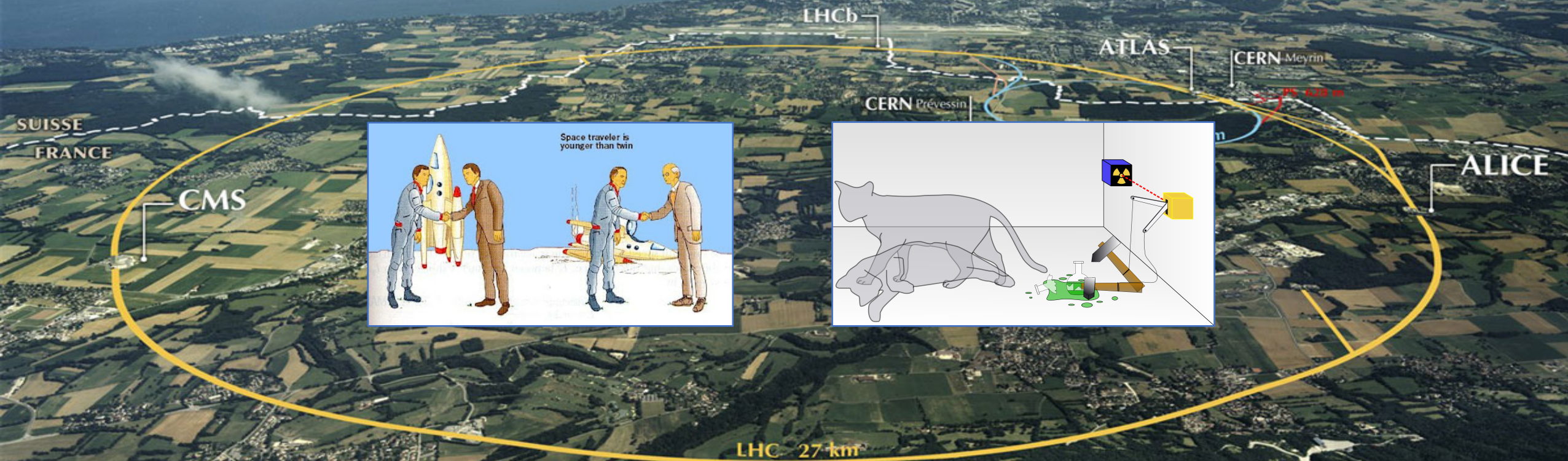


The Relativistic Quantum World

A lecture series on Relativity Theory and Quantum Mechanics

Marcel Merk



University of Maastricht, Sept 16 – Oct 14, 2020

Who am I

1

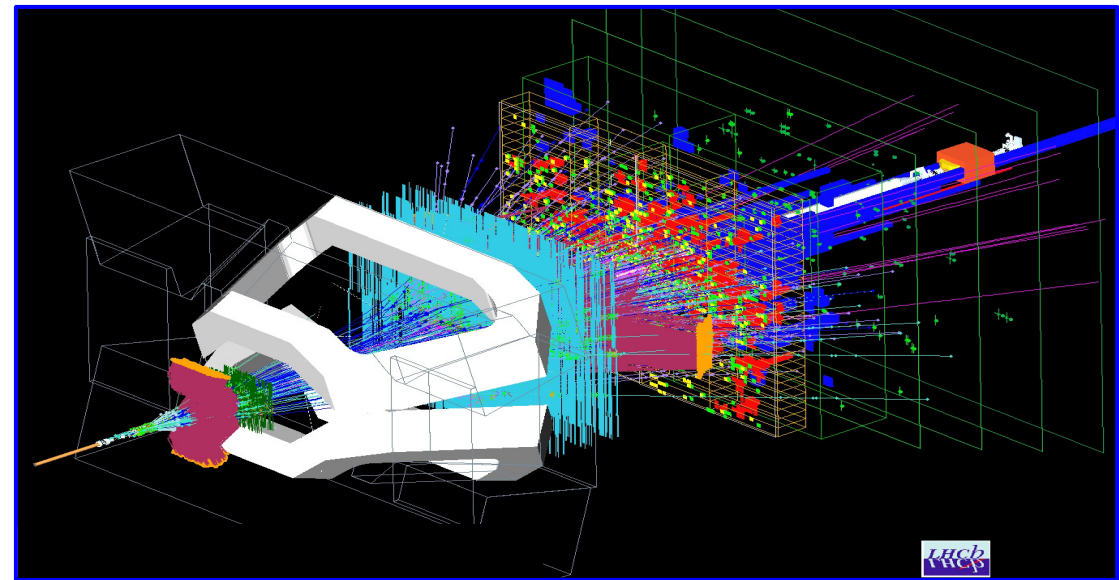
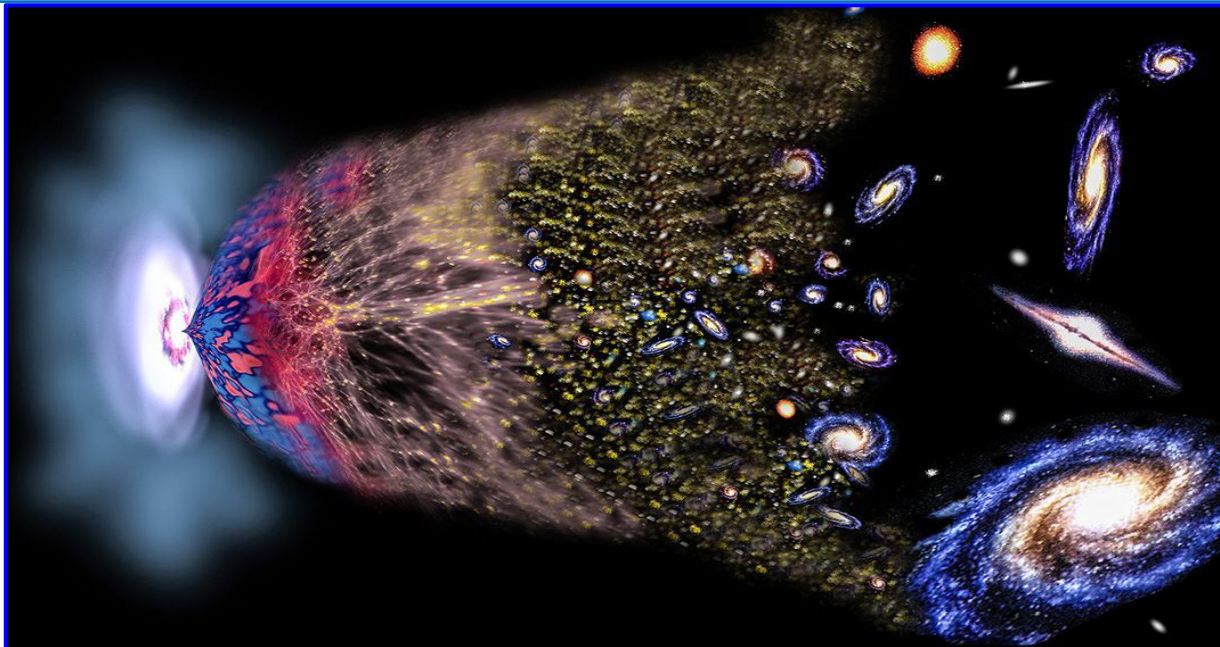
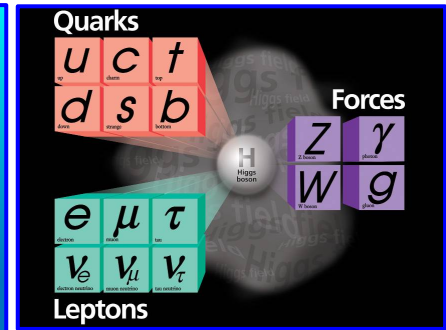
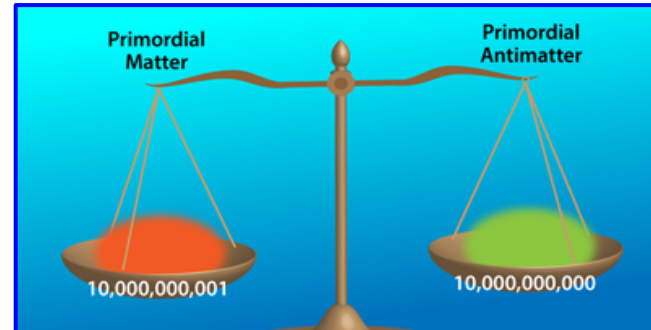
Email: marcel.merk@nikhef.nl

CV: 1976 – 1982 : High-school St. Maartenscollege, Maastricht
1982 – 1987 : Study Physics at Radboud University, Nijmegen
1987 – 1991 : PhD study in Nijmegen and CERN
1991 – 1994 : Postdoc Carnegie Mellon University, Pittsburgh
1994 – 1997 : Postdoc Nikhef, Amsterdam
1997 – 2000 : Fellow Royal Dutch Academy at Utrecht
2000 – today: Researcher at Nikhef, Amsterdam
2005 – today: Extraordinary Professor at the VU, Amsterdam
2020 – today: Professor at the University of Maastricht

Website: www.nikhef.nl/~i93

Research:

- Why a *matter-vs-antimatter asymmetry* in nature?
- Why do we have *three generations* of particles?
- The *Large Hadron Collider* at CERN.



Relativity

Sept. 16:

Lecture 1: The Principle of Relativity and the Speed of Light
Lecture 2: Time Dilation and Lorentz Contraction

Sept. 23:

Lecture 3: The Lorentz Transformation and Paradoxes
Lecture 4: General Relativity and Gravitational Waves

Quantum Mechanics

Sept. 30:

Lecture 5: The Early Quantum Theory
Lecture 6: Feynman's Double Slit Experiment

Oct. 7:

Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat
Lecture 8: Quantum Reality and the EPR Paradox

Standard Model

Oct. 14:

Lecture 9: The Standard Model and Antimatter
Lecture 10: The Large Hadron Collider

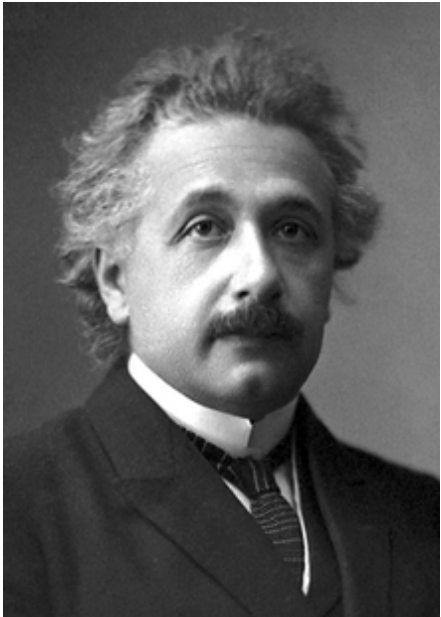
Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

“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 aether → Relativity Theory
2. The stability of the atom → Quantum Mechanics



Albert Einstein



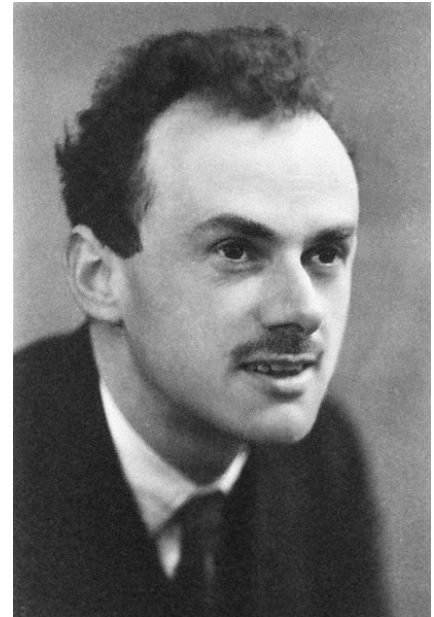
Niels Bohr



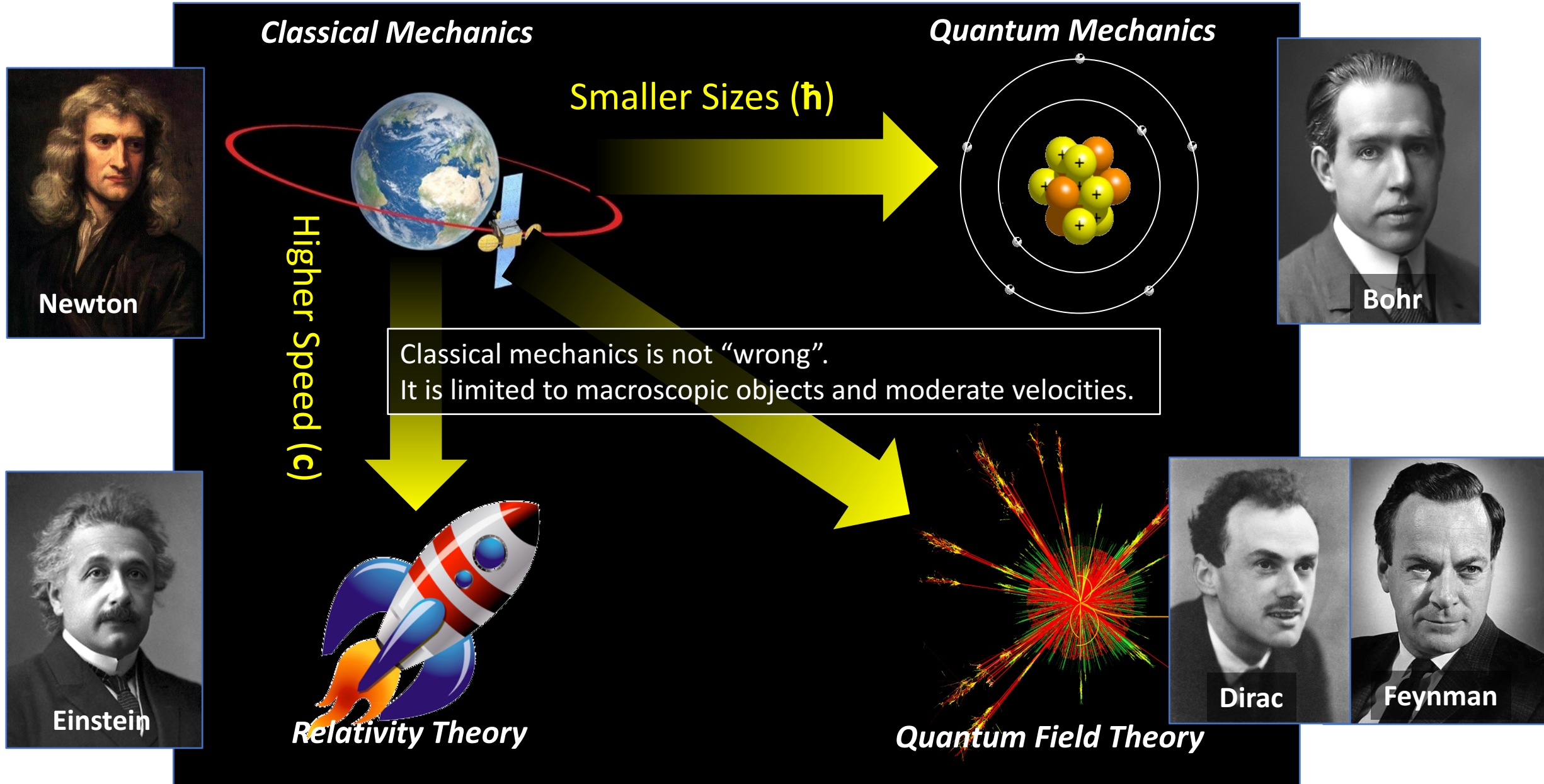
Werner Heisenberg



Erwin Schrödinger



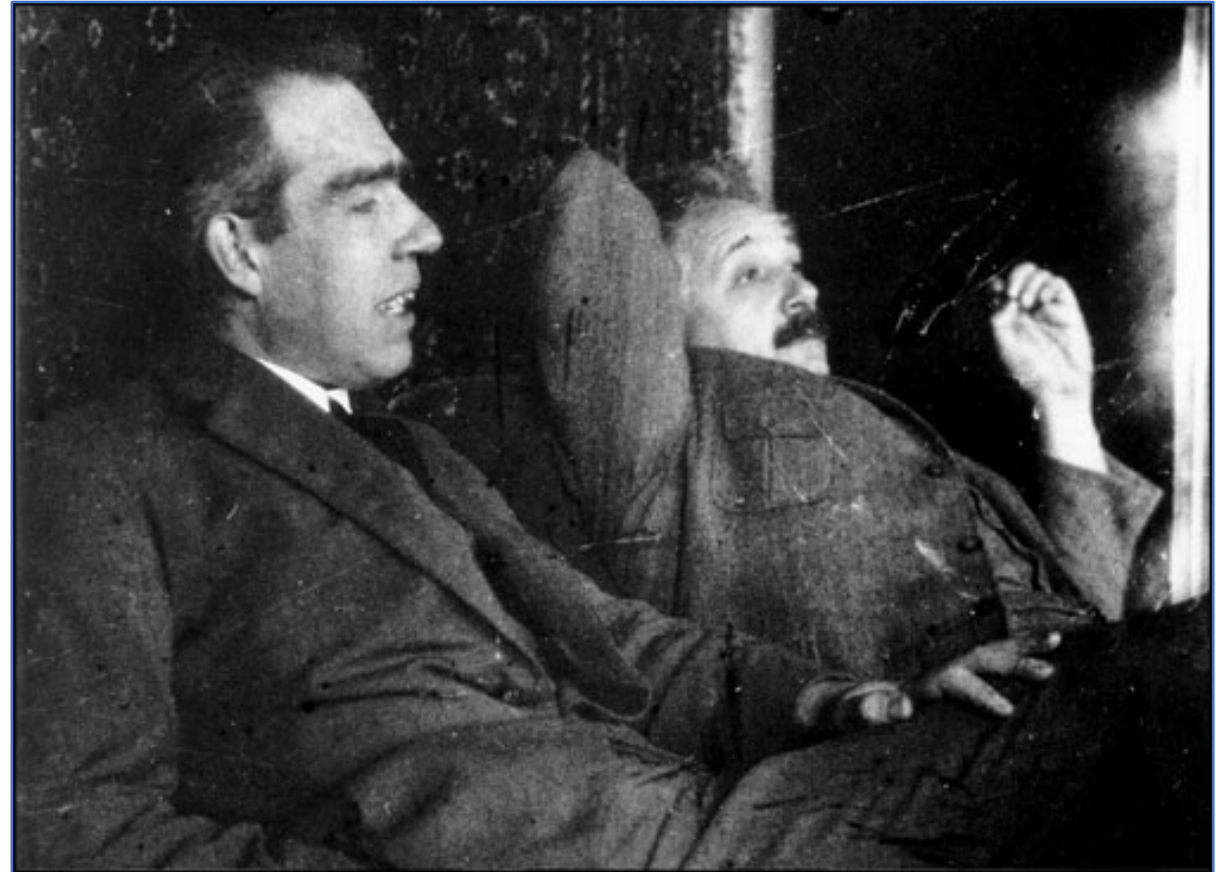
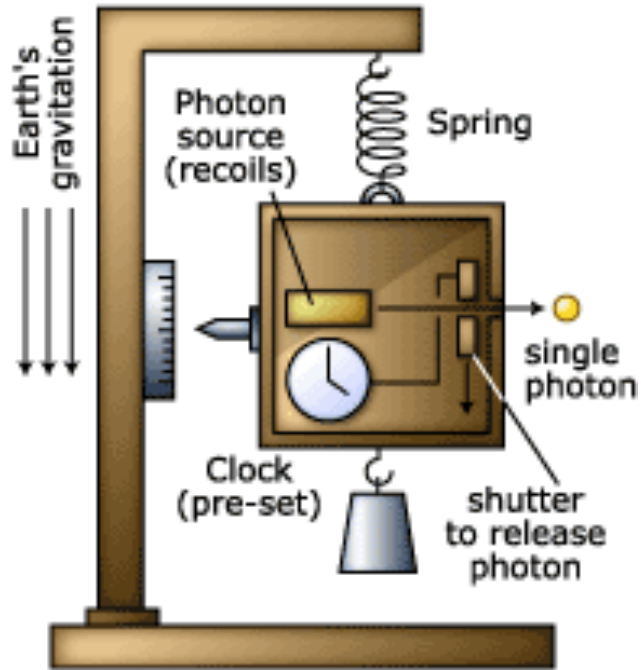
Paul Dirac



A “Gedanken” Experiment

5

Einstein's Light Box
(after a drawing by Bohr)



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!

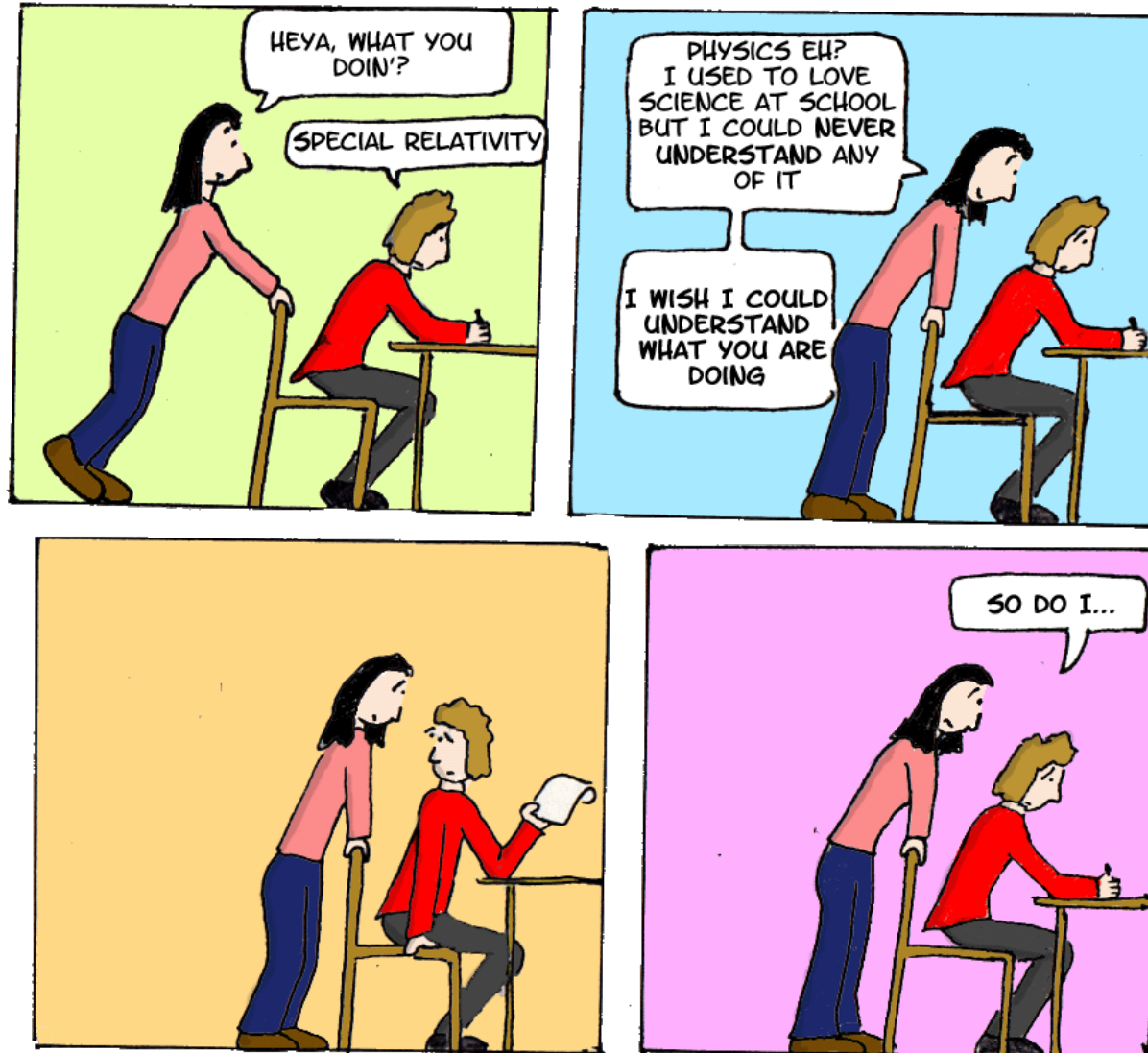
Lecture 1

The Principle of Relativity and the Speed of Light

“If you can’t explain it simply you don’t understand it well enough”

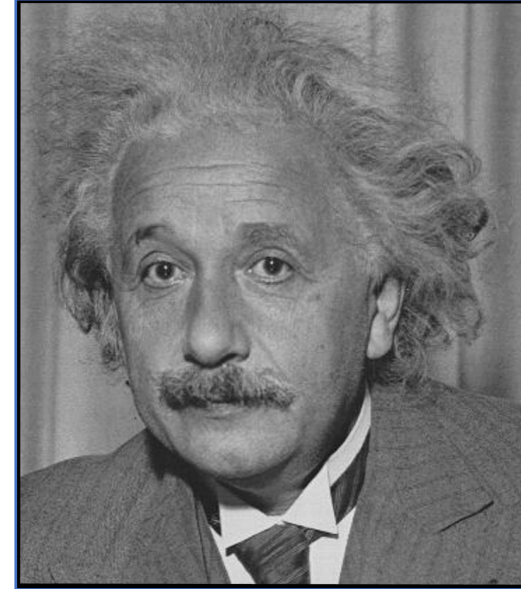
- Albert Einstein

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



“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**
 - 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, ...

“Nothing can move faster than the speed of light”

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What is the speed of light?

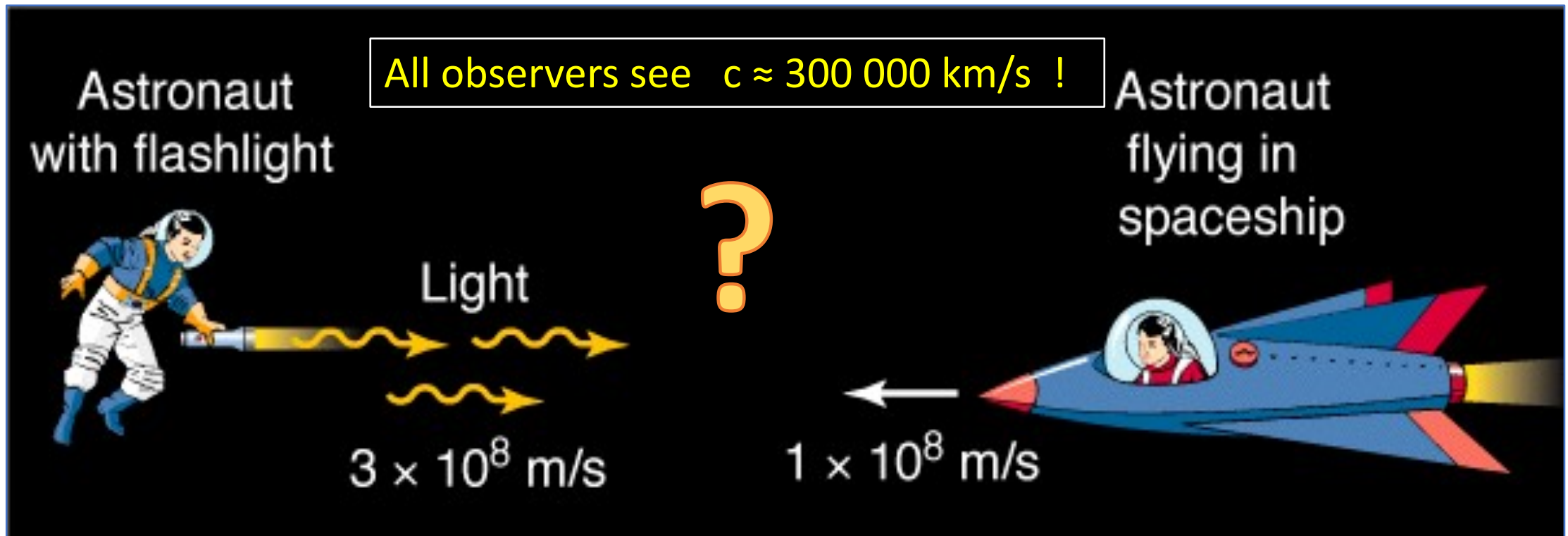
“300 000 km/s”

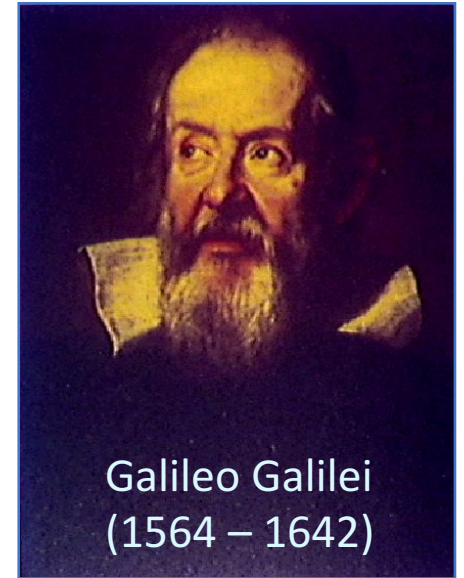
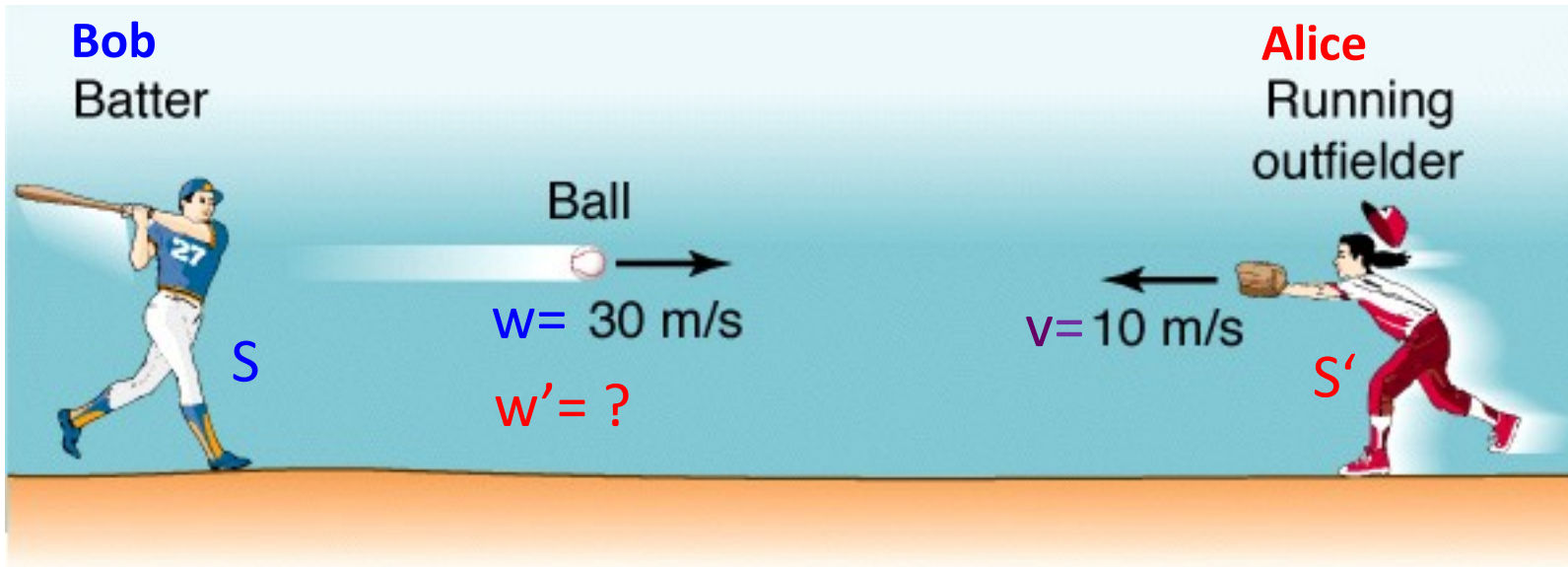
Relative to what?

“to the vacuum”

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

$c \approx 300\,000\text{ km/s}$





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

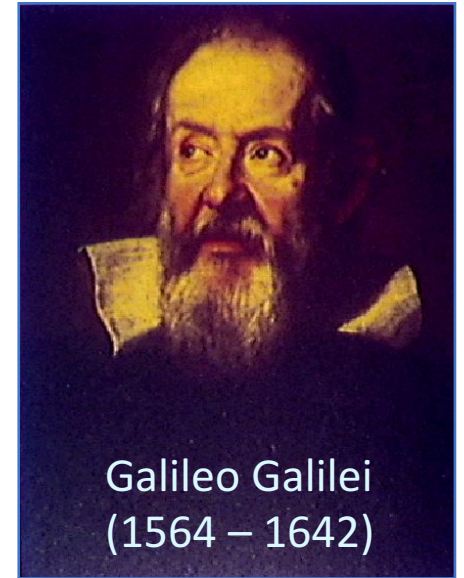
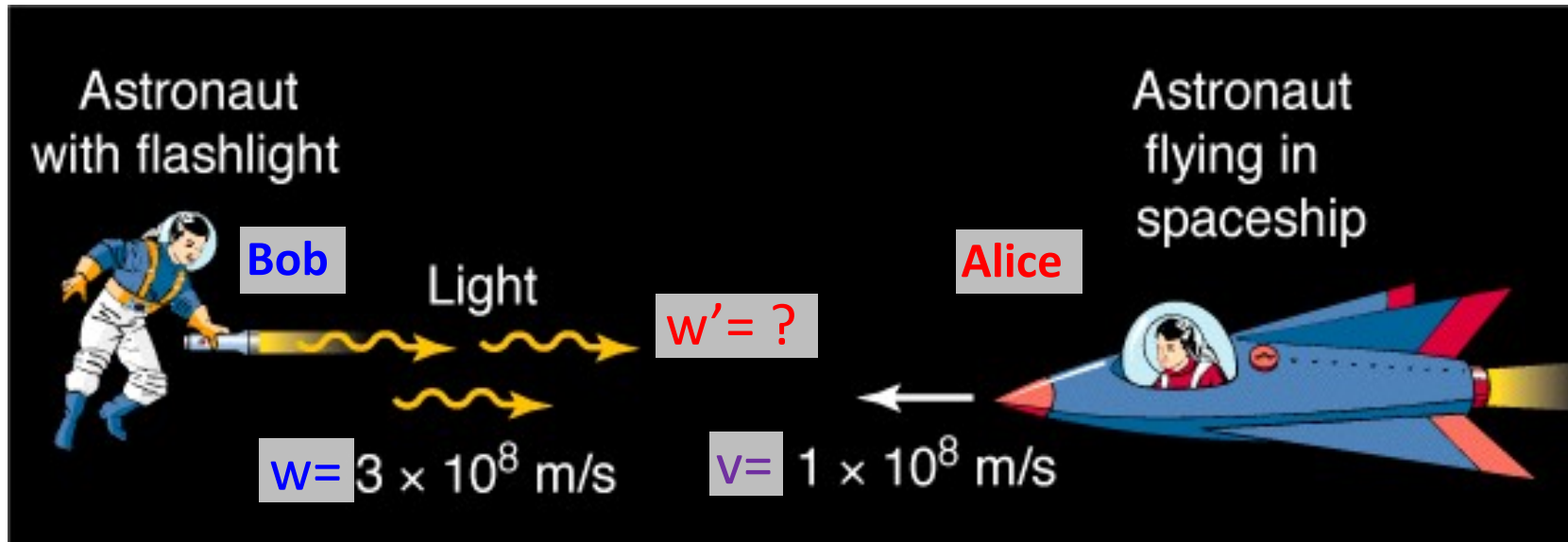
More formal: Observer **S** (**Bob**) observes the ball with relative velocity: w

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.



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

Intuitive law: $300\,000 \text{ km/s} + 100\,000 \text{ km/s} = 400\,000 \text{ km/s} ???$

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.

Alice, Bob and Real Speed

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Alice cycles with $v = 20 \text{ km/h}$

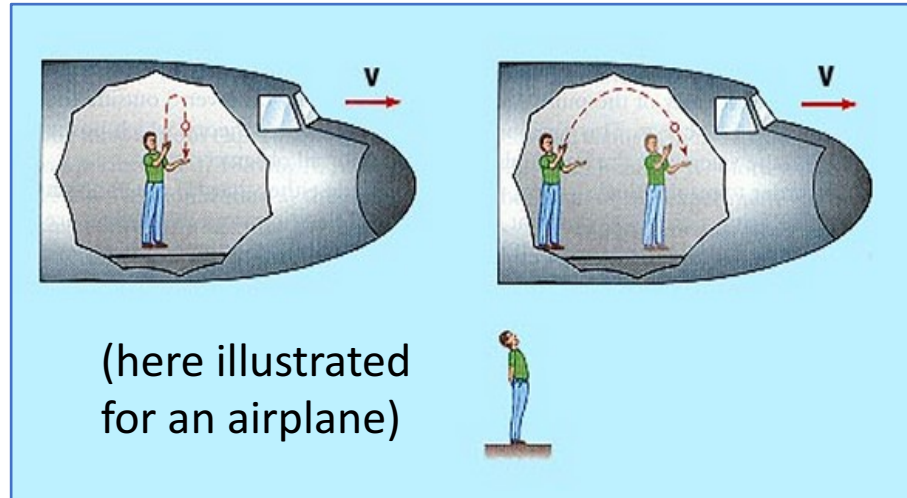
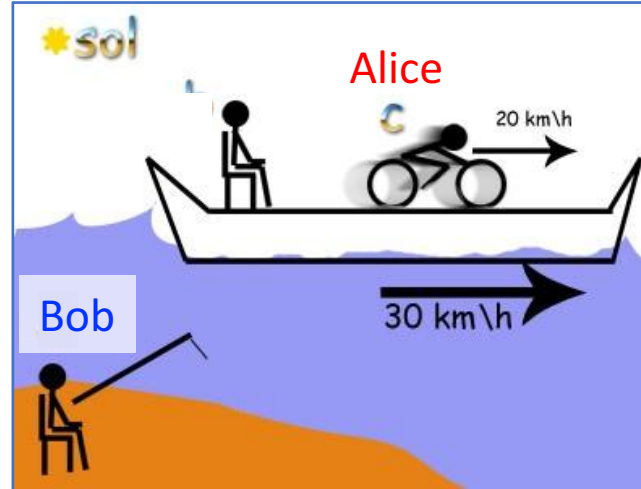
The boat moves with $w = 10 \text{ km/h}$

Bob sees $20 \text{ km/h} + 10 \text{ km/h} = 30 \text{ km/h}$

➔ What is now the “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?



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

Absolute velocity does not exist!!!

Inertial frames: Observers that move with a constant relative velocity

Special Relativity

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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.



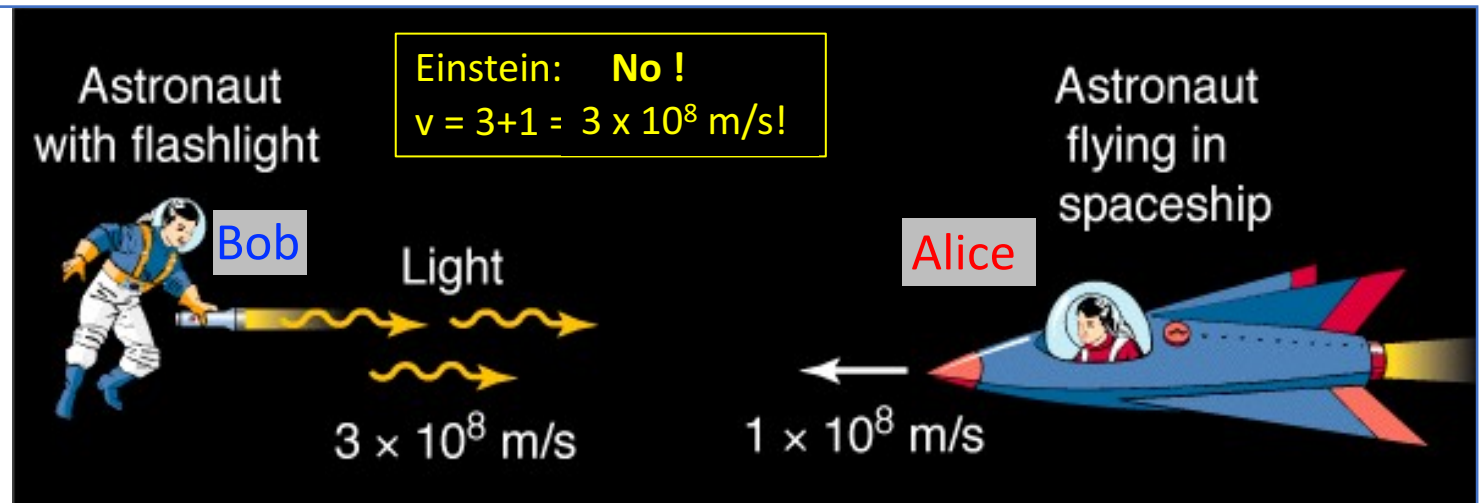
A thought experiment:

Bob measures the speed of light rays.

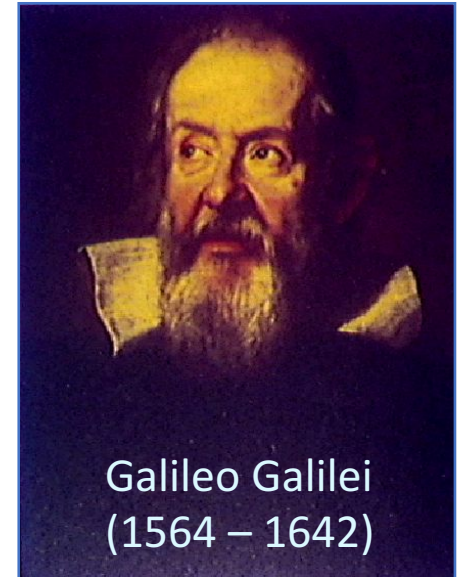
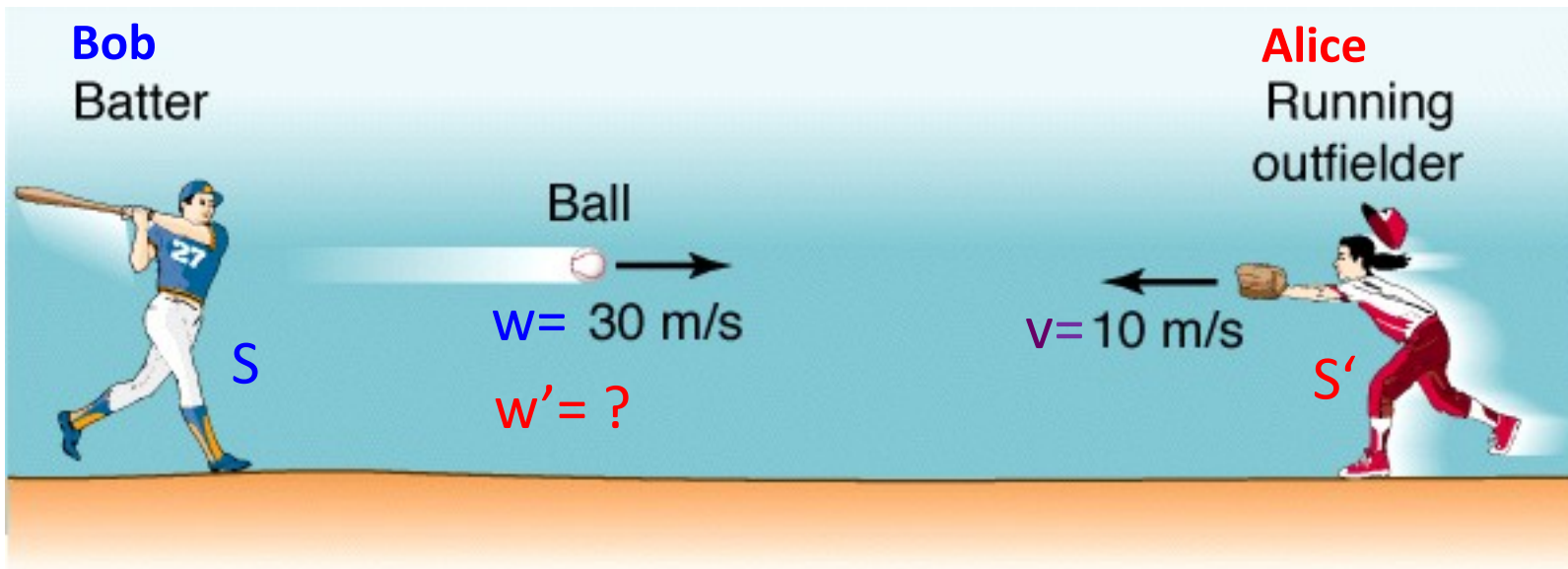
→ *What does he find?* $3 \times 10^8 \text{ m/s}$

Alice also measures the speed of the same light rays.

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



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

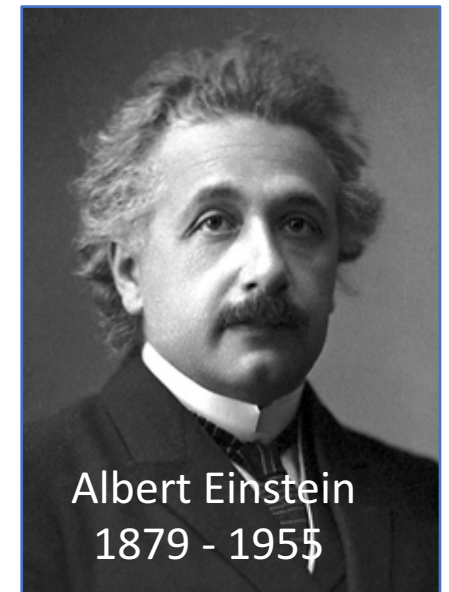


Galileo Galilei
(1564 – 1642)

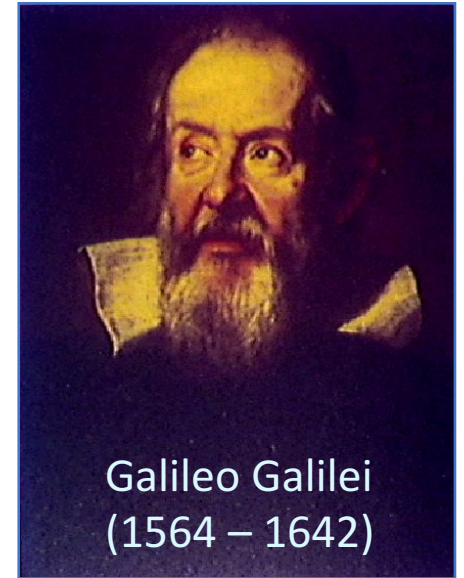
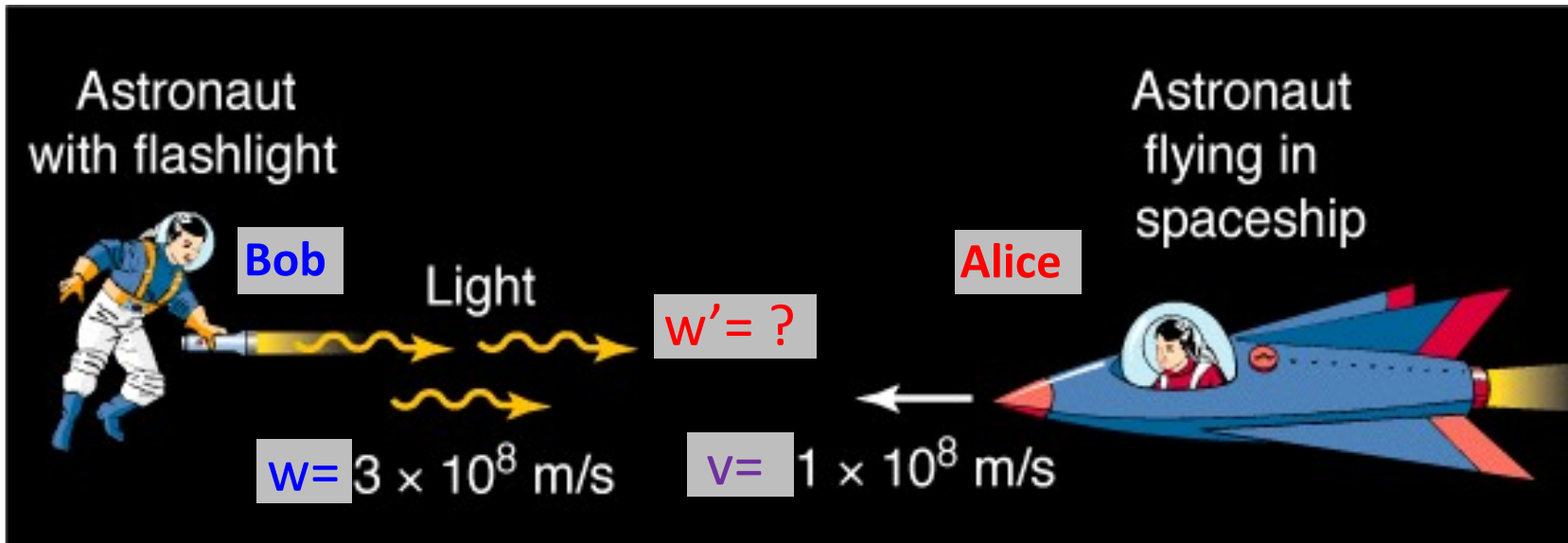
With which speed do **Alice** and the ball hit by **Bob** approach each other?
Intuitive law (daily experience): $30 \text{ m/s} + 10 \text{ m/s} = 40 \text{ m/s}$

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

Einstein formula: $w' = \frac{w + v}{1 + \frac{vw}{c^2}} = \frac{30 + 10}{1 + \frac{30 \times 10}{9 \times 10^{16}}} = 39.9999999999999997 \text{ m/s}$
(see lecture 3)



Albert Einstein
1879 - 1955

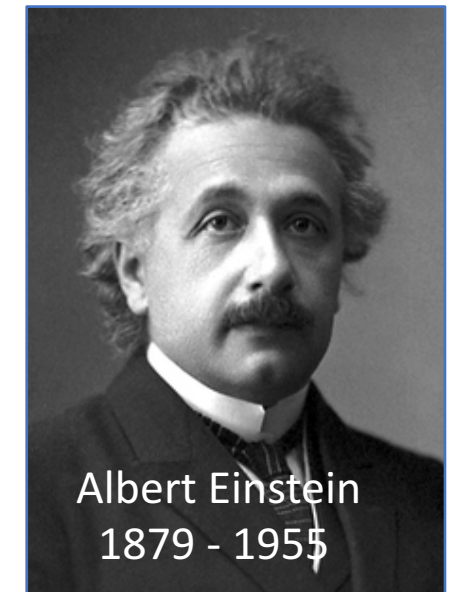


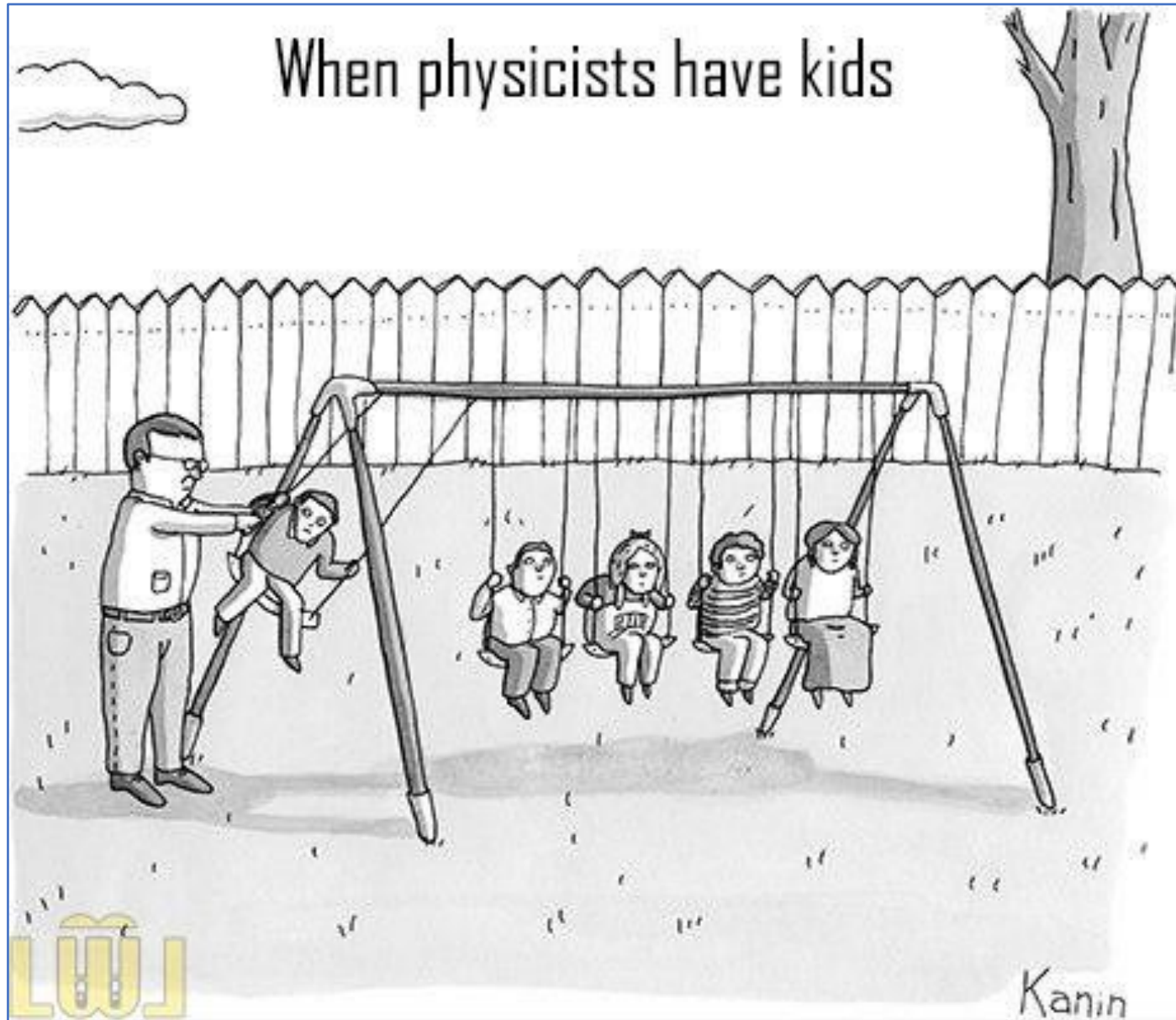
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Intuitive law: $300\,000 \text{ km/s} + 100\,000 \text{ km/s} = 400\,000 \text{ km/s}$

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: $w' = \frac{w + v}{1 + \frac{vw}{c^2}} = \frac{3 \times 10^8 + 1 \times 10^8}{1 + \frac{(3 \times 10^8) \times (1 \times 10^8)}{9 \times 10^{16}}}$
(see lecture 3)
 $= 300\,000 \text{ km/s}$ The same speed of light!





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

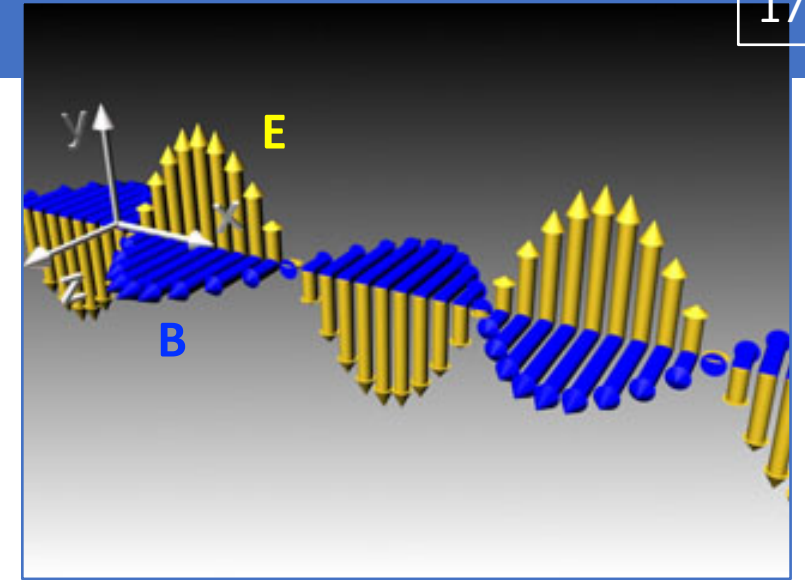
James Clerk Maxwell



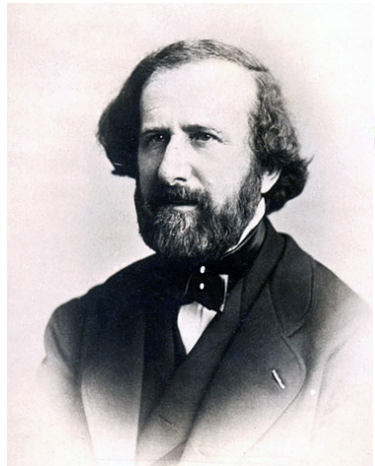
Electromagnetism:

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

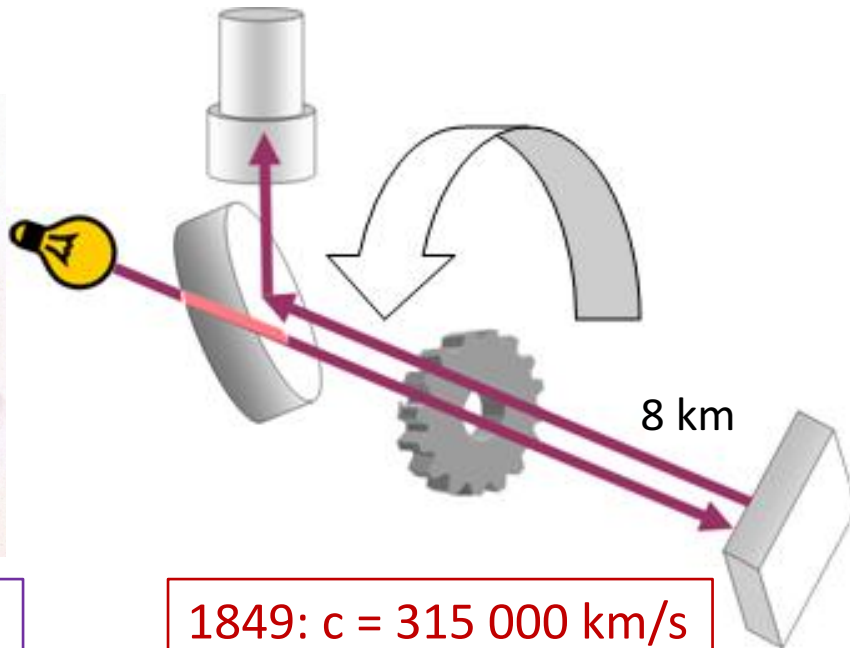
Propagation speed: $c = 1/\sqrt{\epsilon_0\mu_0} = 299\,792\text{ km/s}$



Measure the speed of light directly:



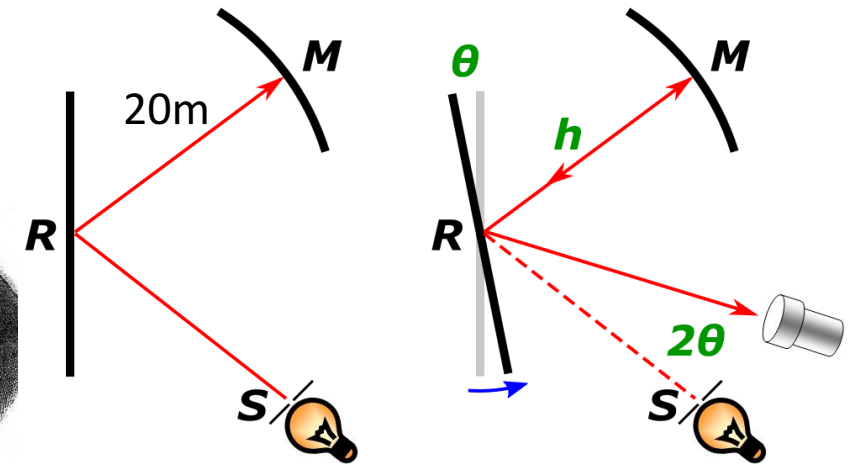
Armand Fizeau



1849: $c = 315\,000\text{ km/s}$



Leon Foucault

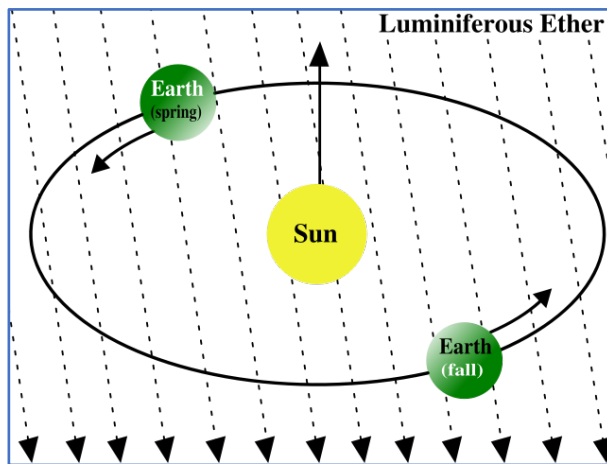
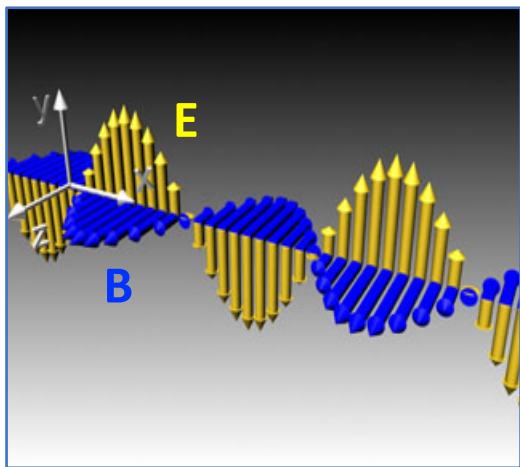


1862: $c = 298\,000\text{ km/s}$

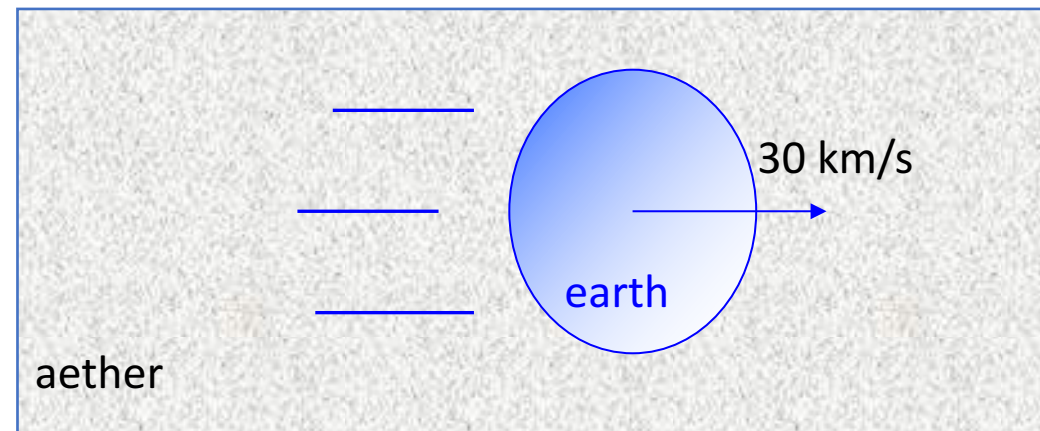
Measurement of the Speed of Light in aether

18

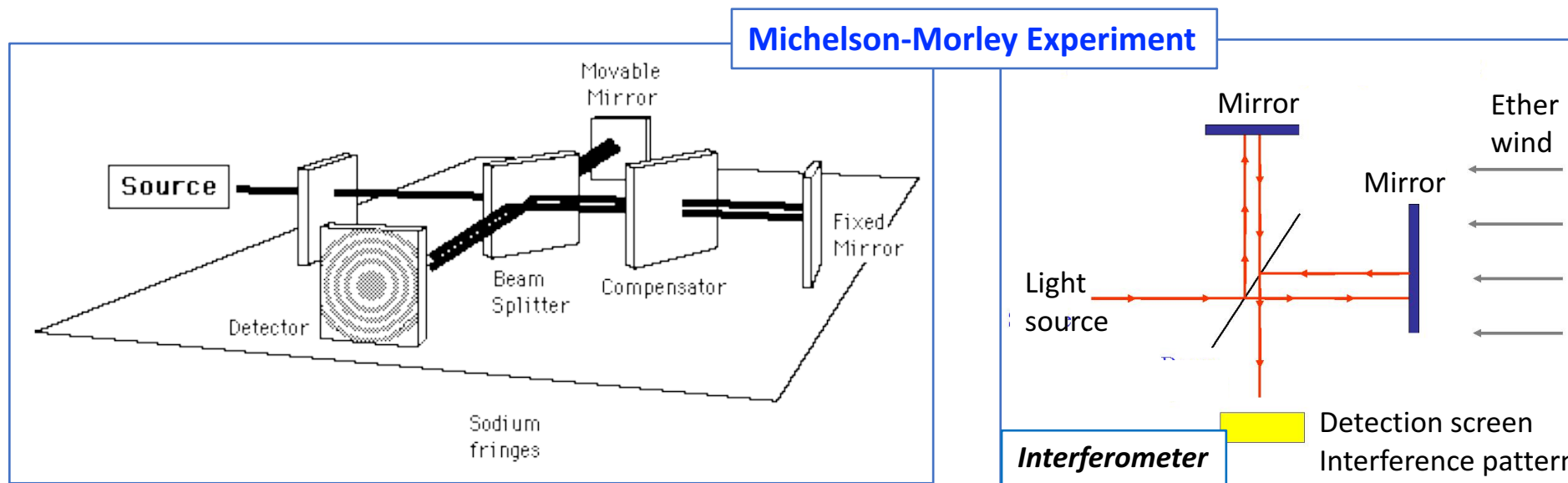
Light waves were believed to be carried by the “aether”.



Earth moves through the aether:



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

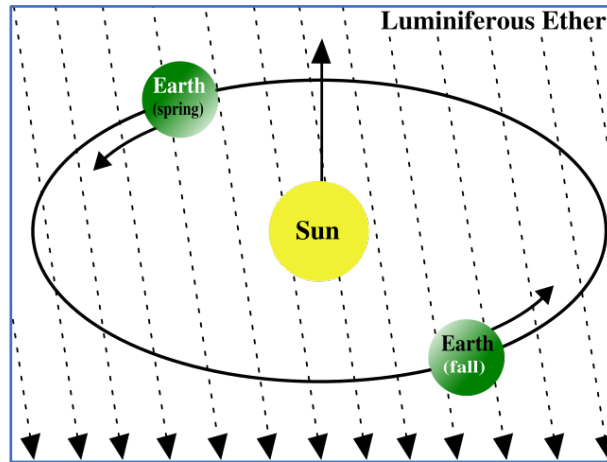
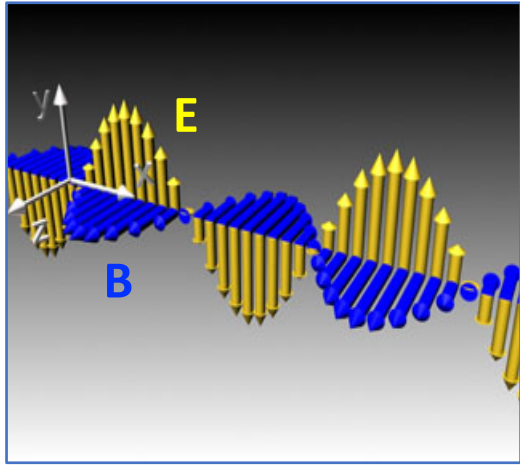


What do we expect to find for the travel times?

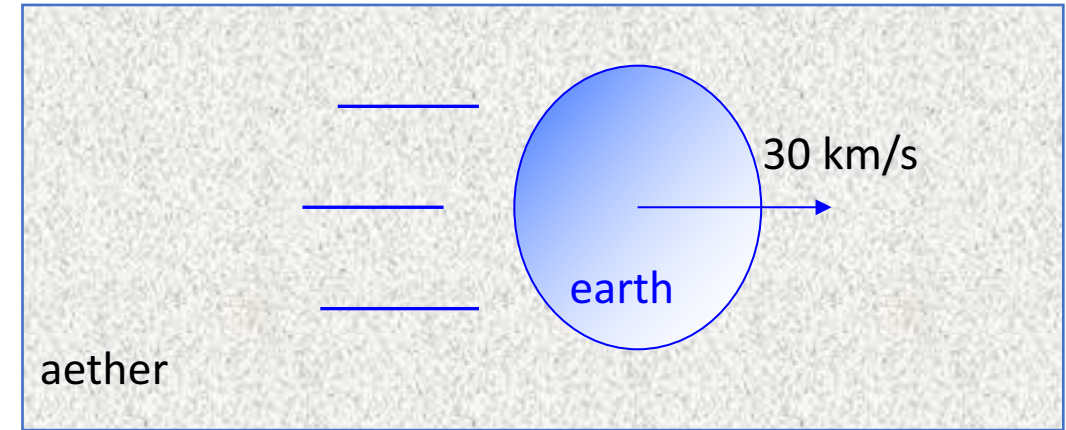
Measurement of the Speed of Light

19

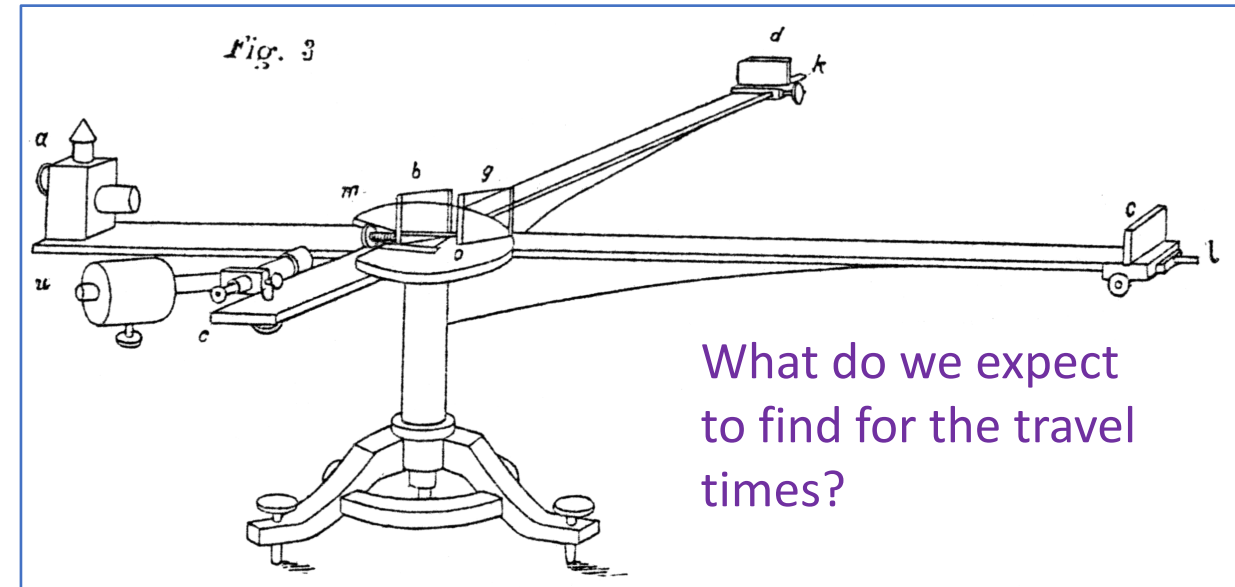
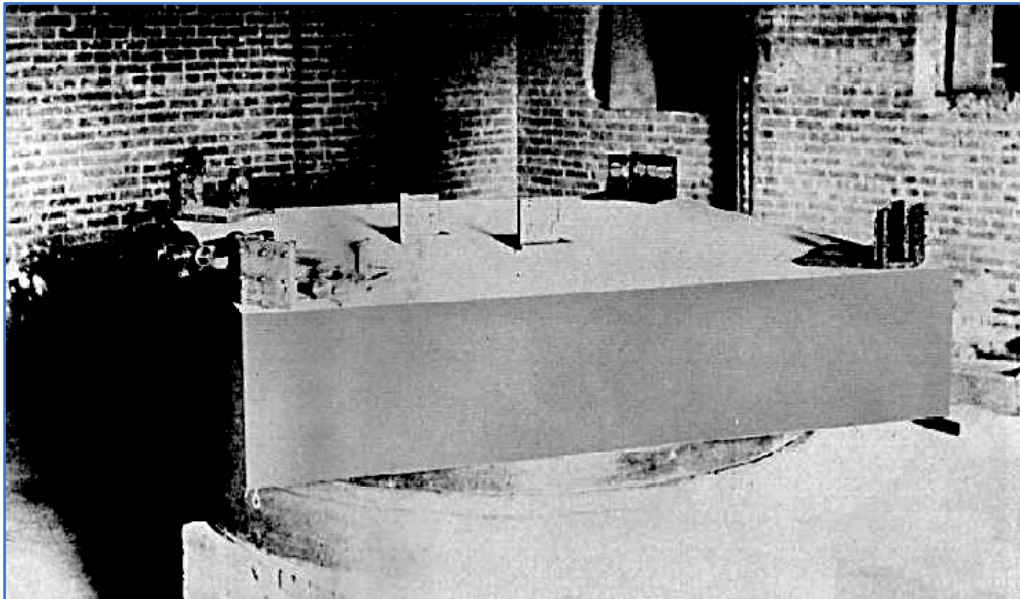
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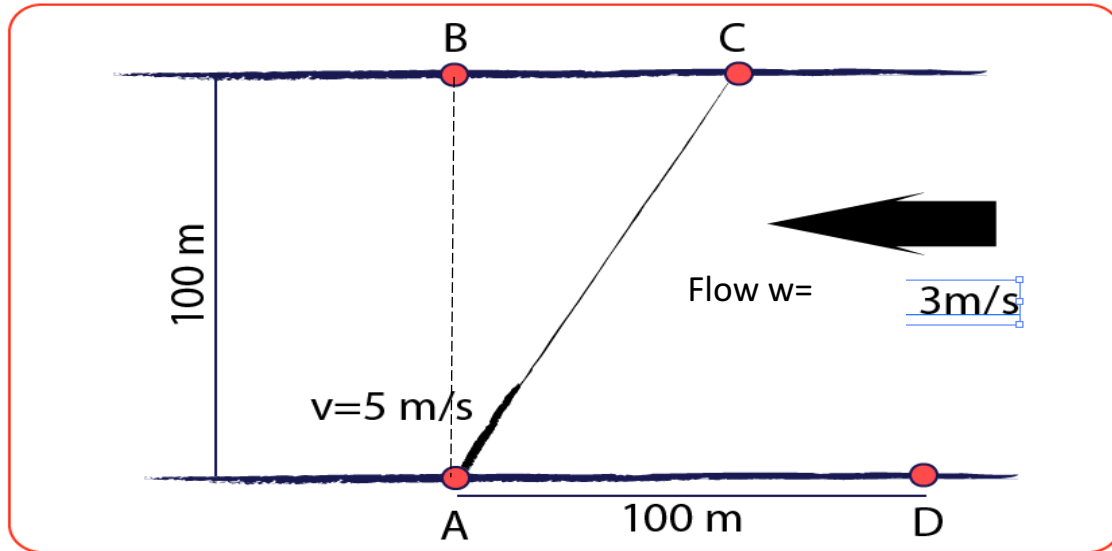


What do we expect to find for the travel times?

Comparison with water in a river

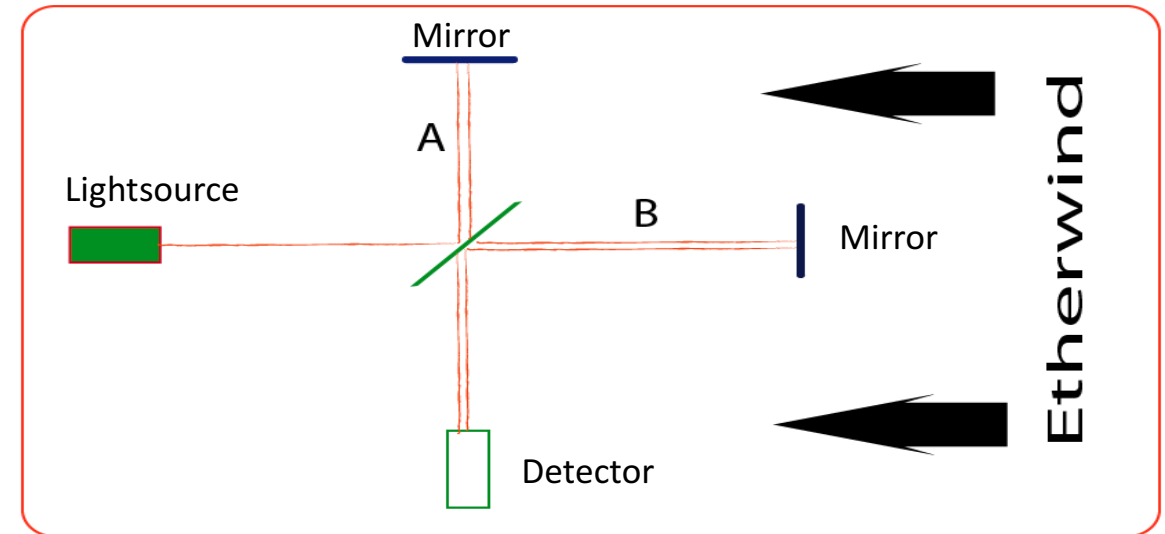
20

Swimmer crossing a river with flowing water



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

Light propagating through the aether wind



Measurement with light: no effect, travel times are the same!

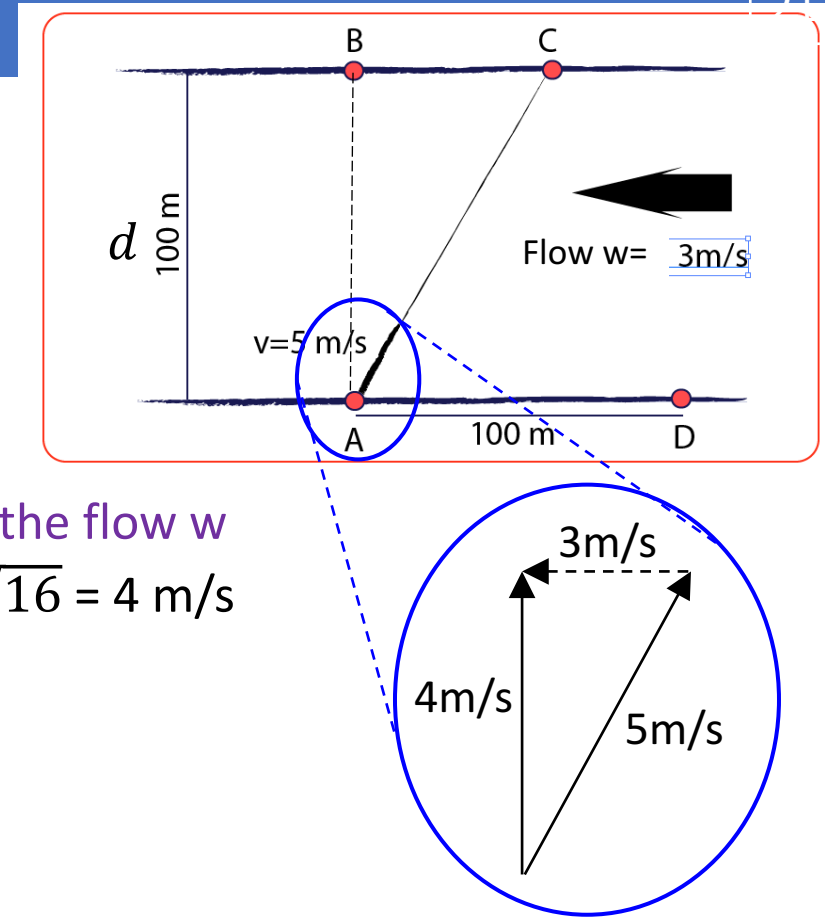
The speed of light is always constant!

The vacuum is the same for any observer

“Crossing” vs “Up-and-Down”

1. Swimming AD + DA: Time = $\text{time}_1 + \text{time}_2 =$
 $= 100/(5 - 3) + 100/(5 + 3)$
 $= 100/2 + 100/8$
 $= 50 + 12.5 = \mathbf{62.5\ s}$

2. Swimming AB + BA: Must swim under an angle A to C to compensate the flow w
Effective crossing speed = $\sqrt{5^2 - 3^2} = \sqrt{25 - 9} = \sqrt{16} = 4\ \text{m/s}$
Time = $\text{time}_1 + \text{time}_2 =$
 $= 100/4 + 100/4$
 $= 25 + 25 = \mathbf{50\ s}$



“Crossing” vs “Up-and-Down”

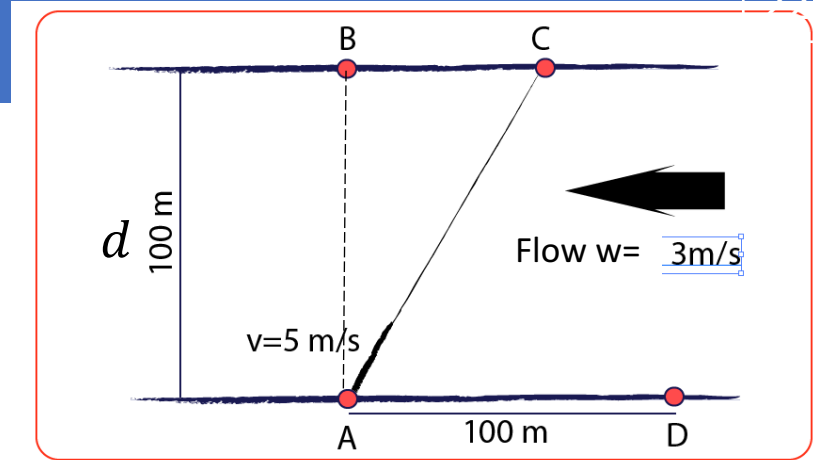
1. Swimming AD + DA: Time = time₁ + time₂ =

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

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

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

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



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

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

Time = time₁ + time₂ =

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

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

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

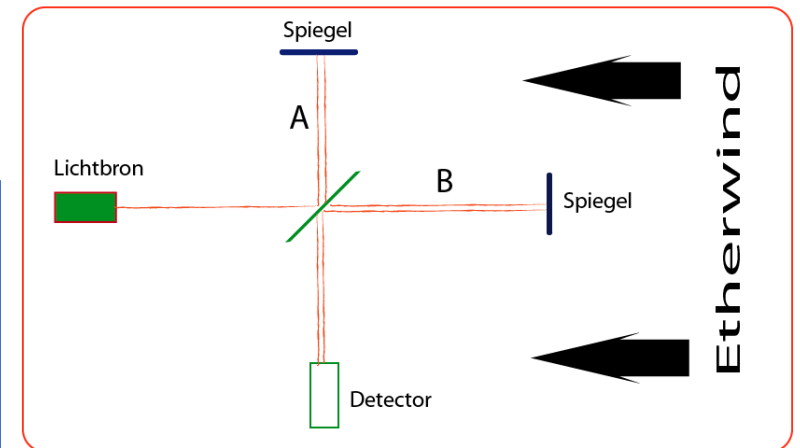
The speed of light is always the same!

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

$$t_A = 2d/c \times 1/\sqrt{1 - w^2/c^2}$$

$$t_B = 2d/c \times 1/(1 - w^2/c^2)$$

Michelson-Morley
measure:
 $t_A = t_B$
(no aether)



Absolute Velocity for Alice and Bob

23

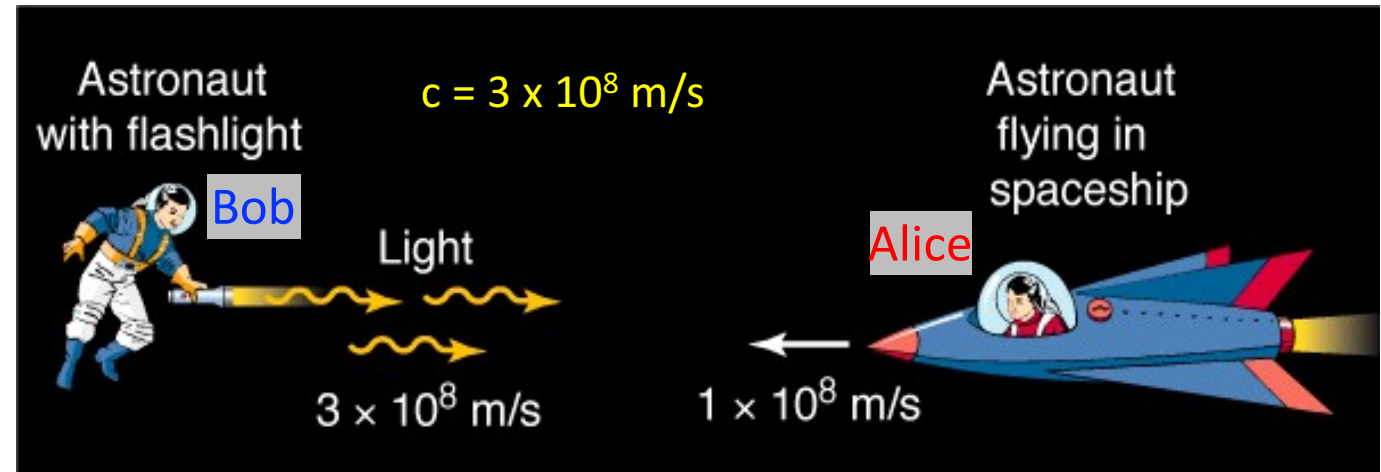
Back to **Alice** and **Bob**:

How can we ever measure an absolute velocity in vacuum?

When are we “standing still” with respect to the vacuum?

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

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

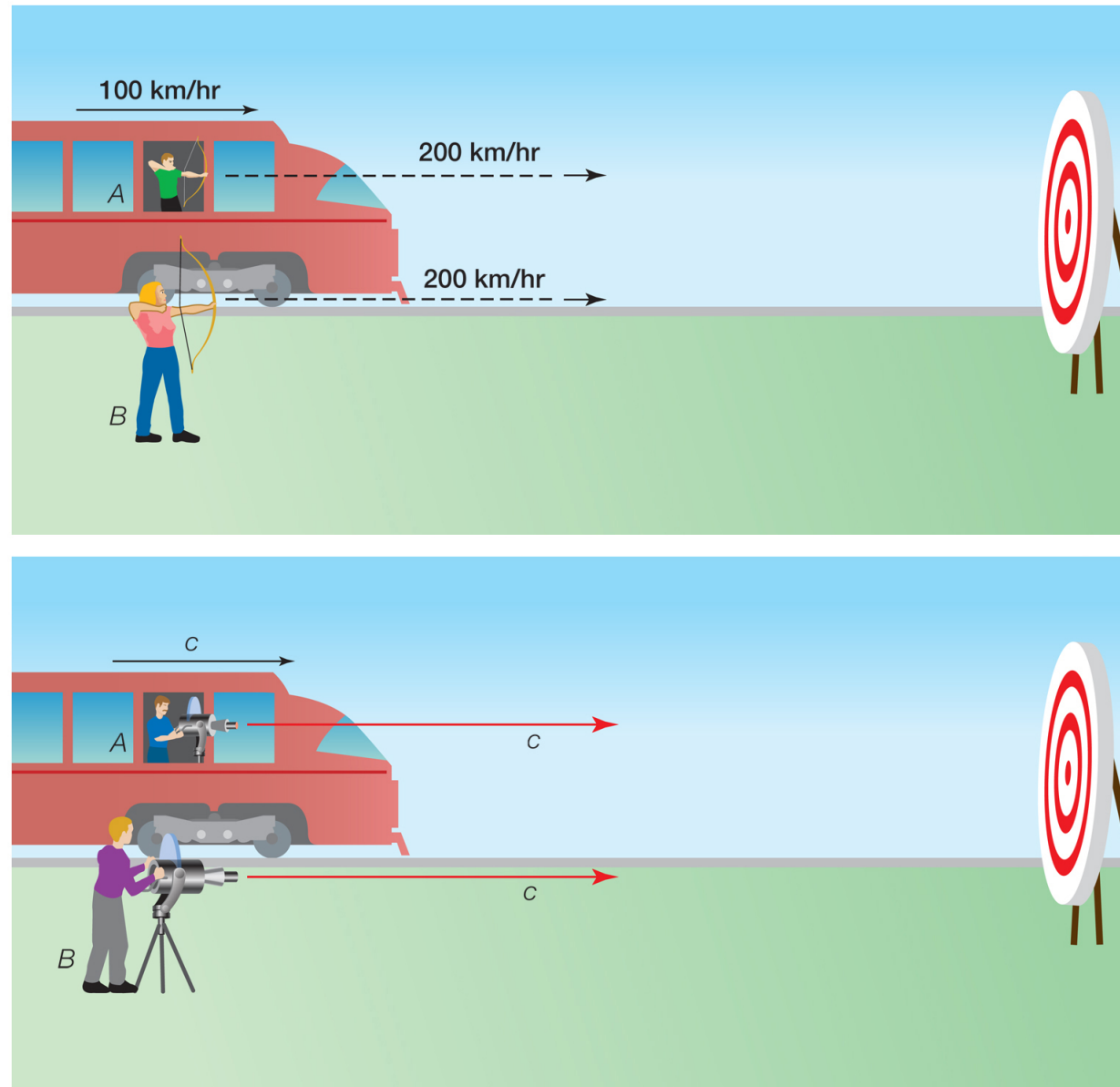


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“Absolute velocity” is meaningless

Completely Counterintuitive!

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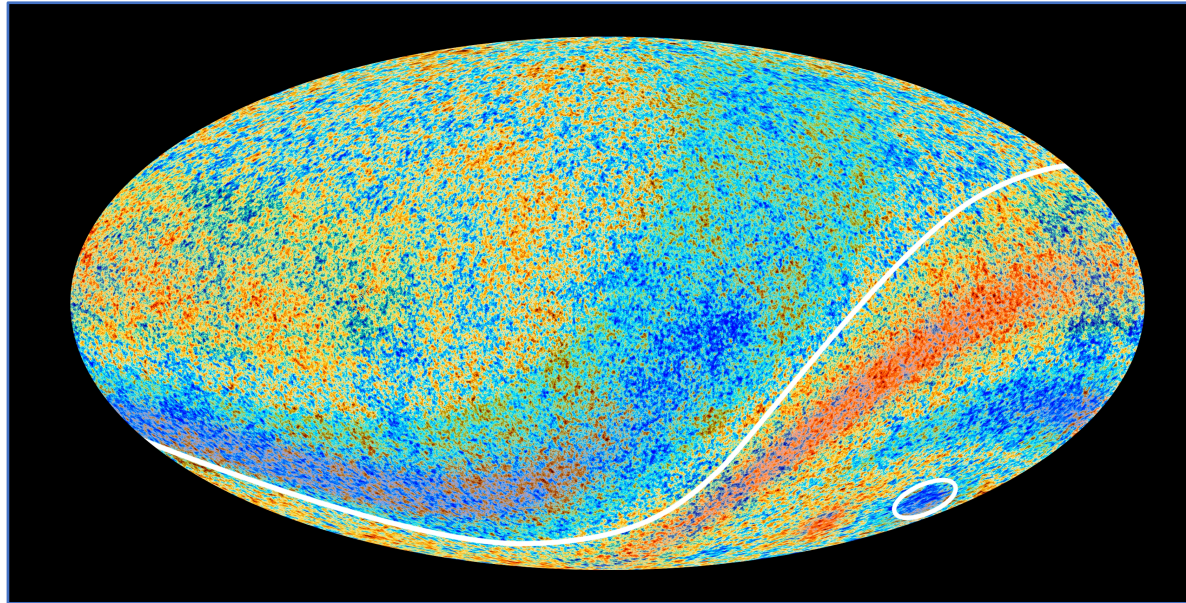
How about the cosmic microwave background? – experts!

25

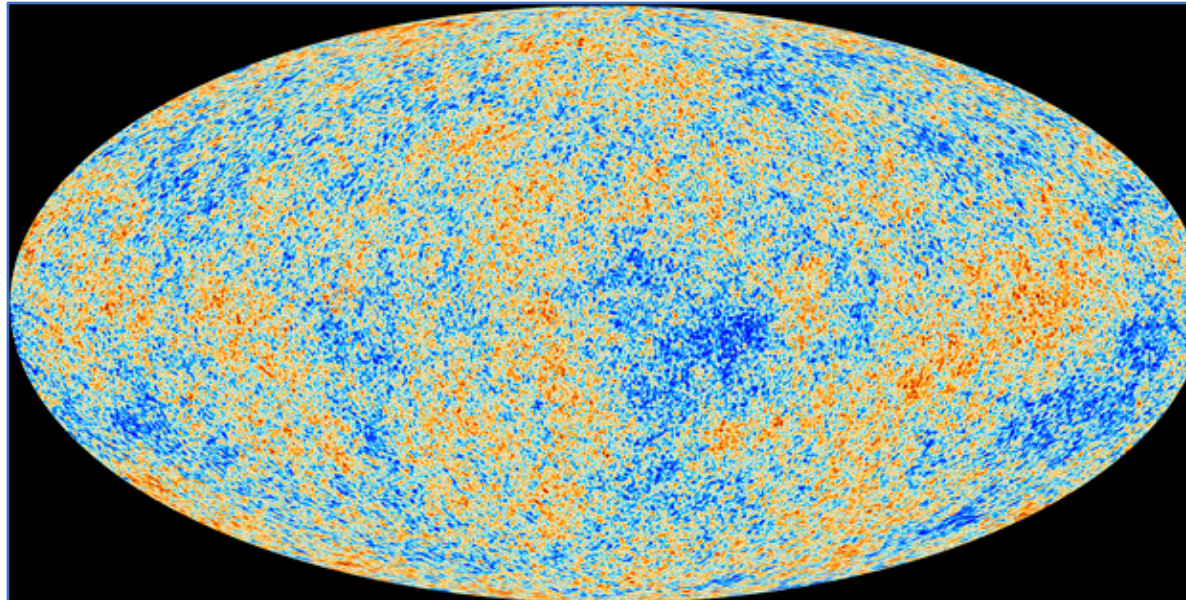
Cosmic microwave background radiation is light that is emitted in early universe and comes from all directions in space!

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