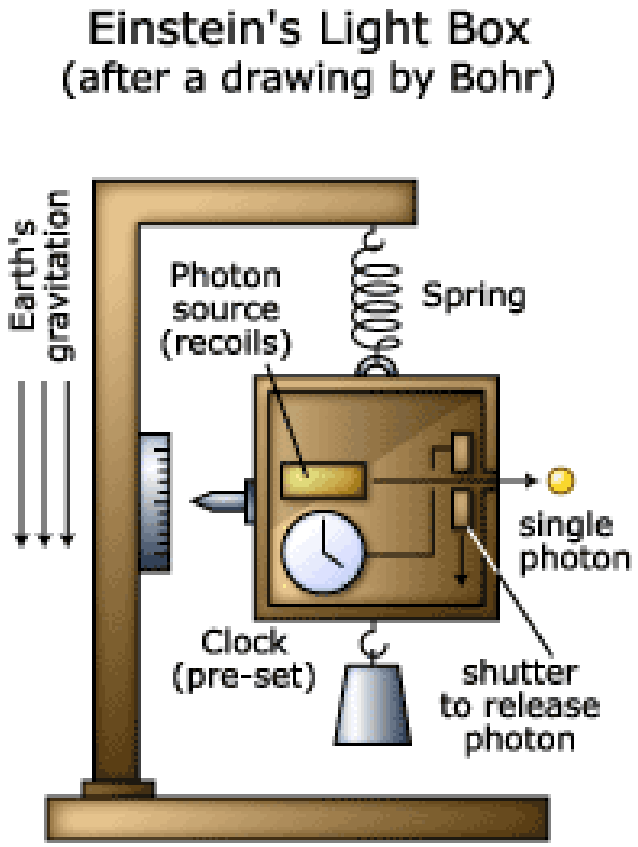
Measurement with light: **no effect**, travel times of A→D→A and A→B→A are the same!

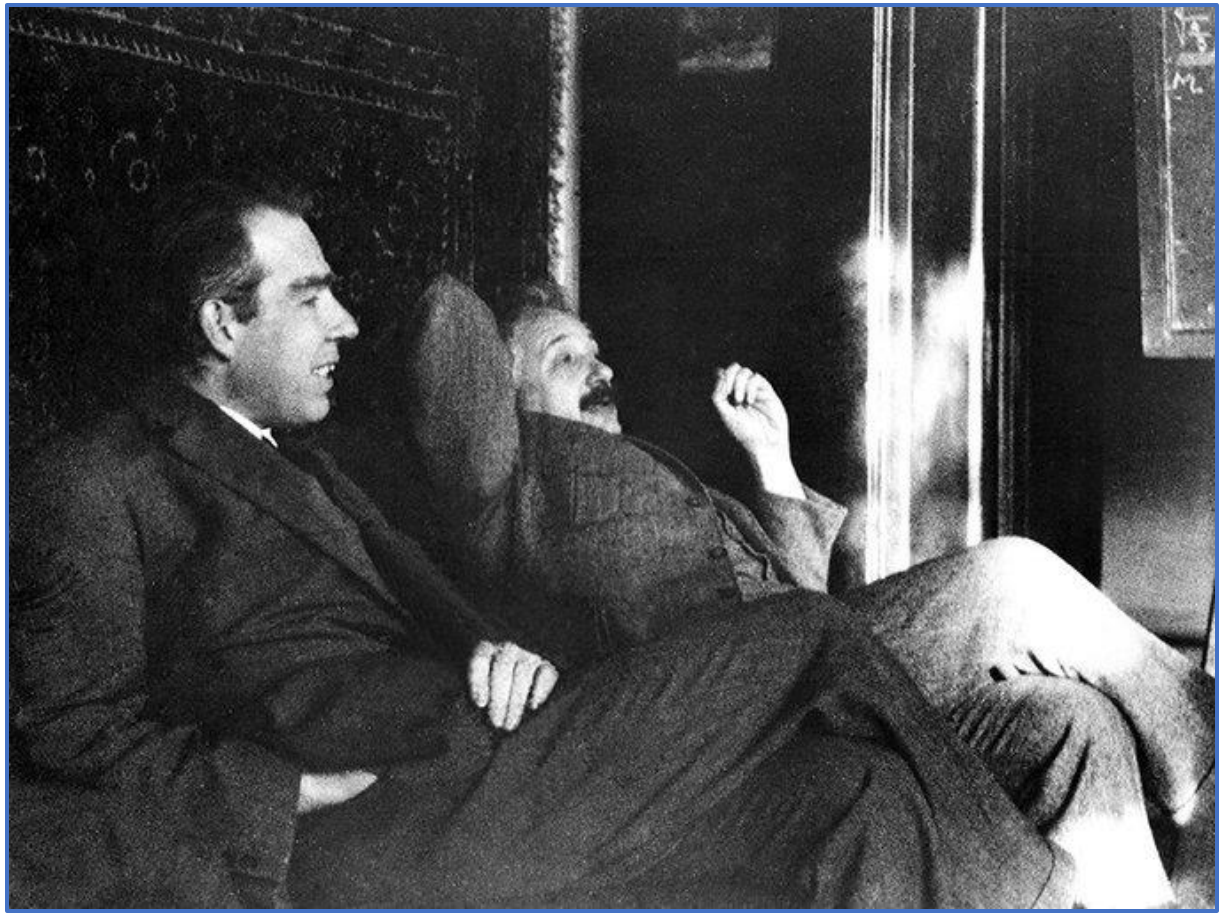
The speed of light is always constant!

"The vacuum is the same for any observer"

There is no ether!

A “Gedanken” Experiment…





Bohr and Einstein at Ehrenfest’s home in Leiden

A useful tool: Thought experiments:

Consider an experiment that is not limited by our level of technology.

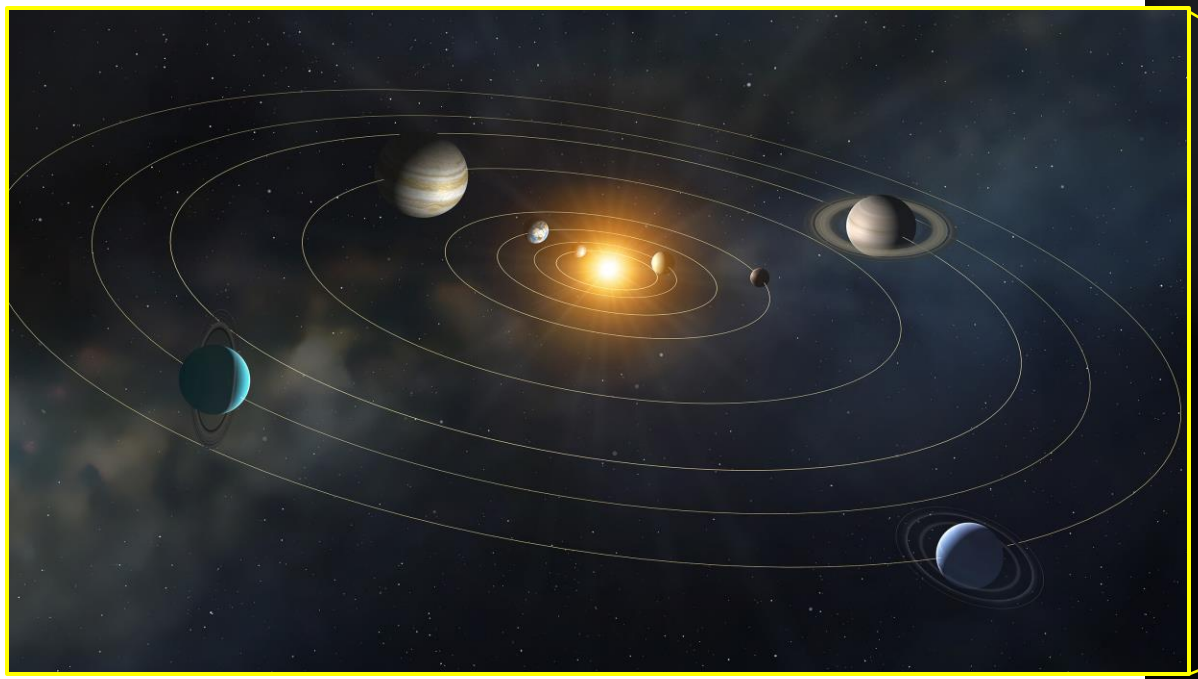
Assume the apparatus works so perfectly that we only test the limits of the laws of nature!

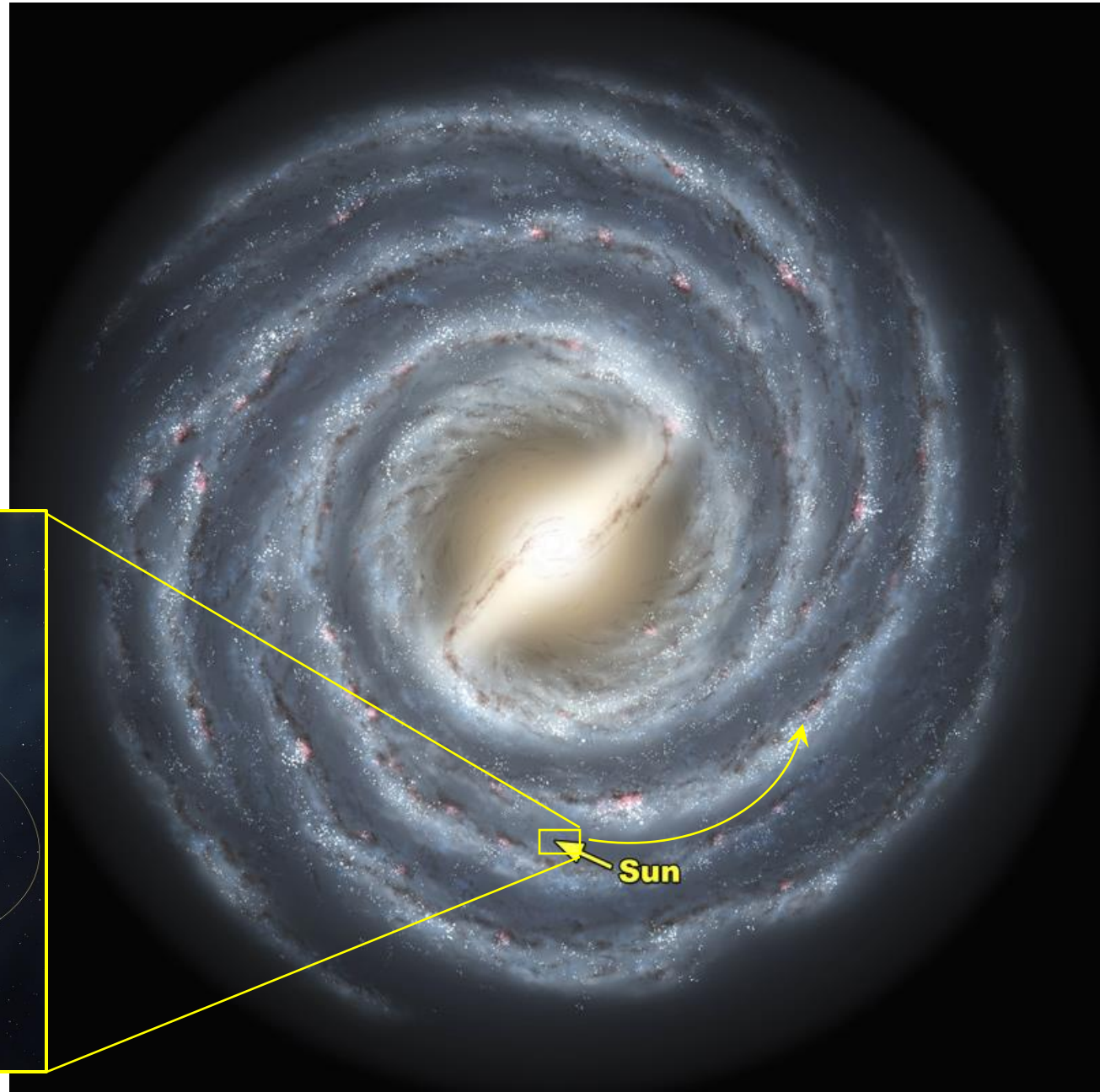
Absolute velocity?

The Sun and earth move in space
with a speed of 828000 km/h.
We do not notice it!

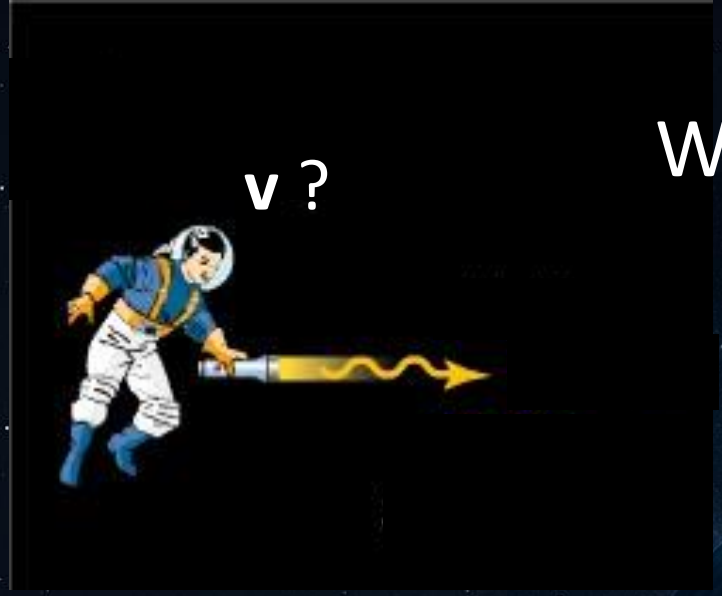
You may ask: speed with respect to what?
- Average of all other galaxies together?
- Cosmic Microwave Background?

But does “absolute velocity” make sense?

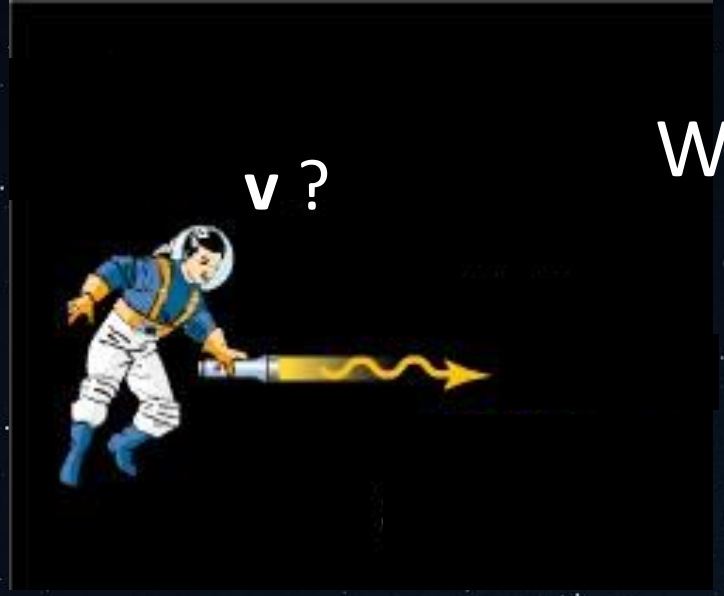




What is absolute velocity?



What is absolute velocity?



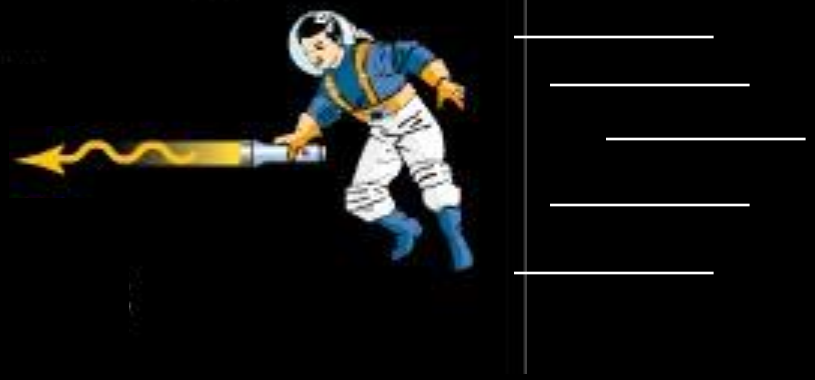
What is absolute velocity?

v ?

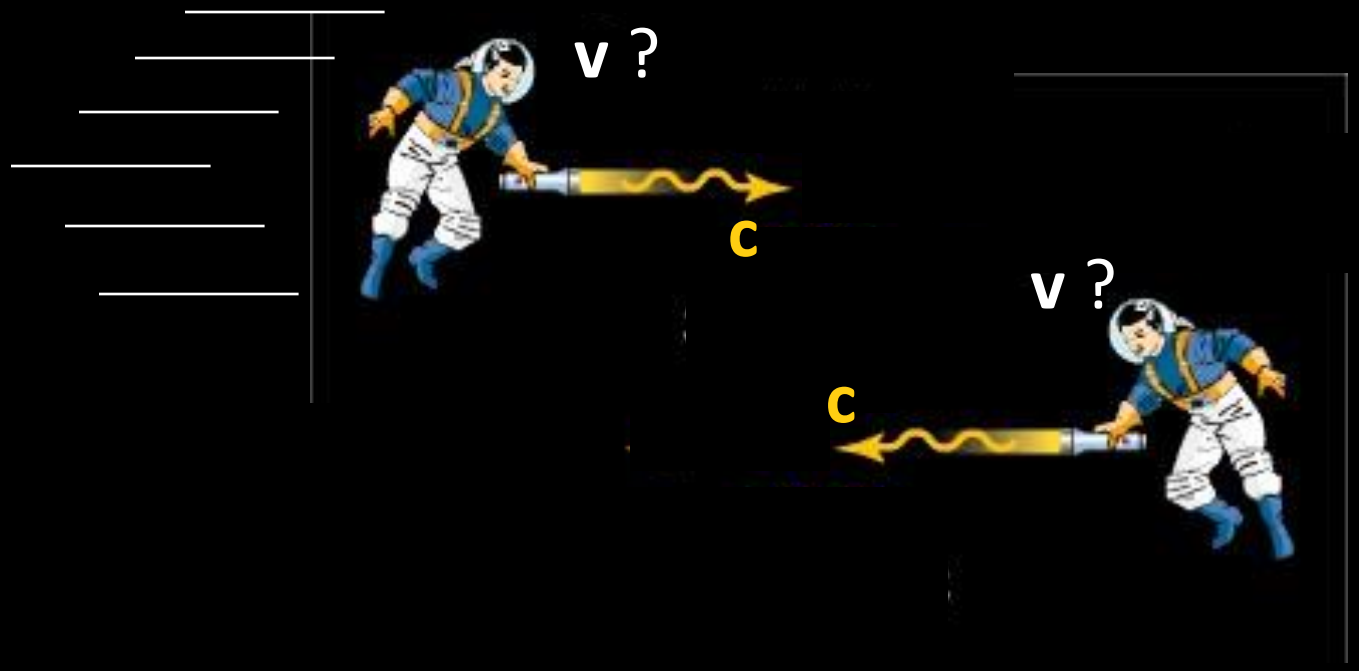
What is absolute velocity?

v ?

v ?



What is absolute velocity?



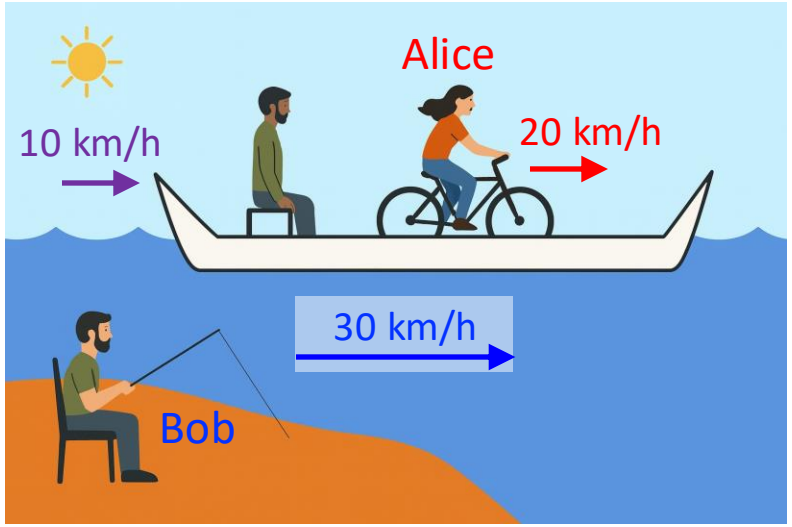
How can we define absolute velocity for an object?

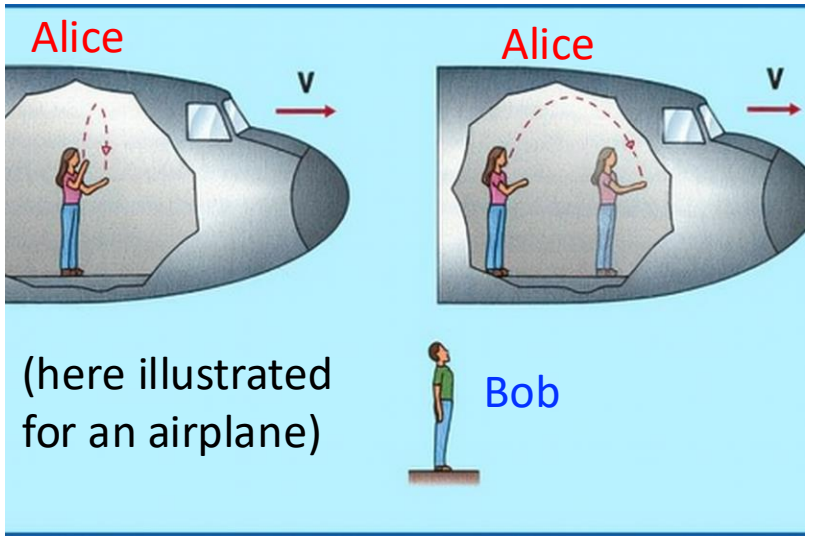
The speed of light “c” is always exactly the same for any observer !

Absolute velocity does not exist!

Thought experiment: Alice, Bob and Real Speed

Alice cycles with v = 20 km/h
The boat moves with w = 10 km/h
Bob sees 20 km/h + 10 km/h = 30 km/h
➔ What is now Alice' "real" speed??





Alice' cabin has no window and she wants to determine whether the boat moves by doing an experiment.
Can she find out she's moving 30 km/h?

➔ There is ***no way*** to determine absolute velocity

Astronauts in the ISS *do not notice* that they move with 29 000 km/h around earth!

Absolute velocity does not exist!!!

Inertial frames: Observers that move with a constant relative velocity

Special Relativity

Postulates of Special Relativity

Two observers in so-called Inertial frames, i.e. they move with a constant relative speed to each other, observe that:

1) The laws of physics for each observer are the same,
2) The speed of light in vacuum for each observer is the same.

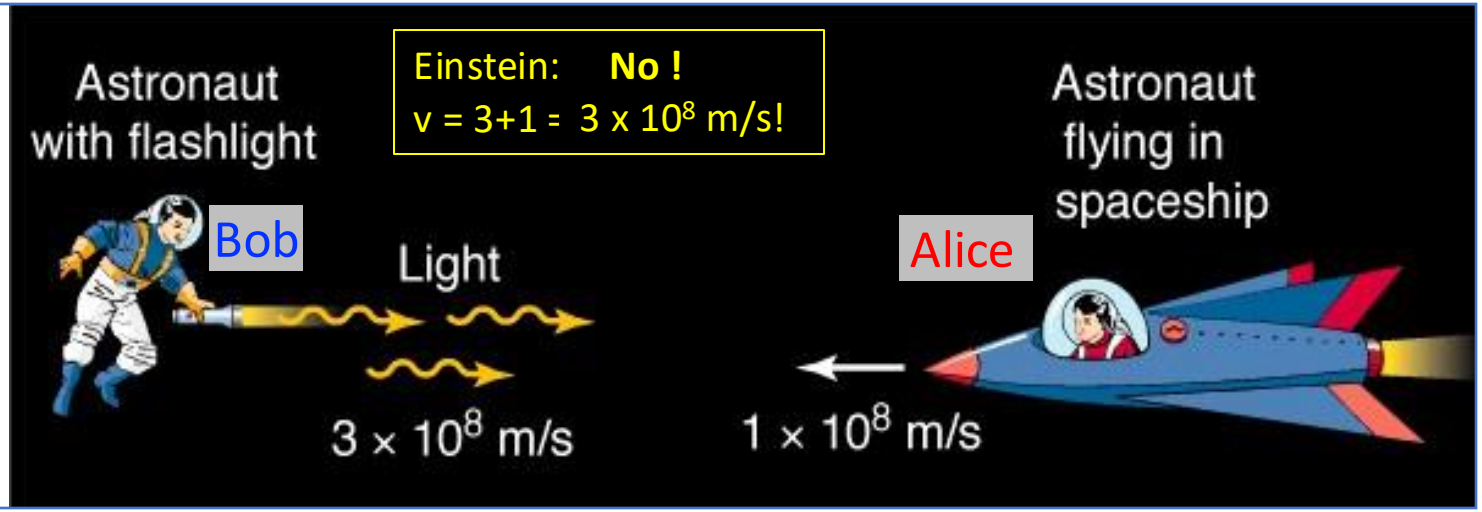
A thought experiment:

Bob measures the speed of light rays.

→ *What does he find?* $3 \times 10^8\ m/s$

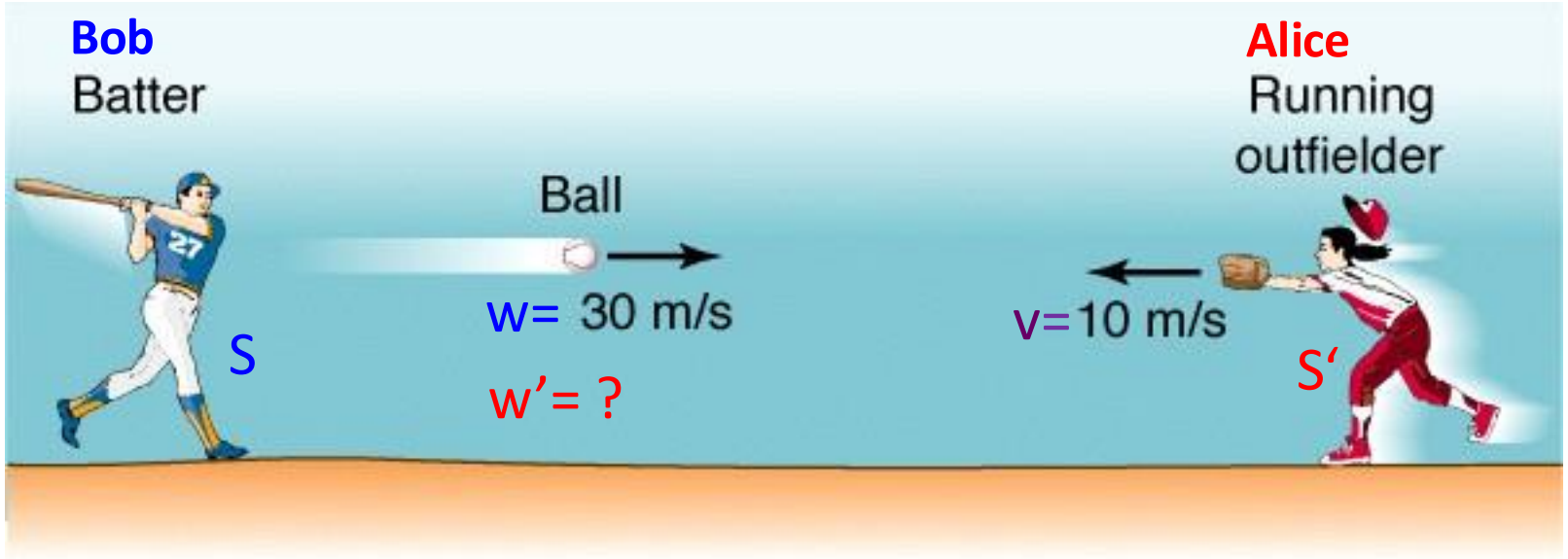
Alice also measures the speed of the same light rays.

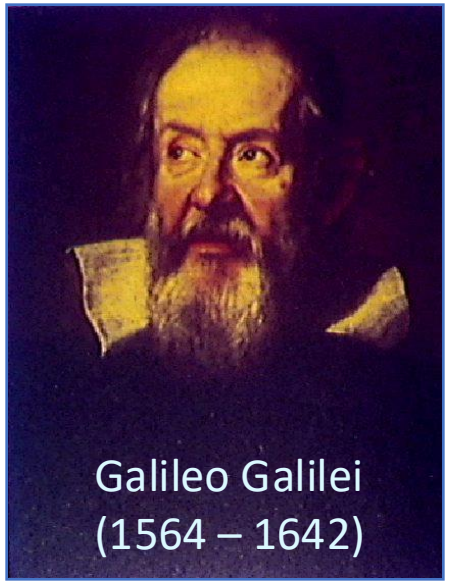
→ *What does she find?* $3 \times 10^8\ m/s$



Special Relativity is in clear contradiction with the Galilei law of addition of velocities!

Galilei and Einstein Transformation law





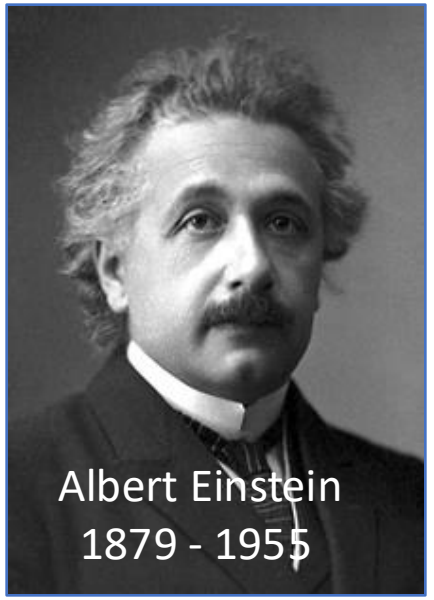
With which speed do Alice and the ball hit by Bob approach each other?
Intuitive law (daily experience): 30 m/s + 10 m/s = 40 m/s

Galilei formula: $w' = w + v = 30 + 10 = 40\ m/s$

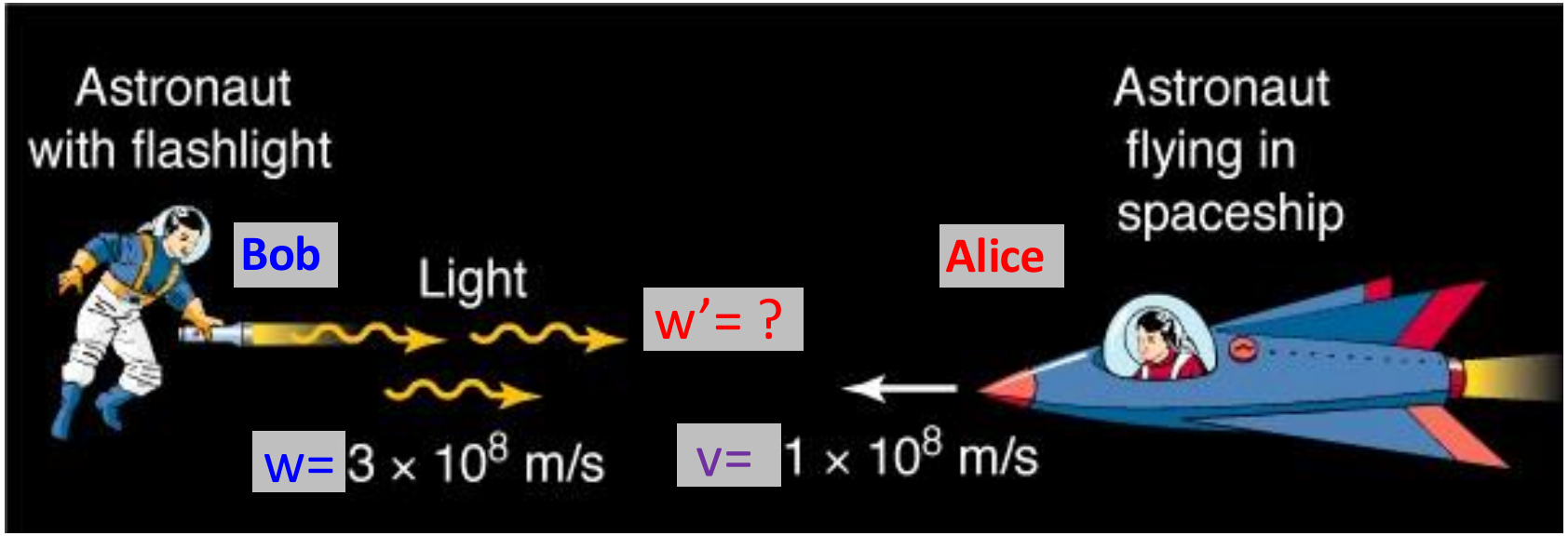
Einstein formula: $w' = \frac{w + v}{1 + \frac{vw}{c^2}} = \frac{30 + 10}{1 + \frac{30 \times 10}{9 \times 10^{16}}} =$

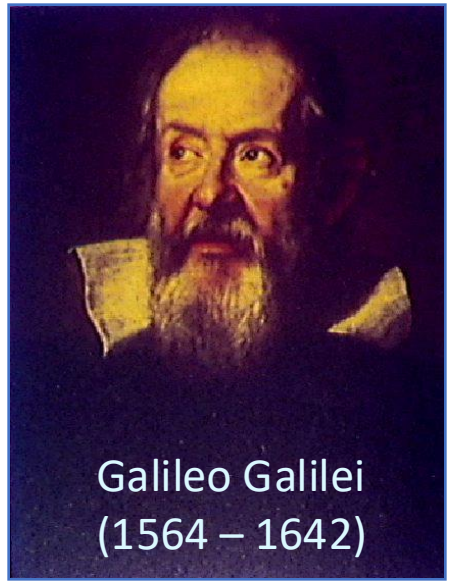
(see lecture 3)

$= 39.999999999999997\ m/s$



Galilei and Einstein Transformation law





With which speed do Alice and the light sent by Bob approach each other?

Intuitive law: 300 000 km/s + 100 000 km/s = 400 000 km/s

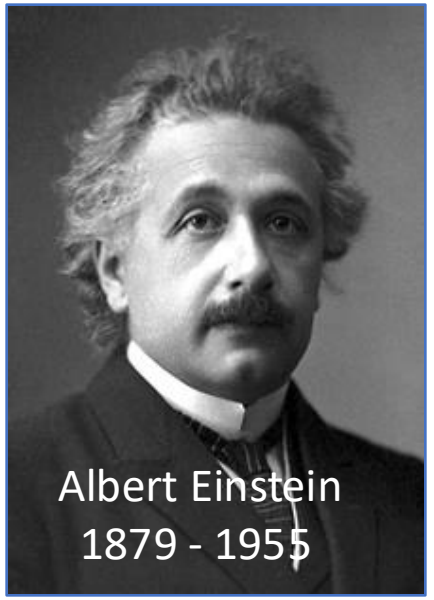
Galilei formula: $w' = w + v = 3 \times 10^8 + 1 \times 10^8 = 4 \times 10^8 \text{ m/s}$

$= 400\,000 \text{ km/s}$

Einstein formula: $w' = \dfrac{w + v}{1 + \dfrac{vw}{c^2}} = \dfrac{3 \times 10^8 + 1 \times 10^8}{1 + \dfrac{(3 \times 10^8) \times (1 \times 10^8)}{9 \times 10^{16}}}$

(see lecture 3)

$= 300\,000 \text{ km/s}$ The same speed of light!



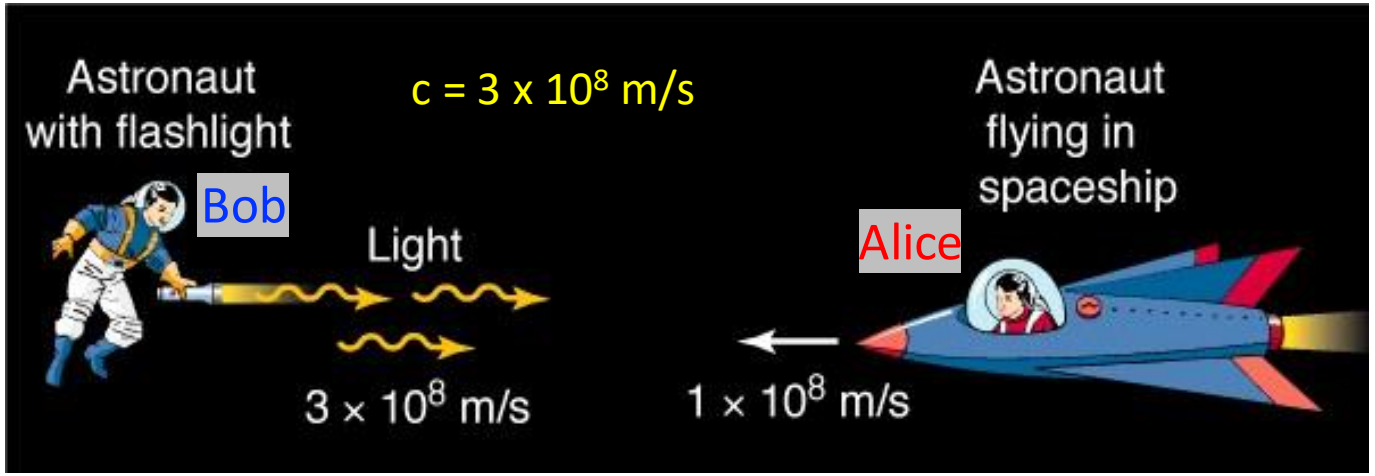
Absolute Velocity for Alice and Bob

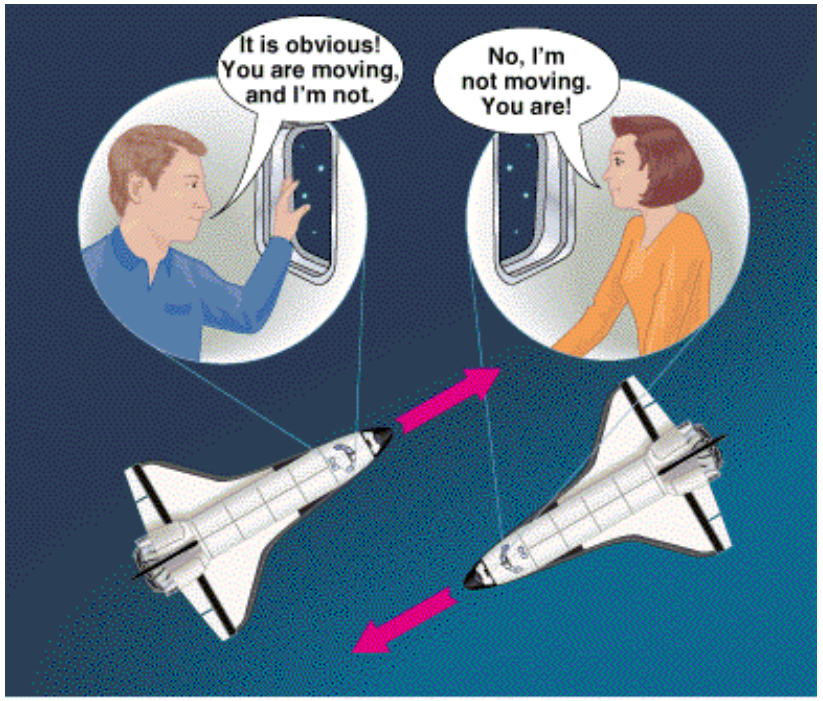
We can never measure an absolute velocity in vacuum.

Impossible to say who is “standing still” with respect to the vacuum.

The only absolute reference is the speed of light and it is always 300 000 km/s for every one.

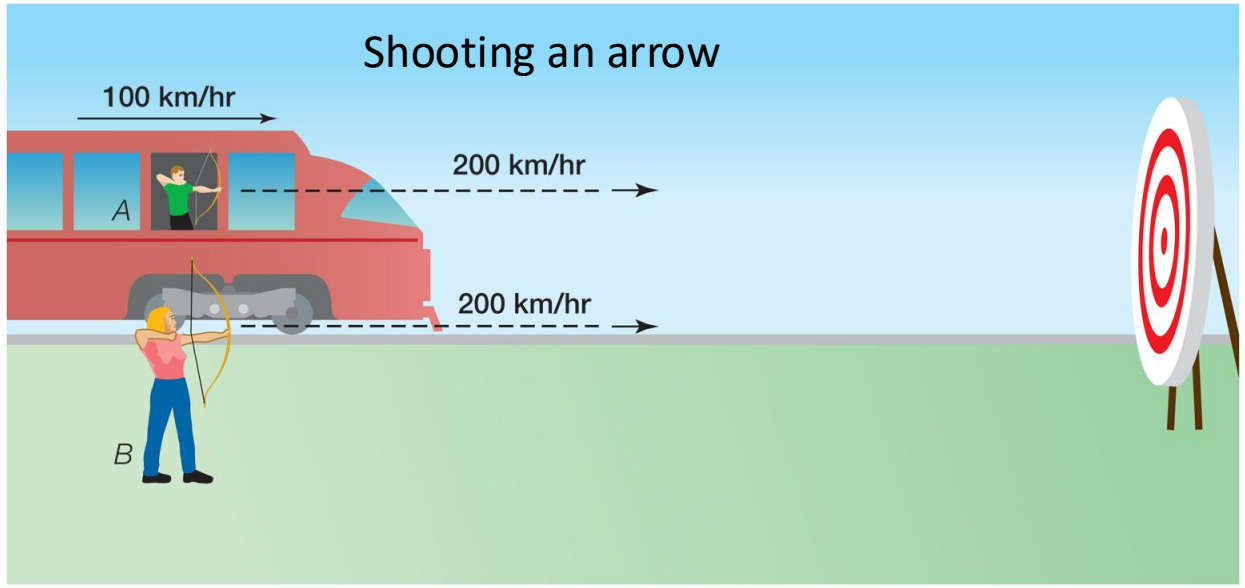
In special relativity absolute velocity has no meaning, only relative velocities do. Hence: “Theory of relativity”.

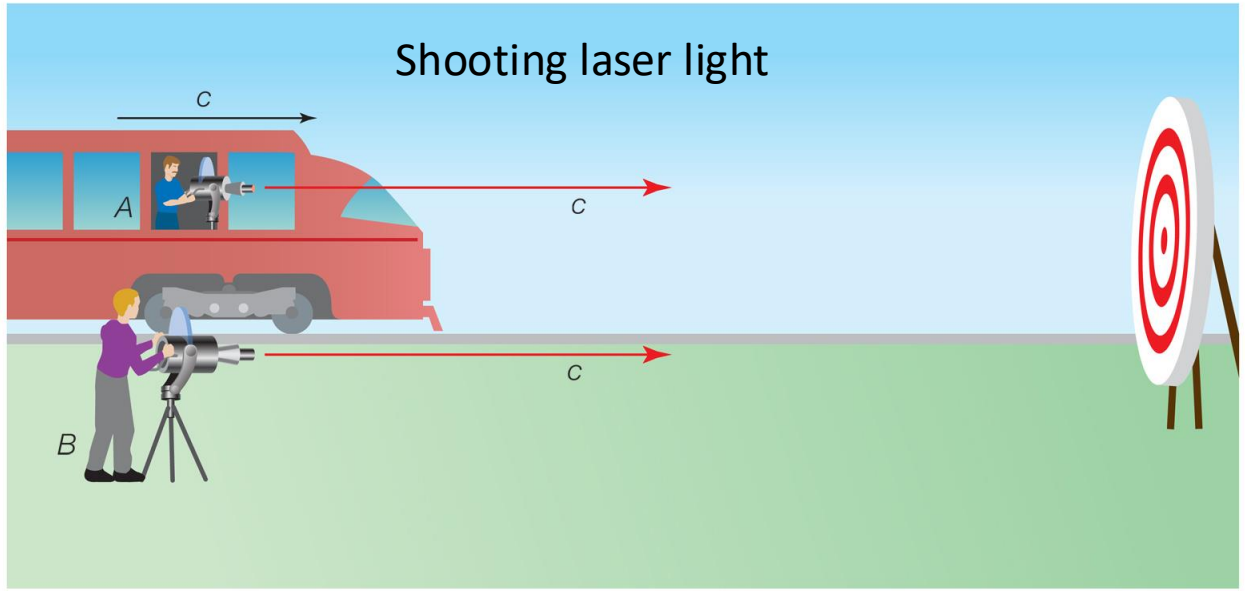




“Absolute velocity” is meaningless

Completely Counterintuitive!



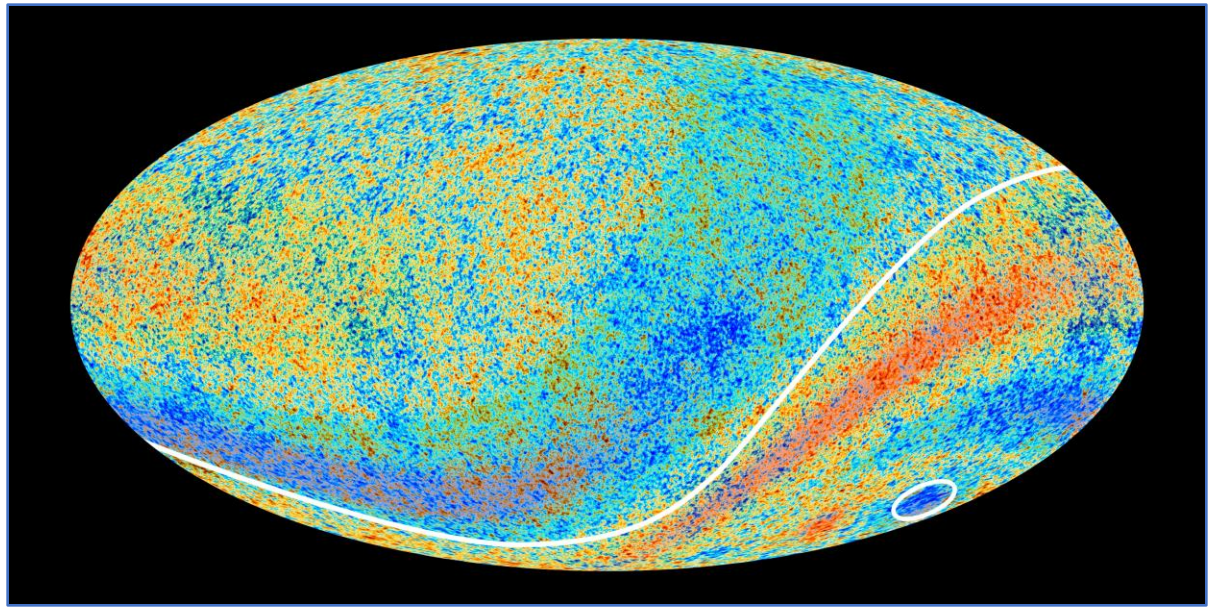


How about the cosmic microwave background? – experts!

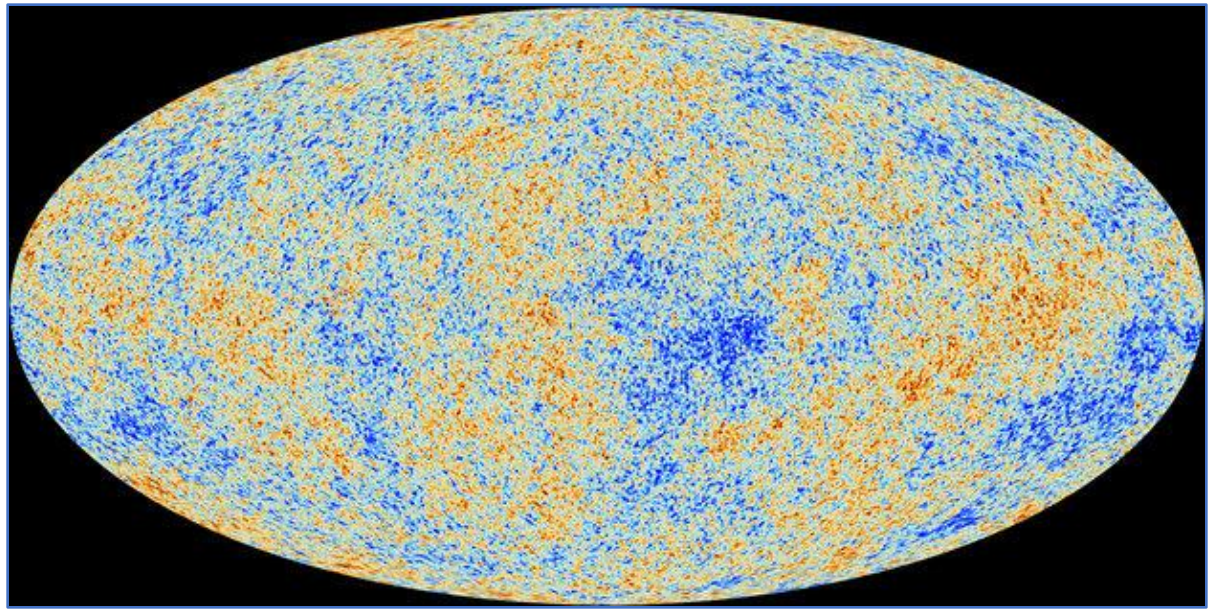
Cosmic microwave background radiation is light that is emitted in early universe and comes from all directions in space!

So does the dipole define an absolute Lorentz frame in the universe?

Can we measure absolute velocity by comparing to that special reference frame?



Dipole effect of earth movement in space visible as a sine wave.



After subtraction of the dipole effect what remains is uniform radiation spectrum of 2.7 K