

# Is there time in the Quantum World?

Presentation: Lorenzo De Vittori

Direction: Antoine Suarez

Center for Quantum Philosophy

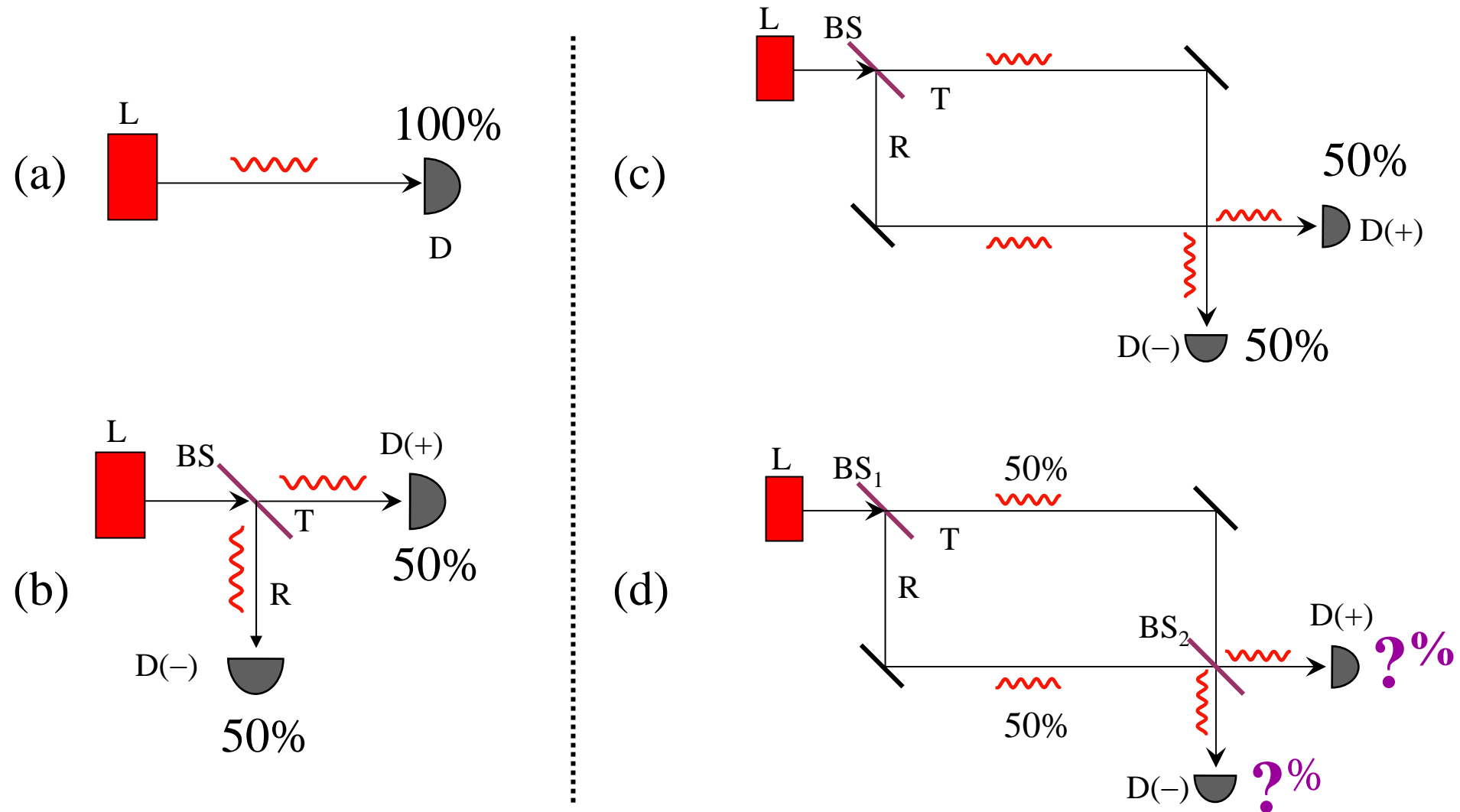
[www.quantumphil.org](http://www.quantumphil.org)

# Story of the „before-before“ Experiment (2001)



Wolfgang Tittel, Hugo Zbinden, Nicolas Gisin,  
Valerio Scarani, Antoine Suarez, André Stefanov

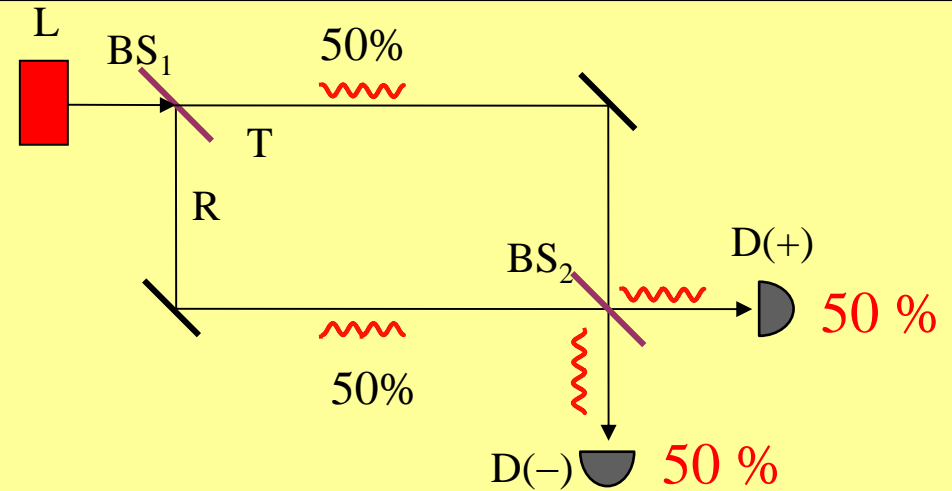
# I. Newton (1643-1727): Light is made of particles



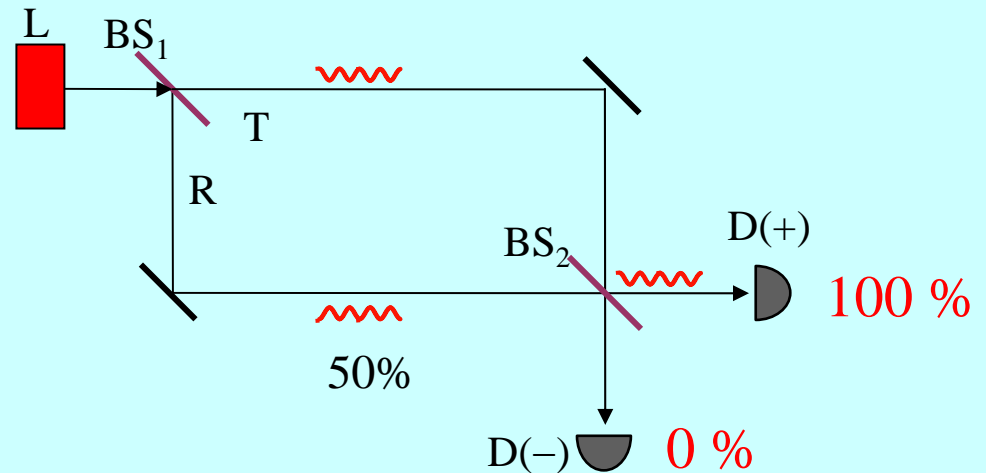
L: Light source; BS: Beam-splitter; D(+) und D(-): Detektoren

# Newton's particle model cannot explain the interference phenomena

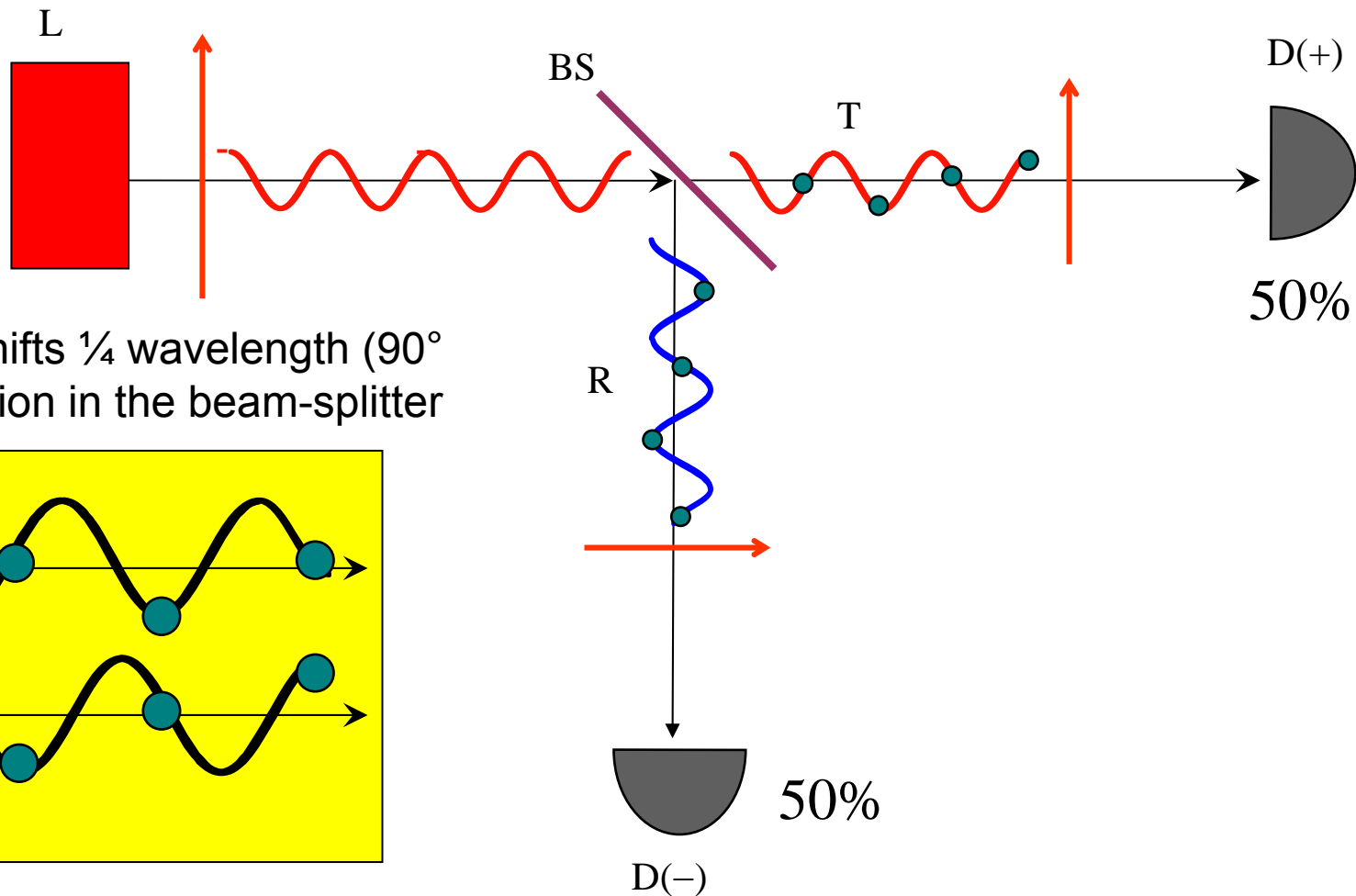
Prediction according to Newton's model



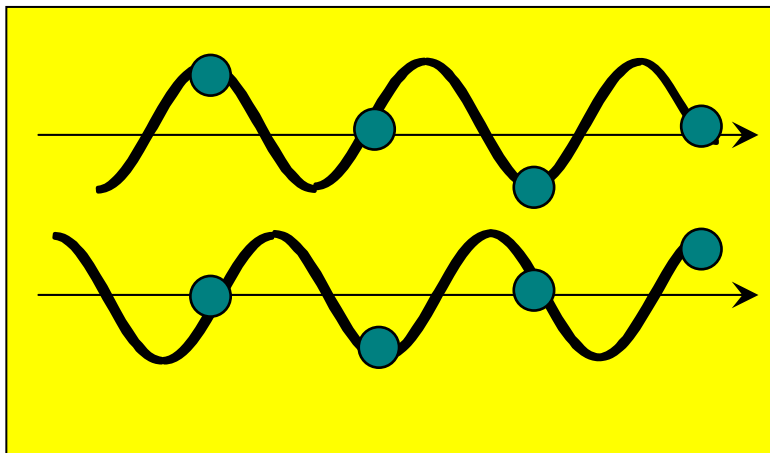
Experiment



# Ch. Huygens (1629-1695), T. Young (1773 – 1829) und A. Fresnel (1788-1827) develop the wave model, which explains very well interference

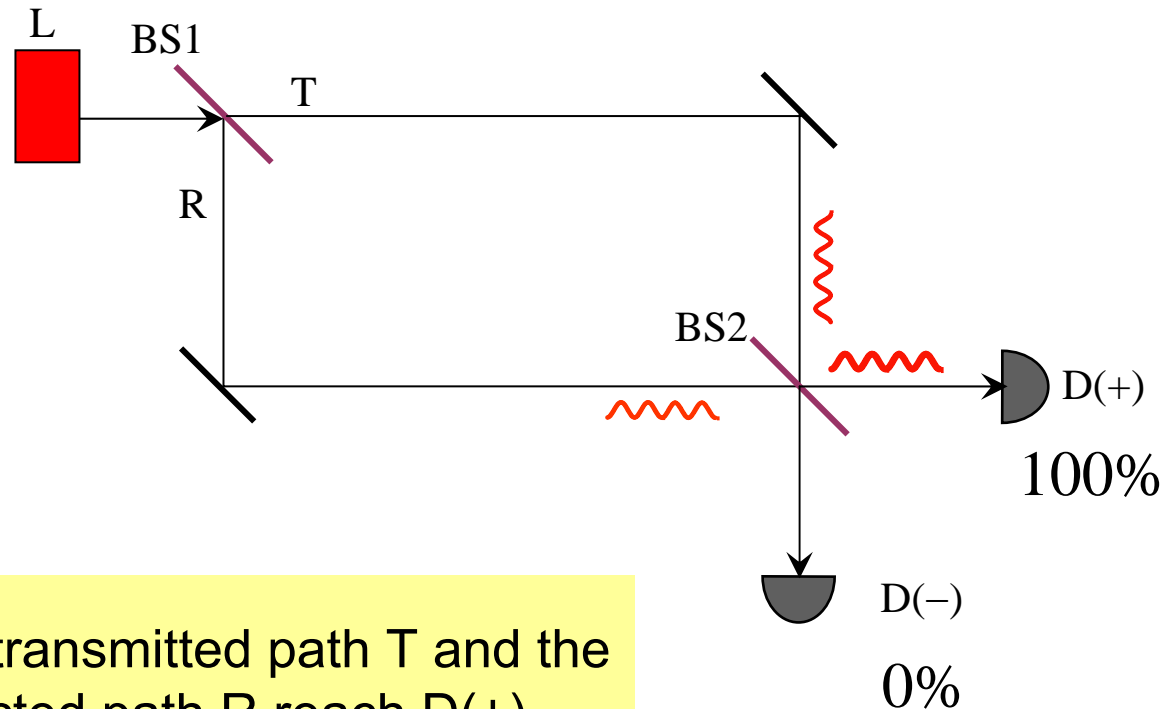


The light wave shifts  $\frac{1}{4}$  wavelength ( $90^\circ$  or  $\pi/2$ ) by reflection in the beam-splitter



# Interference

With two paths  
of equal length

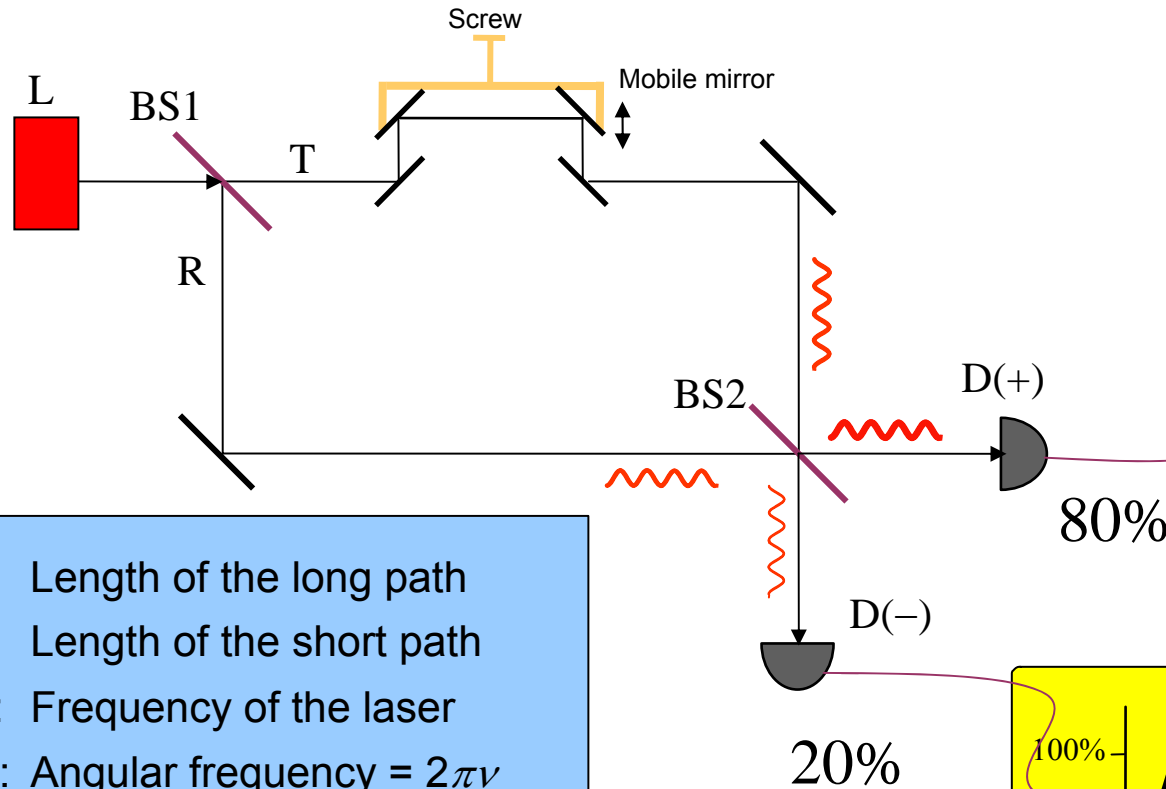


The wave through the transmitted path T and the wave through the reflected path R reach D(+) with the same phase and produce a counting rate of 100% (constructive Interference).

The wave through T and the wave through R reach D(-) with phase shift of  $1/2$  wavelength ( $180^\circ$ ) and produce a counting rate of 0% (destructive Interference).

# Interference

The counting rate depends on the path-length-difference



$l$ : Length of the long path  
 $s$ : Length of the short path  
 $\nu$ : Frequency of the laser  
 $\omega$ : Angular frequency =  $2\pi\nu$   
 $c$ : Velocity of light

$\Phi$ : Phase shift because of the length difference

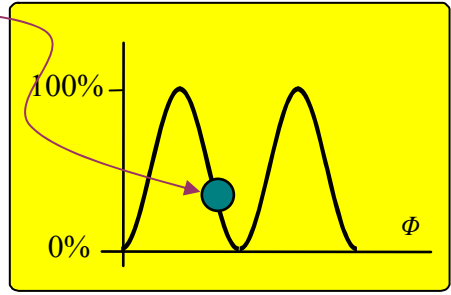
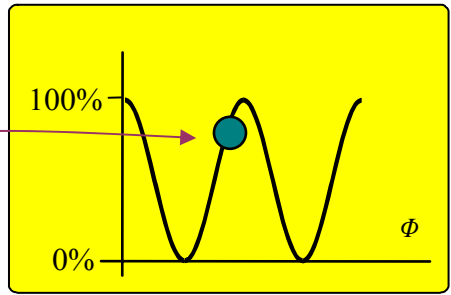
$$\Phi = \omega \frac{l-s}{c}$$

Phase shift in D(+):

$$\theta = \omega \frac{l}{c} + \frac{\pi}{2} - \frac{\pi}{2} - \omega \frac{s}{c} = \Phi$$

Counting rate D(+):

$$\text{Pr}(+) = \frac{1}{2}(1 + \cos \Phi)$$



Phase shift in D(-):

$$\theta = \omega \frac{l}{c} - \frac{\pi}{2} - \frac{s}{c} - \frac{\pi}{2} = \Phi - \pi$$

Counting rate in D(-):

$$\text{Pr}(-) = \frac{1}{2}(1 - \cos \Phi)$$

# Ether?

In which Medium propagate light waves?  
Ether-Hypotheses.

**Michelson-Morley Experiment  
disposes of the ether hypotheses**

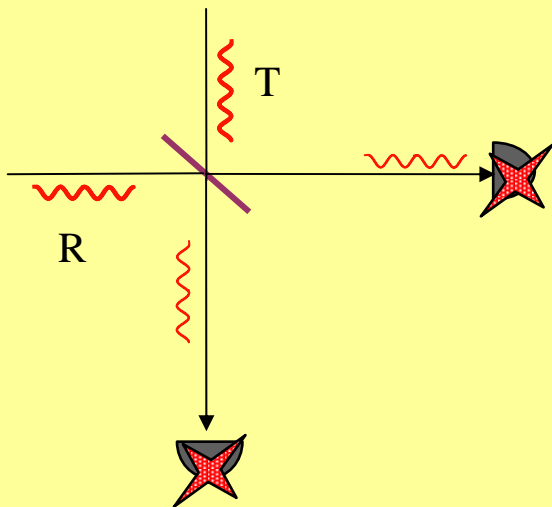


# Photoelectric effect

Light behaves according to the particle model

Prediction according to the wave model:

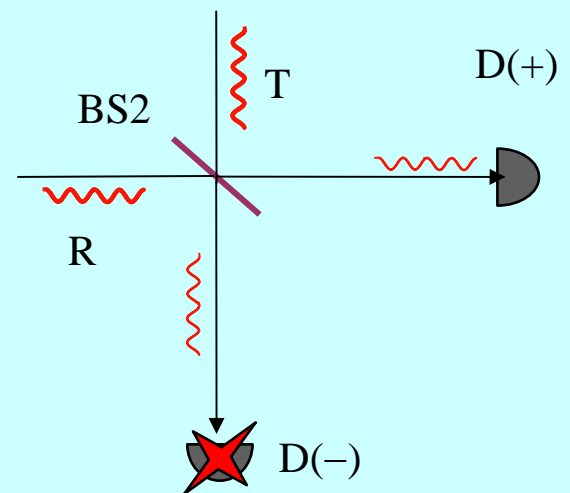
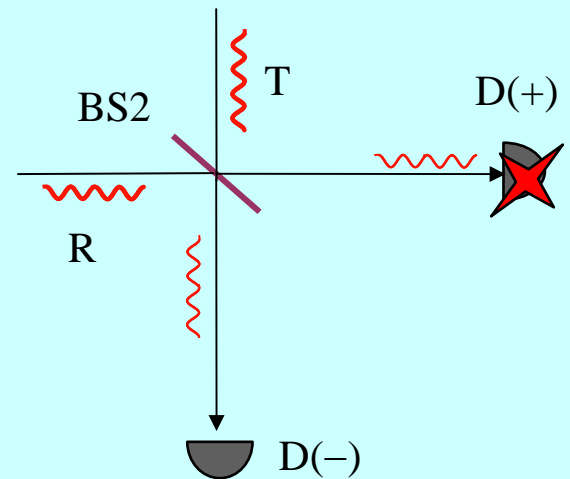
when the intensity of the light grows down, D(+) and D(-) should click weaker but together.



either  
D(+)  
clicks

or  
D(-)  
clicks

## Experiment



# Platform 9 ¾ to the Quantum World

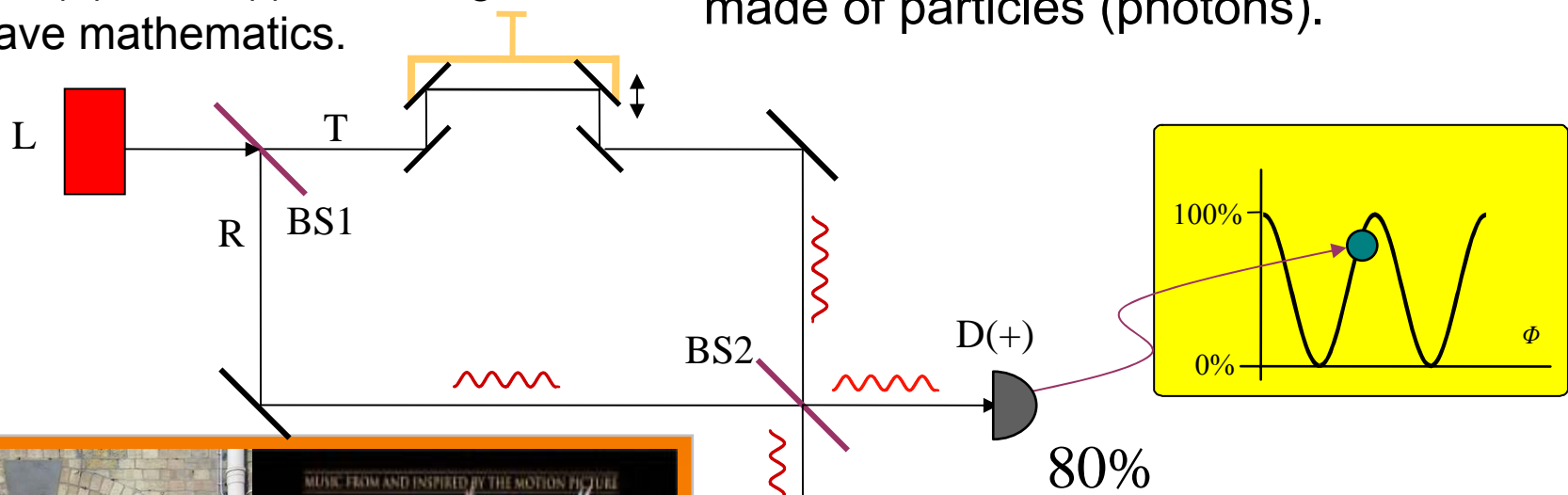
## Interference Experiments:

Distribution of light intensity between D(+) and D(-) according to the wave mathematics.

## Photoelectric Experiments:

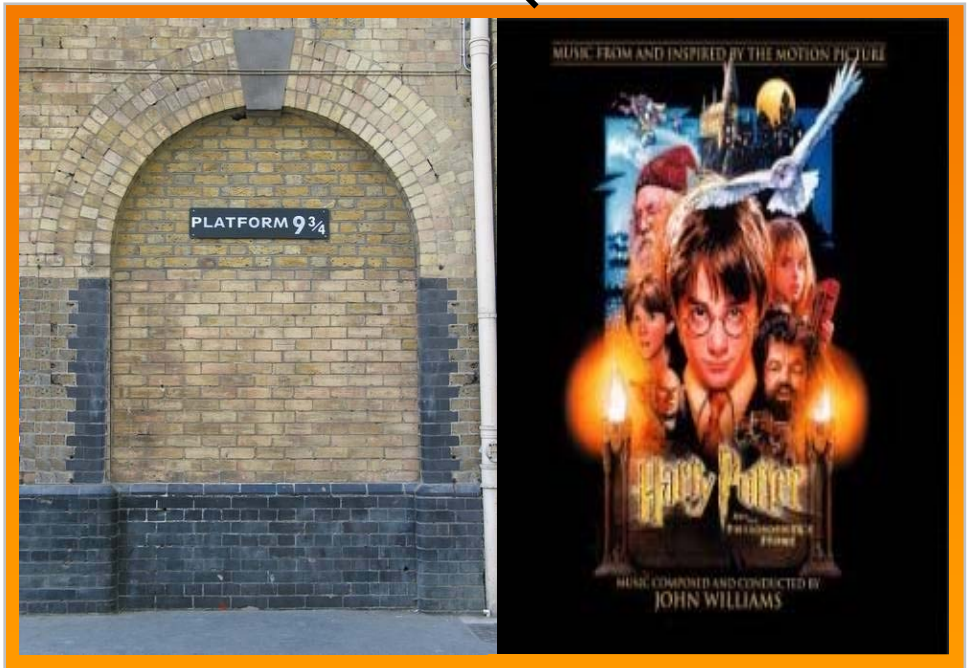
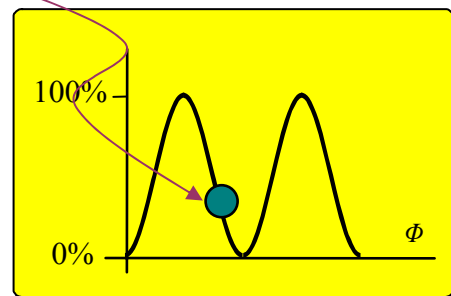
The detections show that light is made of particles (photons).

+



80%

20%



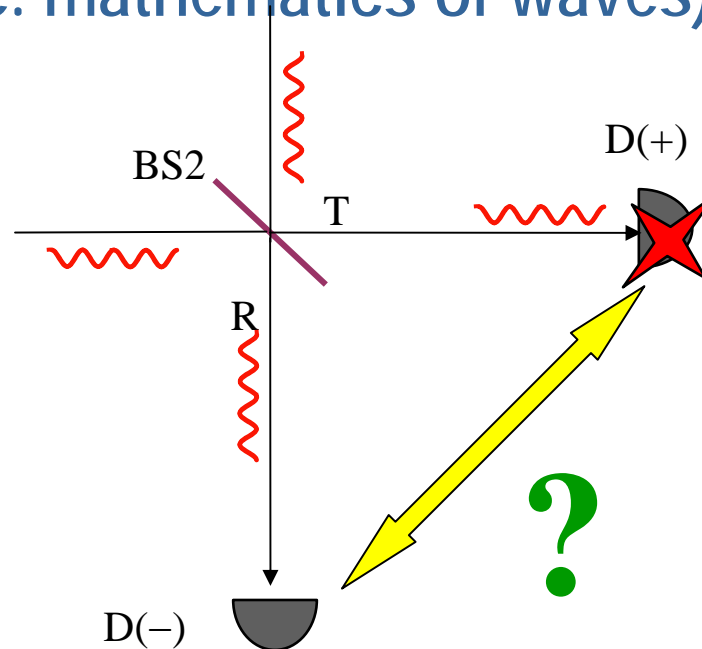
# Copenhagen

(Bohr, Heisenberg, Born, Jordan):

„Agreement“ between Detectors

+

Statistical distribution  
according to quantum mathematics  
(i.e. mathematics of waves)



# Consequences of Copenhagen's explanation

1. Which detector clicks, is decided by a free choice when the wave reaches the detectors.

Dirac: “the choice on the part of nature”

Bohr, Heisenberg: “the choice on the part of the observer”

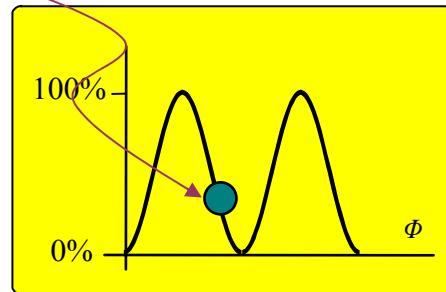
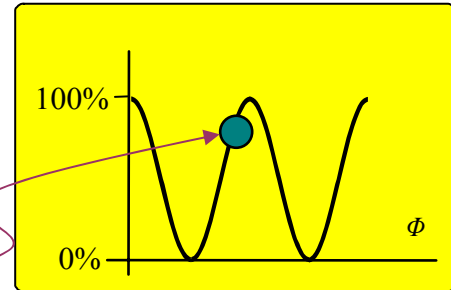
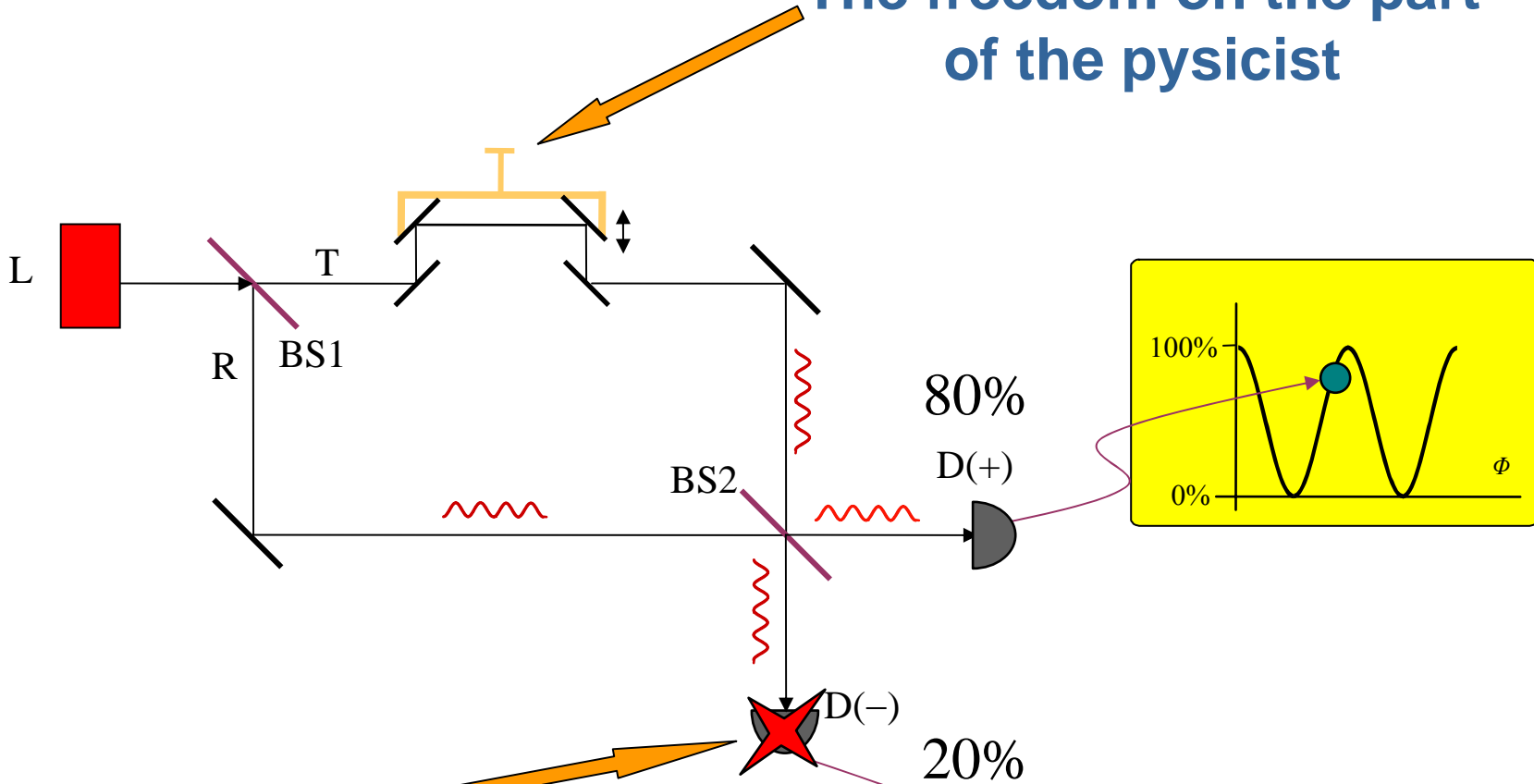
Zeilinger: “the two freedoms” (“die zwei Freiheiten”)

1. **Exchange of information faster than light between  $D(+)$  and  $D(-)$ .**
2. Uncertainty principle (Heisenberg).

# "The two freedoms" ("Die zwei Freiheiten")

Anton Zeilinger  
Die Weltwoche, 48/2005

The freedom on the part  
of the physicist



The freedom on the part  
of nature

# Quanteninformation

Copenhagen expressions like:  
“Collapse of the wavefunction”

actually mean:

Agreement

or

Exchange of Information

or

free choice

between the detectors

By the way:

Avoiding expressions like **“collapse”**  
and using expressions  
like “agreement”, “exchange of information”,  
“choice”, “freedom”

may help you to understand quantum  
mechanics with wondering and delight, and  
you don't need to be **“profoundly shocked”**.

*"If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet." (Bohr)*

# Consequences of Copenhagen's explanation

1. Which detector clicks, is decided by a free choice when the wave reaches the detectors.

Dirac: “the choice on the part of nature”

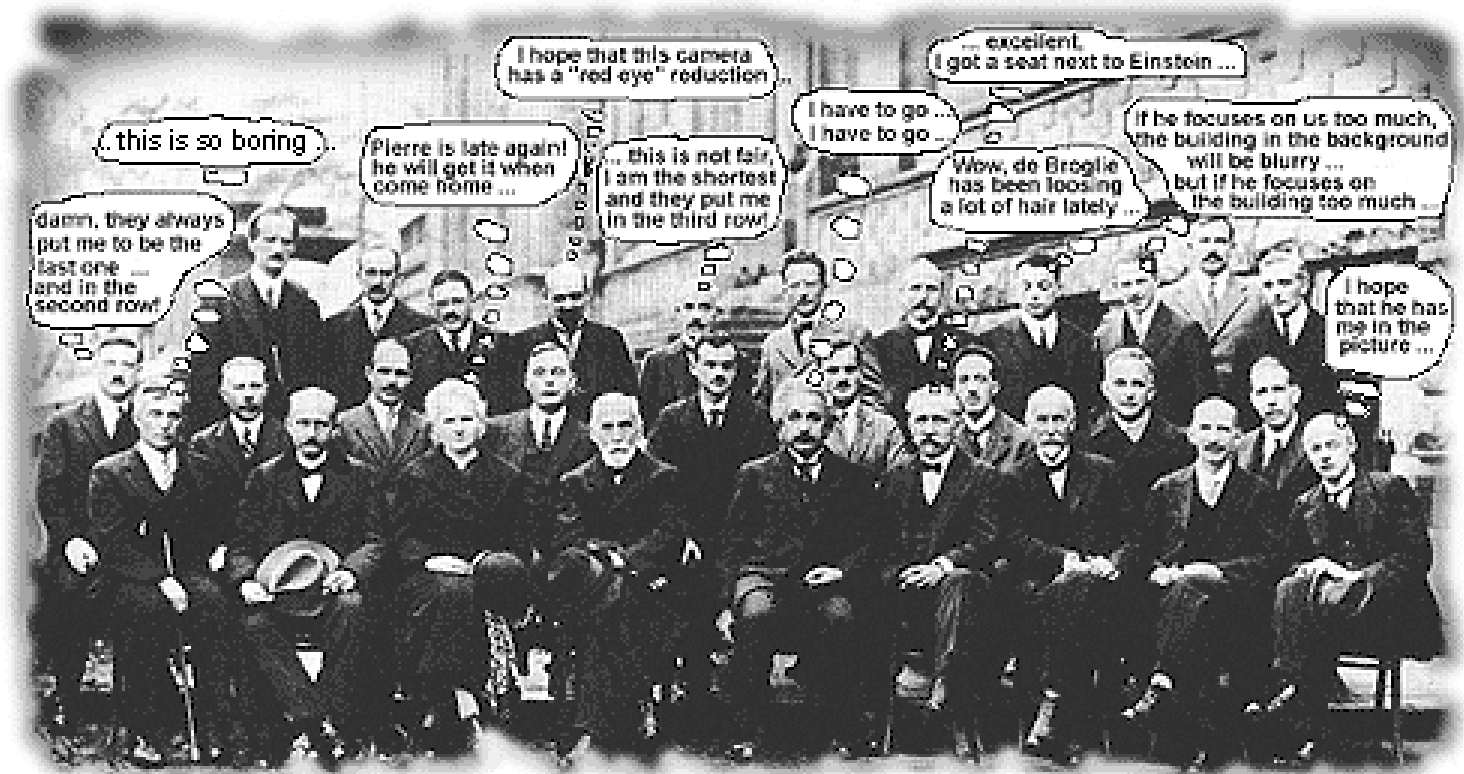
Bohr, Heisenberg: “the choice on the part of the observer”

Zeilinger: “the two freedoms” (“die zwei Freiheiten”)

1. **Exchange of information faster than light between  $D(+)$  and  $D(-)$ .**
2. Uncertainty principle (Heisenberg).



# The Solvay Congress: Brussels 23-27.10.1927



**[first row]** (1) I. Langmuir, (2) M. Planck, (3) M. Curie, (4) H.A. Lorentz, (5) A. Einstein, (6) P. Langevin, (7) C.E. Guye, (8) C.T.R. Wilson, (9) O.W. Richardson

**[second row]** (1) P. Debye, (2) M. Knudsen, (3) W.L. Bragg, (4) H.A. Kramers, (5) P.A.M. Dirac, (6) A.H. Compton, (7) L.V. de Broglie, (8) M. Born, (9) N. Bohr

**[third row]** (1) A. Piccard, (2) E. Henriot, (3) P. Ehrenfest, (4) E. Herzen, (5) Th. de Donder, (6) E. Schroedinger, (7) E. Verschaffelt, (8) W. Pauli, (9) W. Heisenberg, (10) R.H. Fowler, (11) L. Brillouin.

**“God does not play dice!”  
(Einstein)**

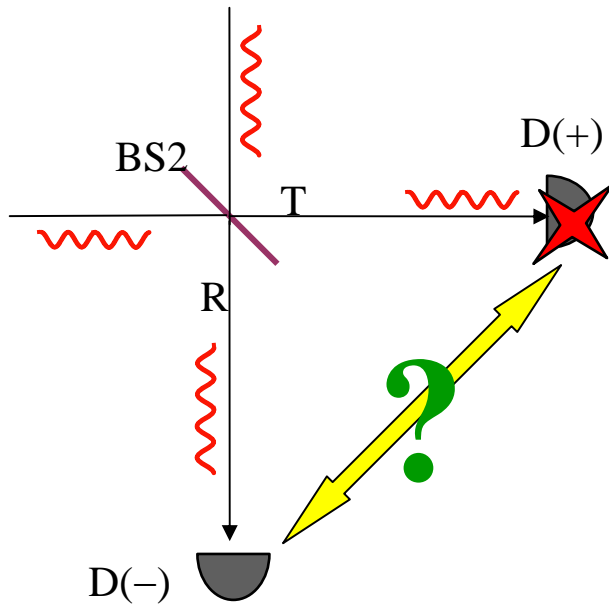
By the way:

The Michelson-Morley Experiment is an interference experiment and, therefore, actually a quantum experiment

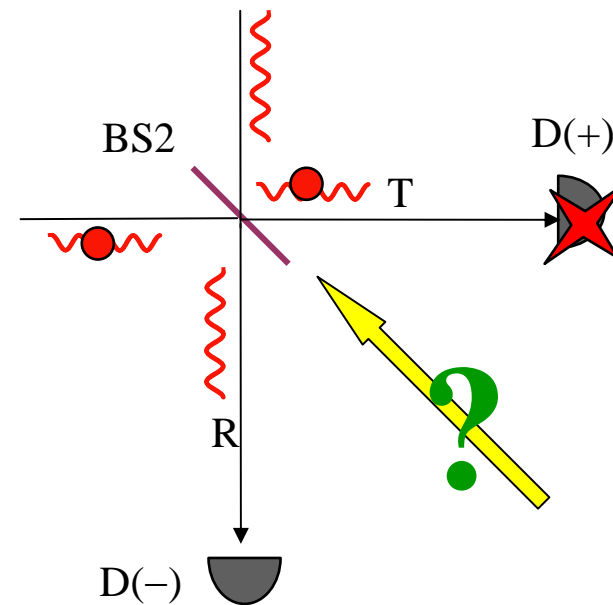
There cannot be a contradiction between the consequences of this experiment and Quantum Mechanics.

If Einstein felt a contradiction, it is because he did extend the validity of relativity beyond the limit the experimental data permitted to.

# De Broglie tries to explain things without communication faster than light, and calms the spirits... though not Einstein



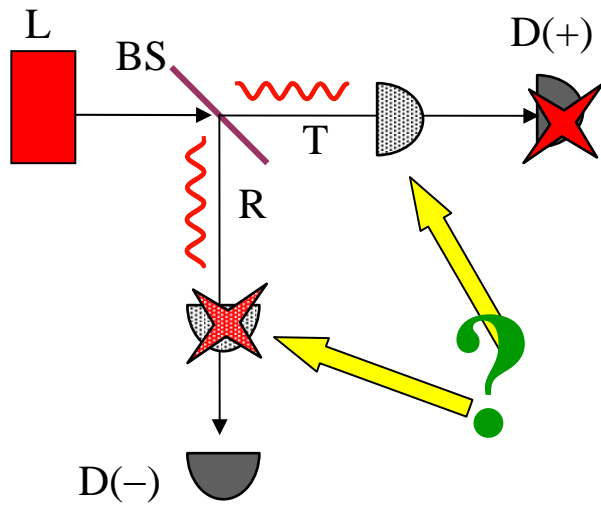
(a) Copenhagen:  
„Collapse of the wavefunction“  
(Exchange of information)



(b) de Broglie:  
„Empty wave“ or „pilot wave“

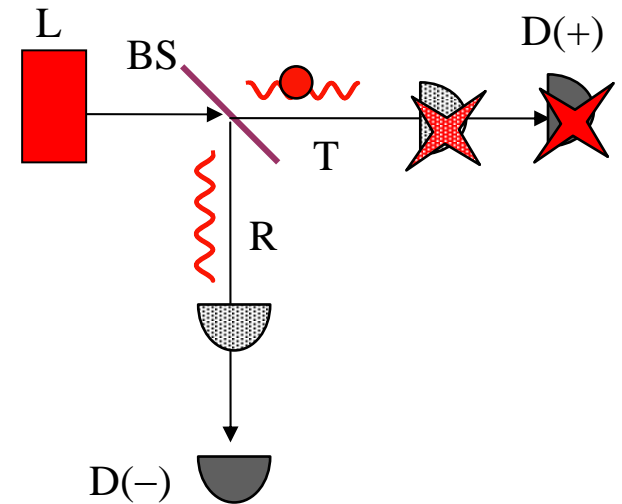
# Trajectory?

## Copenhagen vs De Broglie-Bohm



### (a) Copenhagen:

The concept of trajectory doesn't make sense. The "particle" does not follow any path. Nature takes account of both paths to calculate the counting rates



### (b) de Broglie-Bohm:

The particle always follows a well defined trajectory.

By the way:

## Confusing Expressions

“Delayed choice”:

“If one watches the particle, it takes only one path. If one doesn't watch it, it take two paths” (Wheeler)

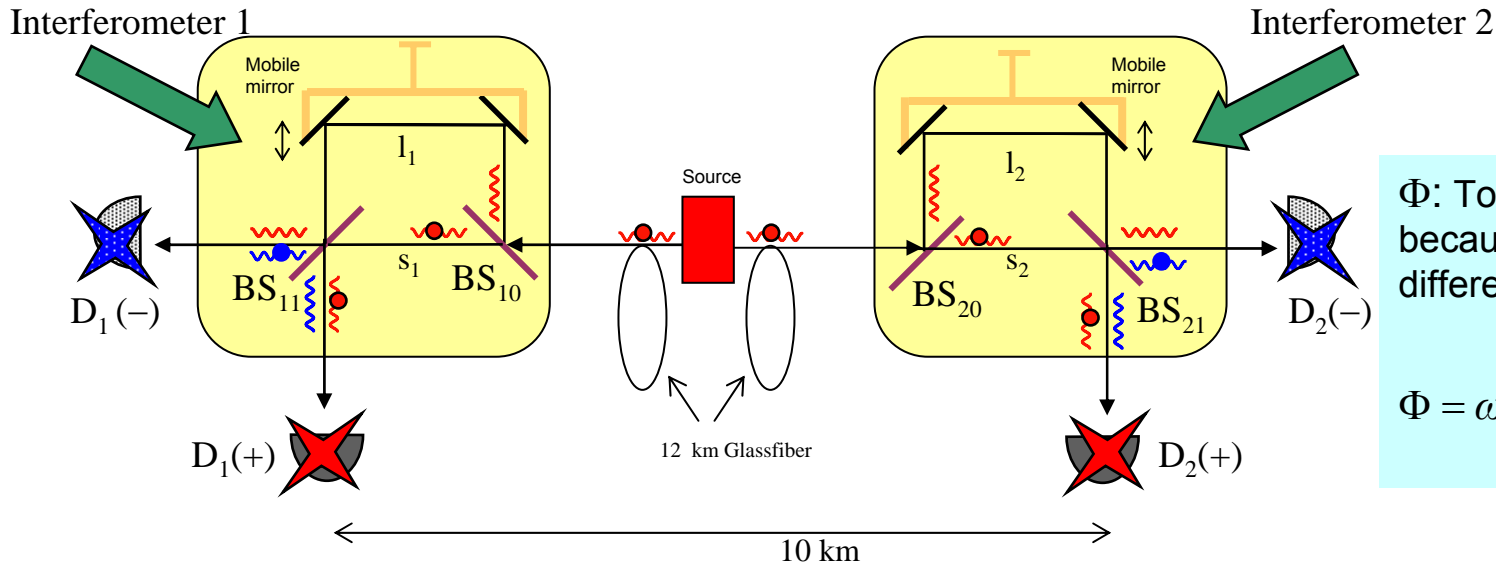
“If one looks at the holes, [...] then one can say that it [the electron] goes through hole 1 or 2. But, when one does not try to tell which way the electron goes, [...] then one may not say that an electron goes either through hole 1 or hole 2”  
(Feymann)

Such expressions help Feymann's claim to prevail:

**„I think I can safely say that nobody understands quantum mechanics.“**

Richard P. Feynman  
*The character of physical law,*  
MIT Press : Massachusetts, 1967

# The EPR(1935)-Bohm(1952) Argument



$\Phi$ : Total phase-shift because path-length-difference

$$\Phi = \omega_1 \frac{l_1 - s_1}{c} + \omega_2 \frac{l_2 - s_2}{c}$$

Probability that D<sub>1</sub>(+) [bzw D<sub>2</sub>(+)] clicks : Pr(+) = 50%

Probability that D<sub>1</sub>(-) [bzw D<sub>2</sub>(-)] clicks : Pr(-) = 50%

Probabilities of the four possible

coincidence counts :

$$\text{Pr}(+,+) = \text{Pr}(-,-)$$

$$\text{Pr}(+,-) = \text{Pr}(-,+)$$

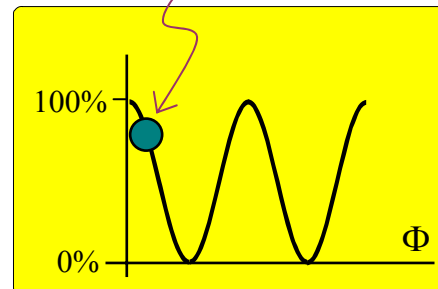
$$\text{Pr}(\text{Concordance}) = \text{Pr}(+,+) + \text{Pr}(-,-)$$

$$= \frac{1}{2}(1 + \cos \Phi)$$

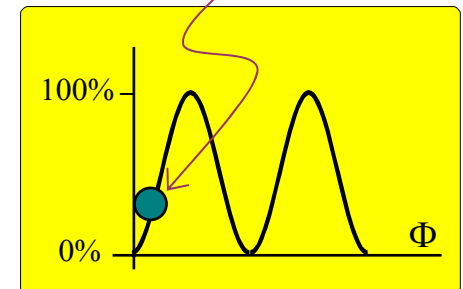
$$\text{Pr}(\text{Discordance}) = \text{Pr}(+,-) + \text{Pr}(-,+)$$

$$= \frac{1}{2}(1 - \cos \Phi)$$

$$\text{Pr}(+,+) + \text{Pr}(-,-)$$



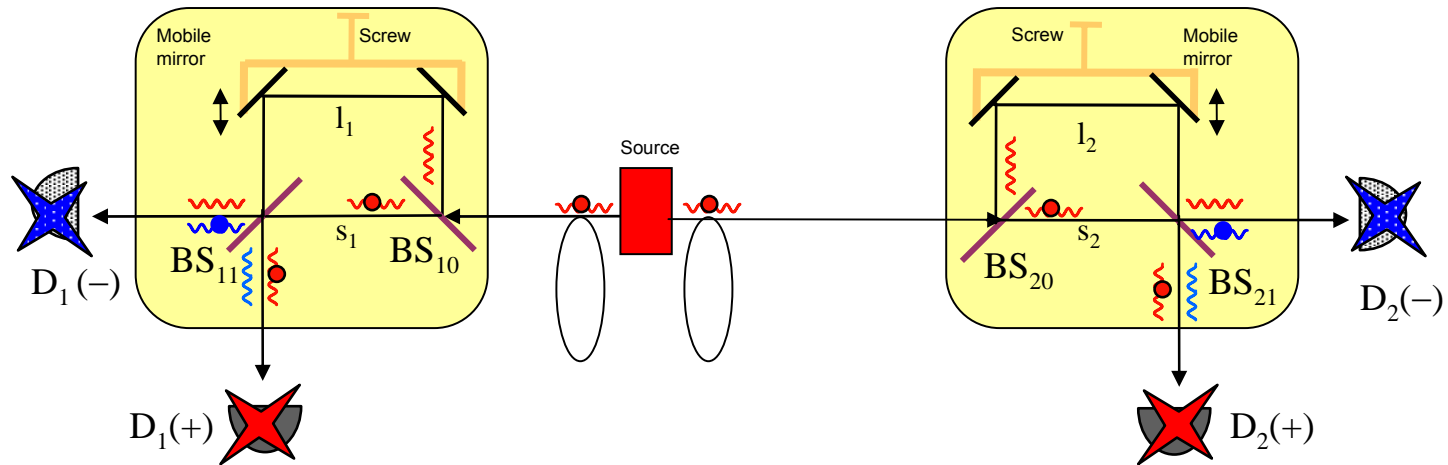
$$\text{Pr}(+,-) + \text{Pr}(-,+)$$



In 2-particle experiments  
de Broglie-Bohm's model implies that  
one choice (say at BS11)  
influences the other (at BS21)  
faster than light.



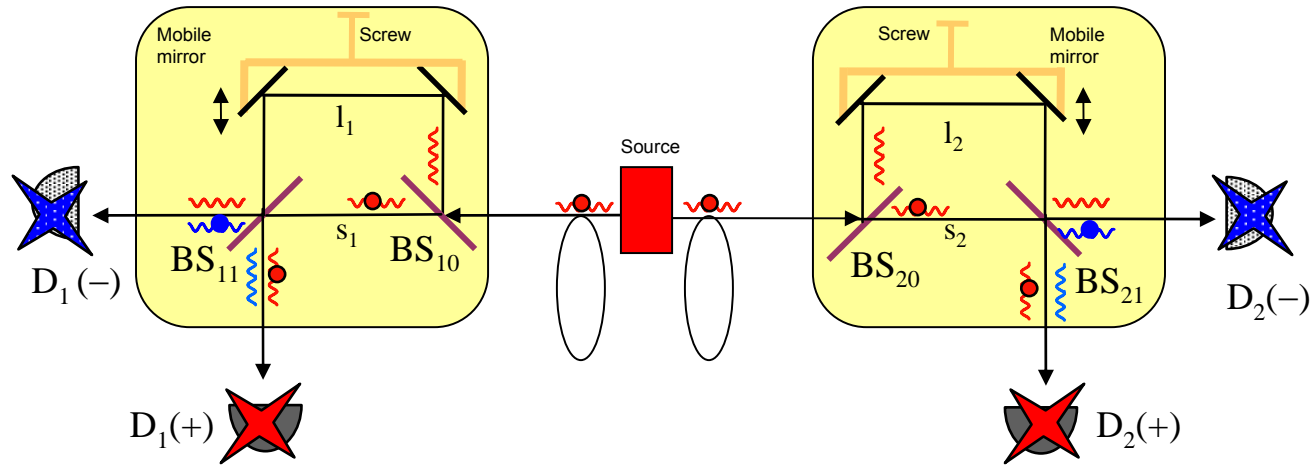
# According to Bohm's model there is a time ordering behind the quantum correlations



Since the glass-fibers from the source to each interferometer cannot be cut exactly equal long (1mm error), one of the particles, say photon 1, hits its beam-splitter  $BS_{11}$  **before** photon 2 hits  $BS_{21}$ . One assumes that photon 1 makes its choice between output + and out put - at will (before photon 2 chooses), and photon 2 chooses **after** that, taking account of photon 1's choice.

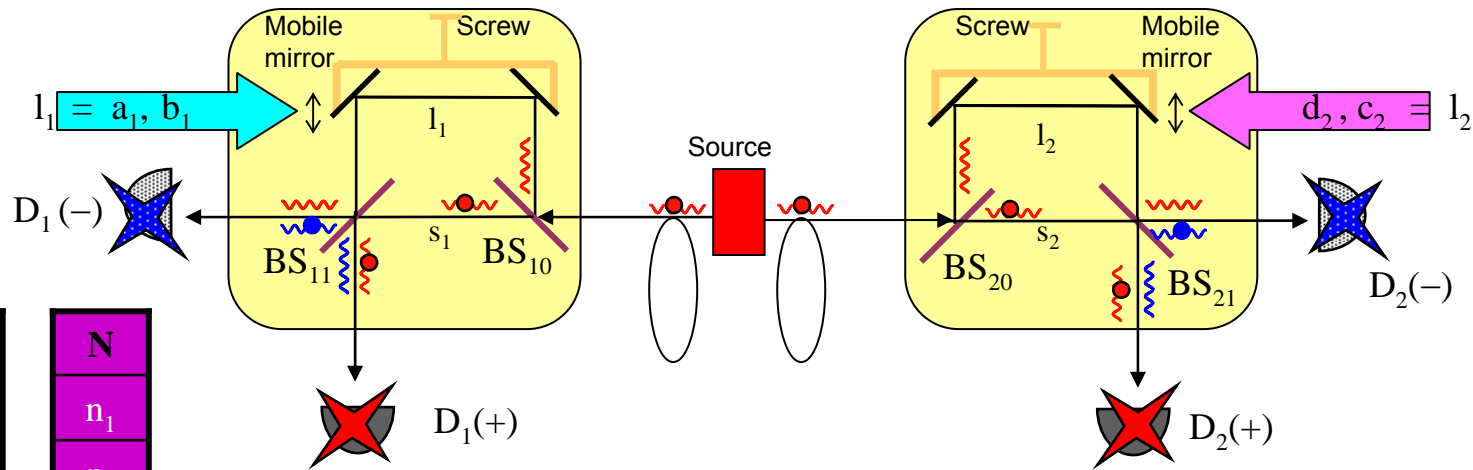
By contrast standard quantum formalism is silent about time!

# Einstein: Quantum mechanics is not complete



The quantum choice implies exchange of information faster than light, no matter of one uses Copenhagen's or De Broglie's model.

Einstein concluded: "Telepathy". Quantum mechanics "cannot be considered complete". The particles carry hidden programs, which produce the correlations.



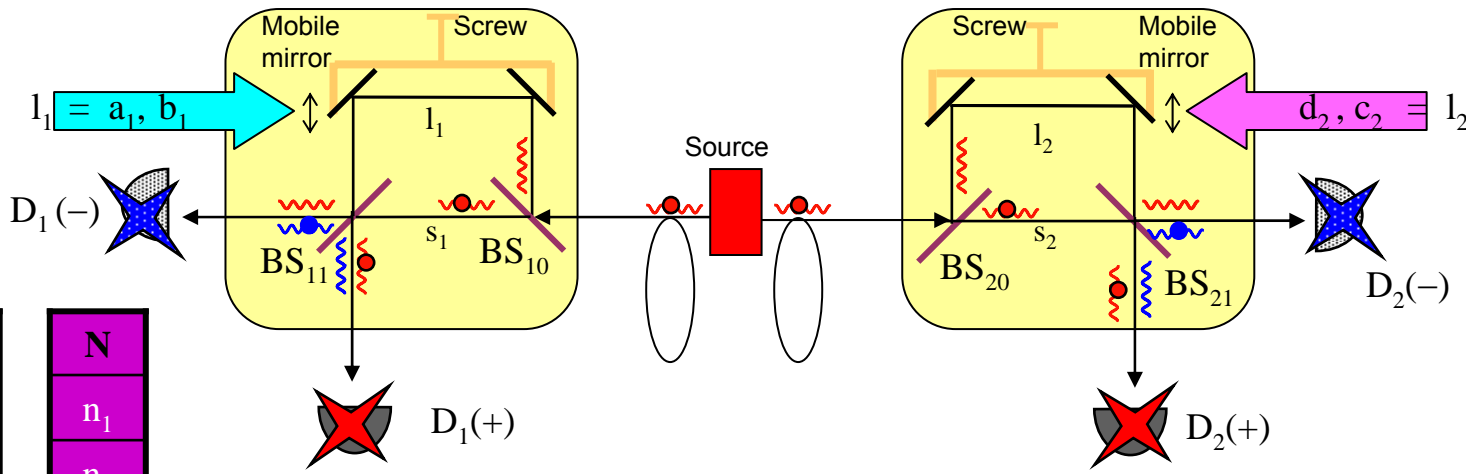
$a_1$	$b_1$	$c_2$	$d_2$	$N$
+	+	+	+	$n_1$
+	+	+	-	$n_2$
+	+	-	+	$n_3$
+	+	-	-	$n_4$
+	-	+	+	$n_5$
+	-	+	-	$n_6$
+	-	-	+	$n_7$
+	-	-	-	$n_8$
-	+	+	+	$n_9$
-	+	+	-	$n_{10}$
-	+	-	+	$n_{11}$
-	+	-	-	$n_{12}$
-	-	+	+	$n_{13}$
-	-	+	-	$n_{14}$
-	-	-	+	$n_{15}$
-	-	-	-	$n_{16}$

## John Bell's inequality (1964)

Is Einstein right, then in a 2-particles experiment with lengths  $a_1$ ,  $b_1$  and  $c_2$ ,  $d_2$ , the particle pairs the source emits are distributed among 16 different classes, according to the detector clicking in a run with the indicated path length.

Each class contributes with a number  $n_i$  of pairs to the total number of pairs  $N$ .

# John Bell's inequality



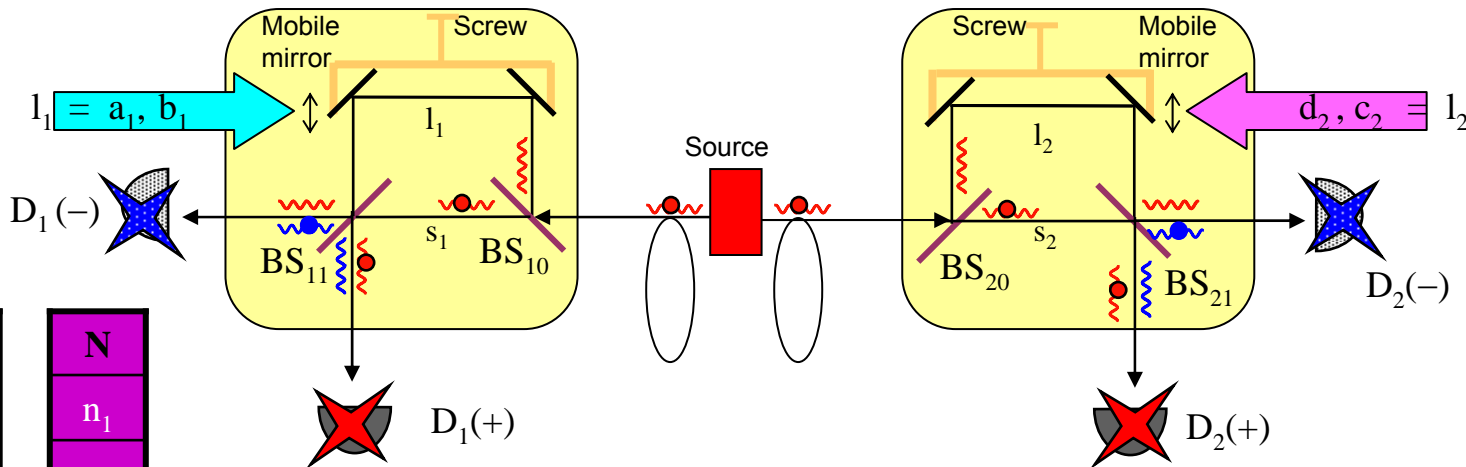
$a_1$	$b_1$	$c_2$	$d_2$
+	+	+	+
+	+	+	-
+	+	-	+
+	+	-	-
+	-	+	+
+	-	+	-
+	-	-	+
+	-	-	-
-	+	+	+
-	+	+	-
-	+	-	+
-	+	-	-
-	-	+	+
-	-	+	-
-	-	-	+
-	-	-	-

- N
- $n_1$
- $n_2$
- $n_3$
- ~~$n_4$~~
- $n_5$
- $n_6$
- ~~$n_7$~~
- ~~$n_8$~~
- ~~$n_9$~~
- ~~$n_{10}$~~
- $n_{11}$
- $n_{12}$
- ~~$n_{13}$~~
- ~~$n_{14}$~~
- $n_{15}$
- $n_{16}$

Suppose an experiment with lengths  $a_1$  and  $c_2$  would produce perfect correlations. This would mean that:

$$n_3 = n_4 = n_7 = n_8 = n_9 = n_{10} = n_{13} = n_{14} = 0$$

# John Bell's inequality



$a_1$	$b_1$	$c_2$	$d_2$	$N$
+	+	+	+	$n_1$
+	+	+	-	$n_2$
+	+	-	+	$n_3$
+	+	-	-	$n_4$
+	-	+	+	$n_5$
+	-	+	-	$n_6$
+	-	-	+	$n_7$
+	-	-	-	$n_8$
-	+	+	+	$n_9$
-	+	+	-	$n_{10}$
-	+	-	+	$n_{11}$
-	+	-	-	$n_{12}$
-	-	+	+	$n_{13}$
-	-	+	-	$n_{14}$
-	-	-	+	$n_{15}$
-	-	-	-	$n_{16}$

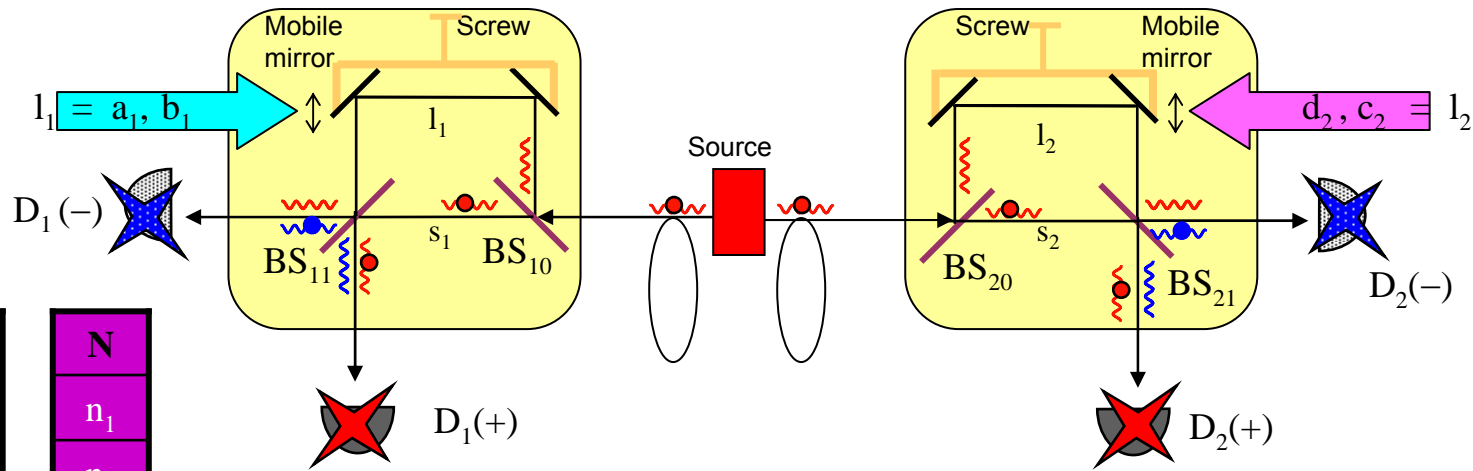
We measure:

- $N$  Pairs with  $a_1$  and  $c_2$
- $N$  Pairs with  $a_1$  and  $d_2$
- $N$  Pairs with  $b_1$  and  $c_2$
- $N$  Pairs with  $b_1$  and  $d_2$

Notice:

On a single pair of particles it is possible to perform **only one** of these 4 measures.

# John Bell's inequality



$a_1$	$b_1$	$c_2$	$d_2$	$N$
+	+	+	+	$n_1$
+	+	+	-	$n_2$
+	+	-	+	$n_3$
+	+	-	-	$n_4$
+	-	+	+	$n_5$
+	-	+	-	$n_6$
+	-	-	+	$n_7$
+	-	-	-	$n_8$
-	+	+	+	$n_9$
-	+	+	-	$n_{10}$
-	+	-	+	$n_{11}$
-	+	-	-	$n_{12}$
-	-	+	+	$n_{13}$
-	-	+	-	$n_{14}$
-	-	-	+	$n_{15}$
-	-	-	-	$n_{16}$

We define :

$a_1 = +1$ , resp.  $b_1 = +1$ , if  $a_1 = +$ , resp.  $b_1 = +$   
 $a_1 = -1$ , resp.  $b_1 = -1$ , if  $a_1 = -$ , resp.  $b_1 = -$   
 $c_2 = +1$ , resp.  $d_2 = +1$ , if  $c_2 = +$ , resp.  $d_2 = +$   
 $c_2 = -1$ , resp.  $d_2 = -1$ , if  $c_2 = -$ , resp.  $d_2 = -$

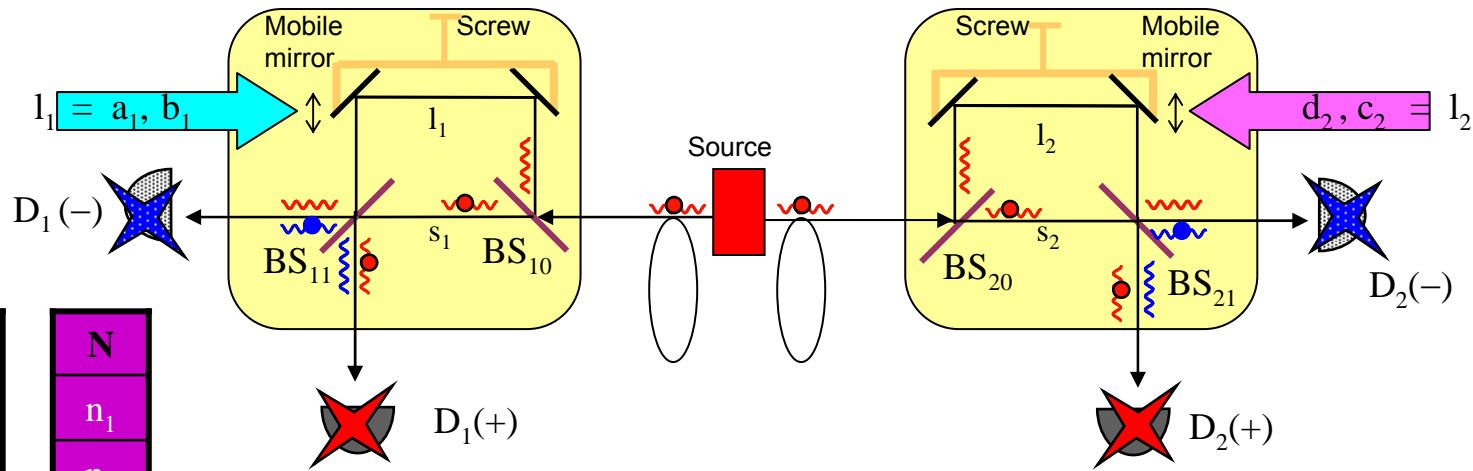
For each of the 16 classes of pairs we define the value:

$$S_i = a_1 \cdot c_2 + a_1 \cdot d_2 + b_1 \cdot c_2 - b_1 \cdot d_2$$

It holds that : either  $S_i = +2$ , or  $S_i = -2$

Where the 4 terms of  $S_i$  result from measurements on 4 different particle pairs, since on a single particle pair one can perform only one of the 4 corresponding measurements.

# John Bell's CHSH inequality



$a_1$	$b_1$	$c_2$	$d_2$	$N$
+	+	+	+	$n_1$
+	+	+	-	$n_2$
+	+	-	+	$n_3$
+	+	-	-	$n_4$
+	-	+	+	$n_5$
+	-	+	-	$n_6$
+	-	-	+	$n_7$
+	-	-	-	$n_8$
-	+	+	+	$n_9$
-	+	+	-	$n_{10}$
-	+	-	+	$n_{11}$
-	+	-	-	$n_{12}$
-	-	+	+	$n_{13}$
-	-	+	-	$n_{14}$
-	-	-	+	$n_{15}$
-	-	-	-	$n_{16}$

We consider the average:

$$S = \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot a_1 \cdot c_2 + \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot a_1 \cdot d_2 + \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot b_1 \cdot c_2 - \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot b_1 \cdot d_2$$

$$S = \frac{1}{N} \sum_{i=1}^{i=16} n_i S_i$$

Suppose all particle pairs would belong to the same class. Then:

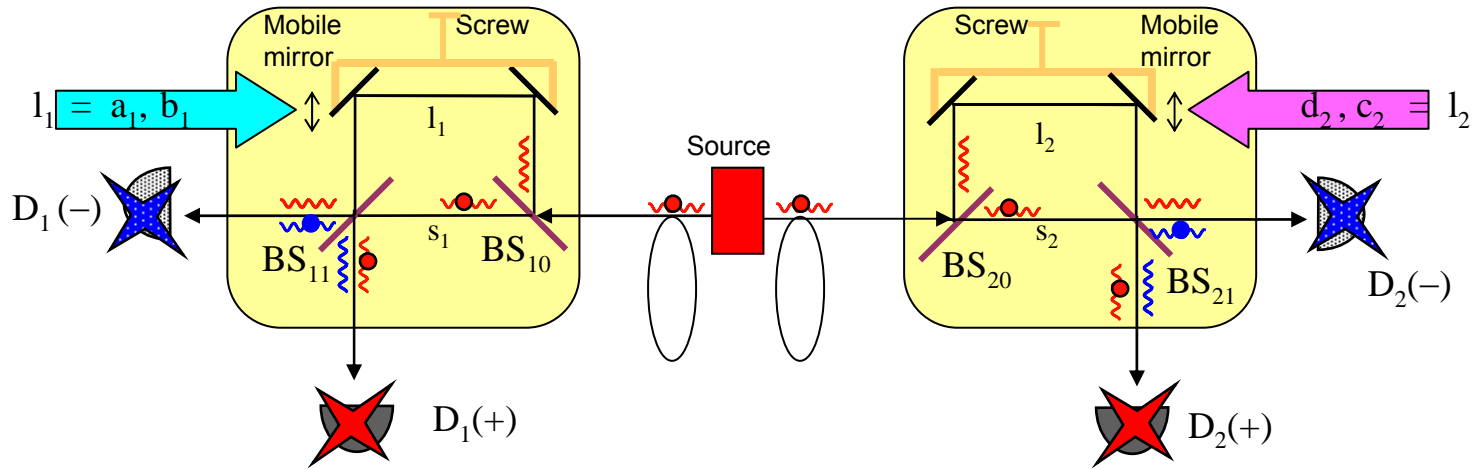
$$\text{either } S_i = +2, \text{ or } S_i = -2$$

Therefore, for the 16 different classes one is led to the Bell's inequality:

$$-2 \leq S \leq +2$$

Also called CHSH (Clauser, Horne, Shimony, Holt) inequality:

# The prediction of quantum mechanics for the value $S$



$$S = \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot a_1 \cdot c_2 + \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot a_1 \cdot d_2 + \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot b_1 \cdot c_2 - \frac{1}{N} \sum_{i=1}^{i=16} n_i \cdot b_1 \cdot d_2$$

= Pr(Konkordanz) – Pr(Diskordanz) bei den Messungen mit  $a_1$  und  $c_2$

+ Pr(Konkordanz) – Pr(Diskordanz) bei den Messungen mit  $a_1$  und  $d_2$

+ Pr(Konkordanz) – Pr(Diskordanz) bei den Messungen mit  $b_1$  und  $c_2$

– Pr(Konkordanz) – Pr(Diskordanz) bei den Messungen mit  $b_1$  und  $d_2$

$$\Phi(a_1, c_2) = \omega_1 \frac{a_1 - s_1}{c} + \omega_2 \frac{c_2 - s_2}{c}$$

$$\Phi(a_1, d_2) = \omega_1 \frac{a_1 - s_1}{c} + \omega_2 \frac{d_2 - s_2}{c}$$

$$\Phi(b_1, c_2) = \omega_1 \frac{b_1 - s_1}{c} + \omega_2 \frac{c_2 - s_2}{c}$$

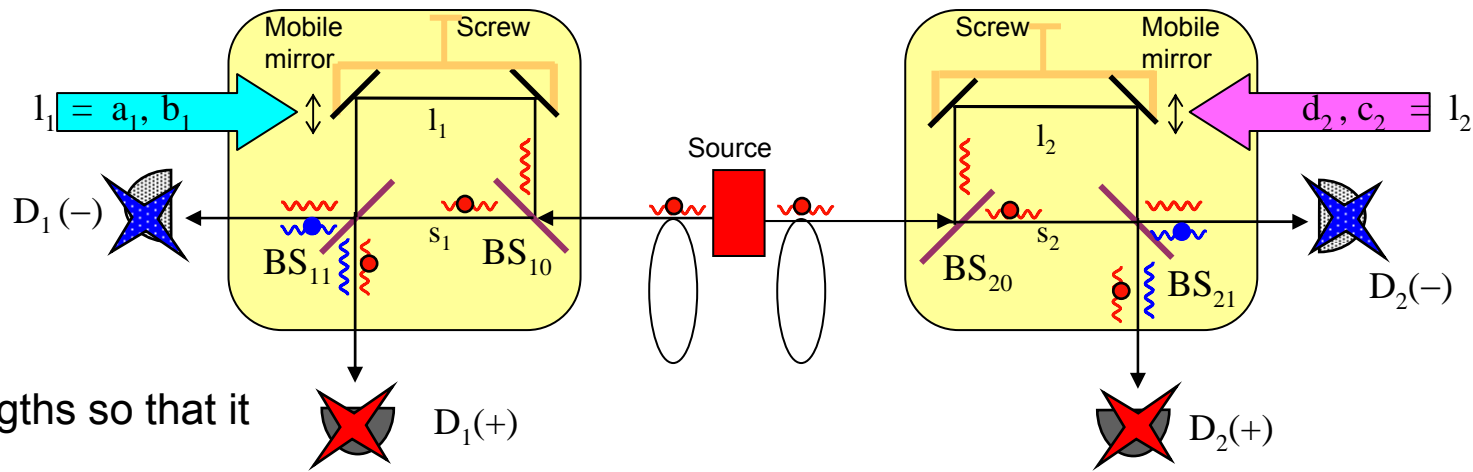
$$\Phi(b_1, d_2) = \omega_1 \frac{b_1 - s_1}{c} + \omega_2 \frac{d_2 - s_2}{c}$$

Gemäss Quantentheorie:

$$S = \cos \Phi(a_1, c_2) + \cos \Phi(a_1, d_2) + \cos \Phi(b_1, c_2) - \cos \Phi(b_1, d_2)$$



# Quantum mechanics contradicts Einstein



We choose path lengths so that it holds:

$$\Phi(a_1, c_2) = \omega_1 \frac{a_1 - s_1}{c} + \omega_2 \frac{c_2 - s_2}{c} = -\frac{\pi}{4} + 0 = -\frac{\pi}{4}$$

$$\Phi(a_1, d_2) = \omega_1 \frac{a_1 - s_1}{c} + \omega_2 \frac{d_2 - s_2}{c} = -\frac{\pi}{4} + \frac{\pi}{2} = \frac{\pi}{4}$$

$$\Phi(b_1, c_2) = \omega_1 \frac{b_1 - s_1}{c} + \omega_2 \frac{c_2 - s_2}{c} = \frac{\pi}{4} + 0 = \frac{\pi}{4}$$

$$\Phi(b_1, d_2) = \omega_1 \frac{b_1 - s_1}{c} + \omega_2 \frac{d_2 - s_2}{c} = \frac{\pi}{4} + \frac{\pi}{2} = \frac{3\pi}{4}$$

For this path lengths quantum mechanics predicts:

$$\begin{aligned} S &= \cos \Phi(a_1, c_2) + \cos \Phi(a_1, d_2) \\ &\quad + \cos \Phi(b_1, c_2) - \cos \Phi(b_1, d_2) \\ &= \frac{\sqrt{2}}{2} + \frac{\sqrt{2}}{2} + \frac{\sqrt{2}}{2} - \frac{\sqrt{2}}{2} = 2\sqrt{2} \end{aligned}$$

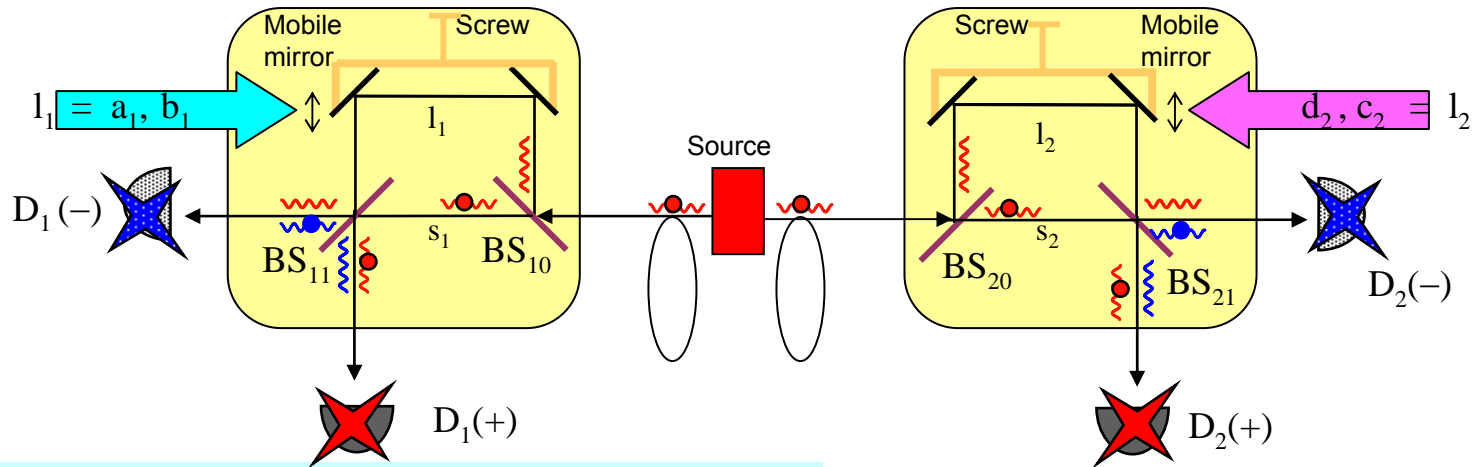
Since the experimental correlation degree deviates from the maximal theoretical value, we introduce a Visibility-coefficient  $V_{is}$ :

$$S = V_{is} \cos \Phi(a_1, c_2) + V_{is} \cos \Phi(a_1, d_2) + V_{is} \cos \Phi(b_1, c_2) - V_{is} \cos \Phi(b_1, d_2) = V_{is} \cdot 2\sqrt{2}$$

For  $V_{is} > \frac{1}{\sqrt{2}} \approx 0.71$  One is led to a violation of the Bell's inequality,

i.e. a contradiction between Einstein's explanation and Quantum Theory.

# Measuring $V_{is}$ one can test the Bell's inequality



$V_{is} > 0.71 \Rightarrow$  Violation of Bell's inequality

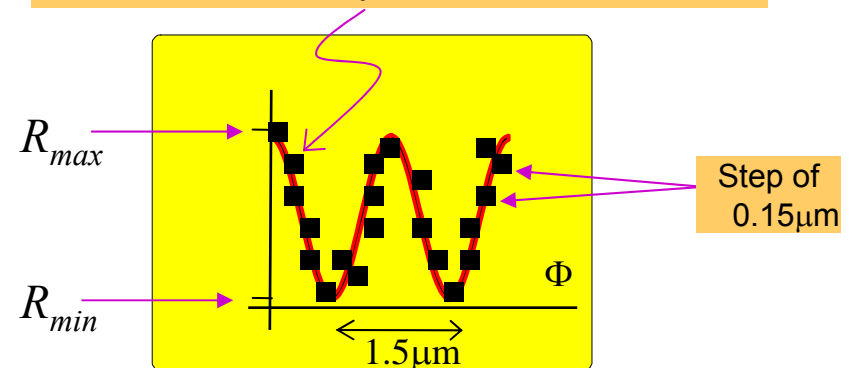
$$\text{Pr}_{\max}(+, +) = \frac{1}{4}(1 + V_{is})$$

$$\text{Pr}_{\min}(+, +) = \frac{1}{4}(1 - V_{is})$$

$$V_{is} = \frac{\text{Pr}_{\max}(+, +) - \text{Pr}_{\min}(+, +)}{\text{Pr}_{\max}(+, +) + \text{Pr}_{\min}(+, +)}$$

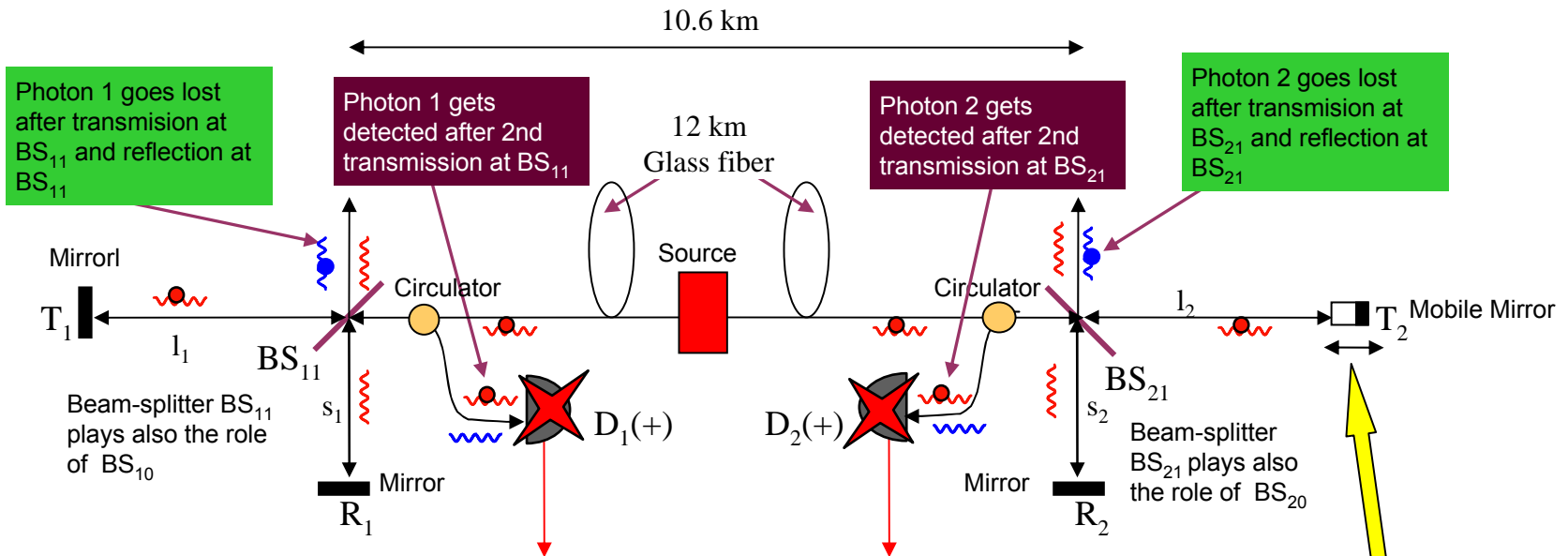
$$V_{is} = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}}$$

$R$ : Number of coincident counts in the two detectors per 10 seconds



# One of the Bell's Experiments

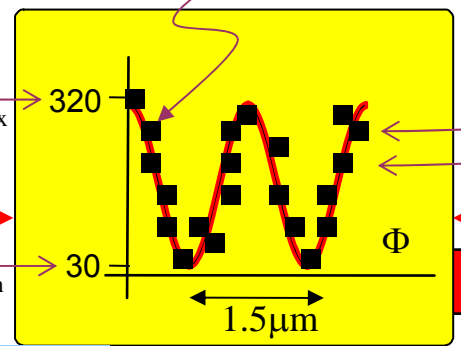
von H. Zbinden, J. Brendel, W. Tittel, und N. Gisin (2000)



$R$ : Number of coincident counts in the two detectors per 10 seconds

$$V_{is} = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}}$$

$$= \frac{320 - 30}{320 + 30} \approx 83\% > 71\%$$



One choice "influences" the other at:  
*Velocity* > 10<sup>6</sup> c

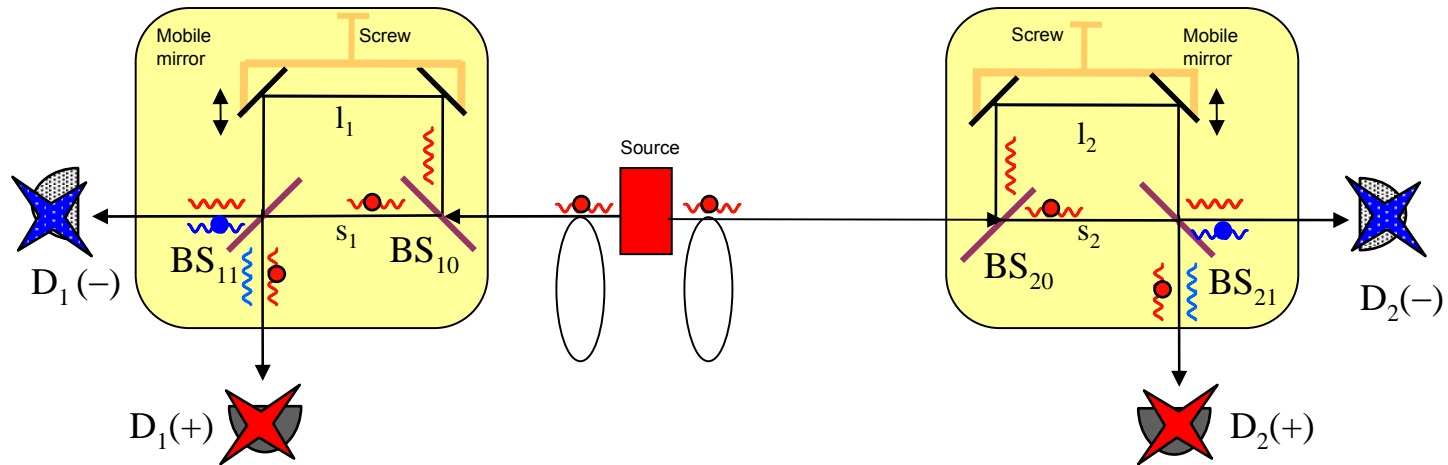
⇒ Violation of the Bell inequality!!

# Einstein is wrong!

The particles do not carry hidden programs.

In Nature there are influences going faster than light, though we cannot use this feature for phoning or teleporting faster than light.

# According to Bohm's model there is a time ordering behind the quantum correlations



Since the glass-fibers from the source to each interferometer cannot be cut exactly equal long (1mm error), one of the particles, say photon 1, hits its beam-splitter  $BS_{11}$  **before** photon 2 hits  $BS_{21}$ . One assumes that photon 1 makes its choice between output + and out put - at will (before photon 2 chooses), and photon 2 chooses **after** that, taking account of photon 1's choice.

By contrast standard quantum formalism is silent about time!

# Is there time in the quantum world?

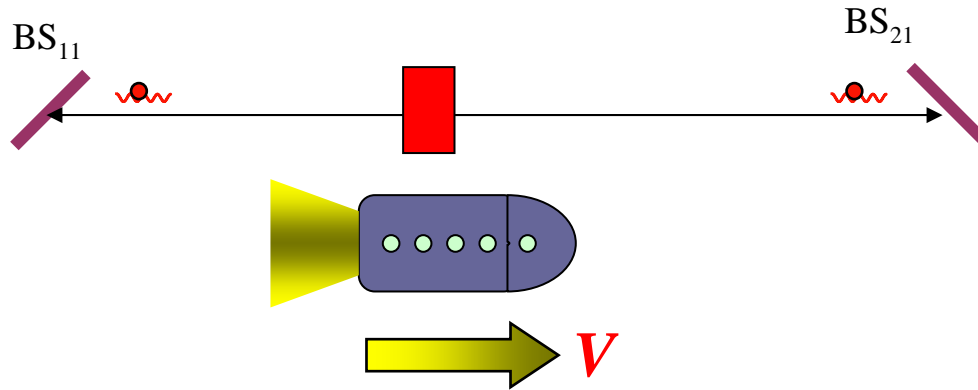
Does the choice happening **before** in time  
influence the choice happening **later** in time?

Which clock matters for measuring the time of the photon's arrival at the beam-splitter?

**We assume the clock associated to the inertial frame of the corresponding beam-splitter**

# The principle of multsimultaneity

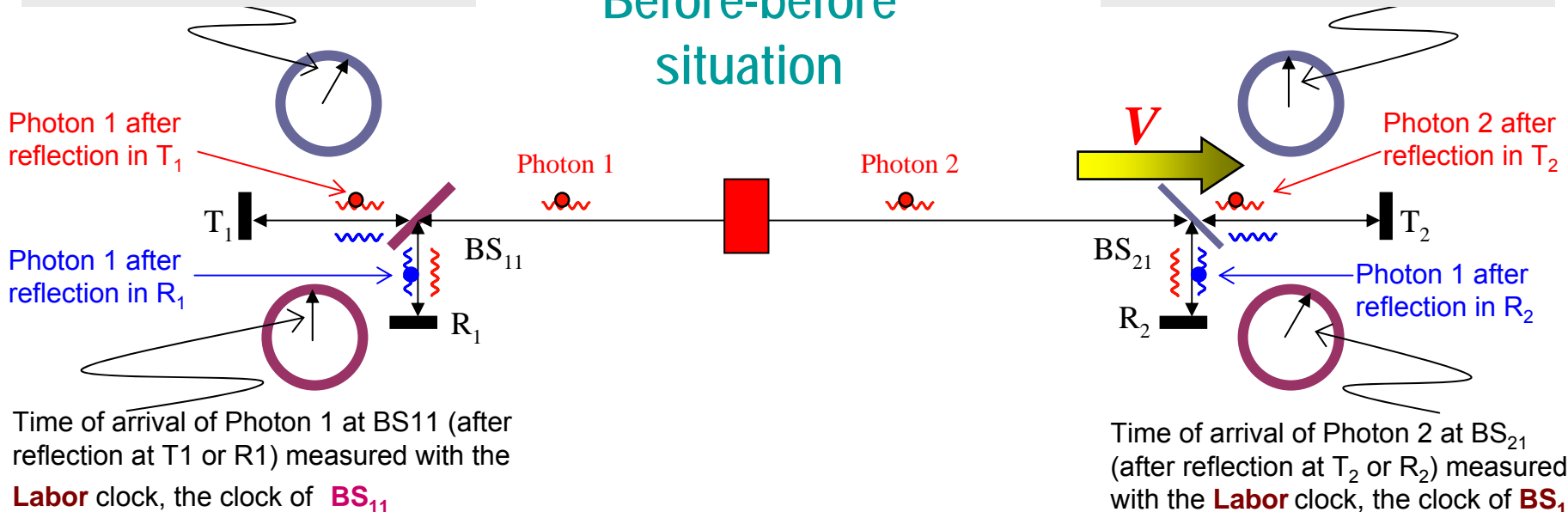
Relativity of time



Time of arrival of Photon 1 at  $BS_{11}$  (after reflection at  $T_1$  or  $R_1$ ) measured with the clock of  $BS_{21}$

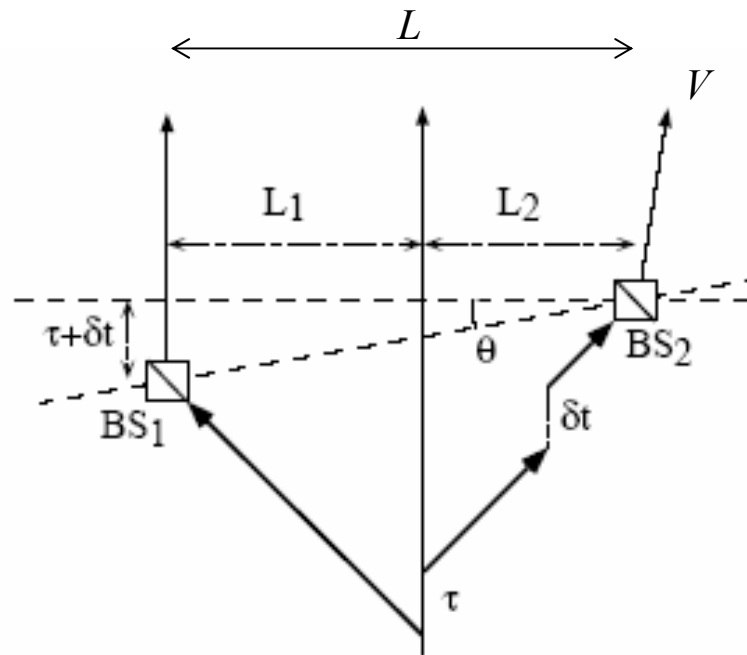
Time of arrival of Photon 2 at  $BS_{21}$  (after Reflection at  $T_2$  or  $R_2$ ) measured with the clock of  $BS_{21}$

Before-before situation



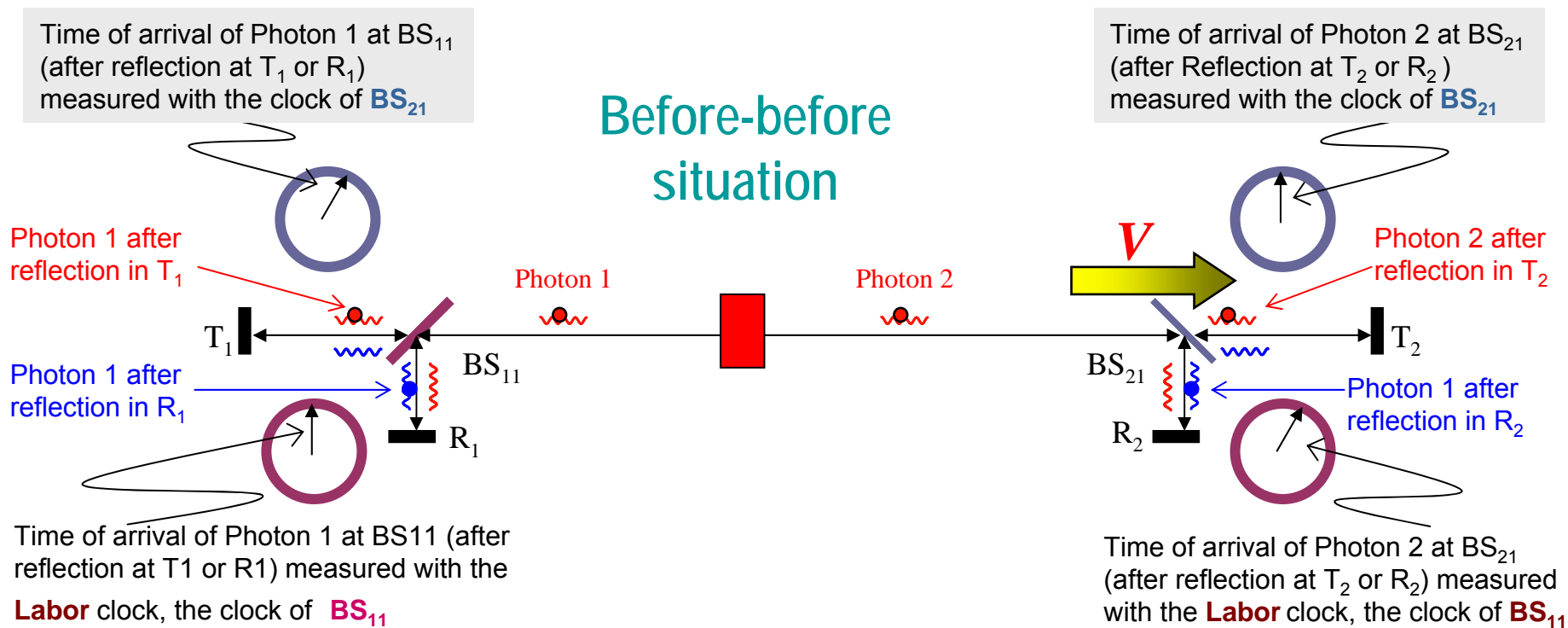


# The condition for the before-before experiment



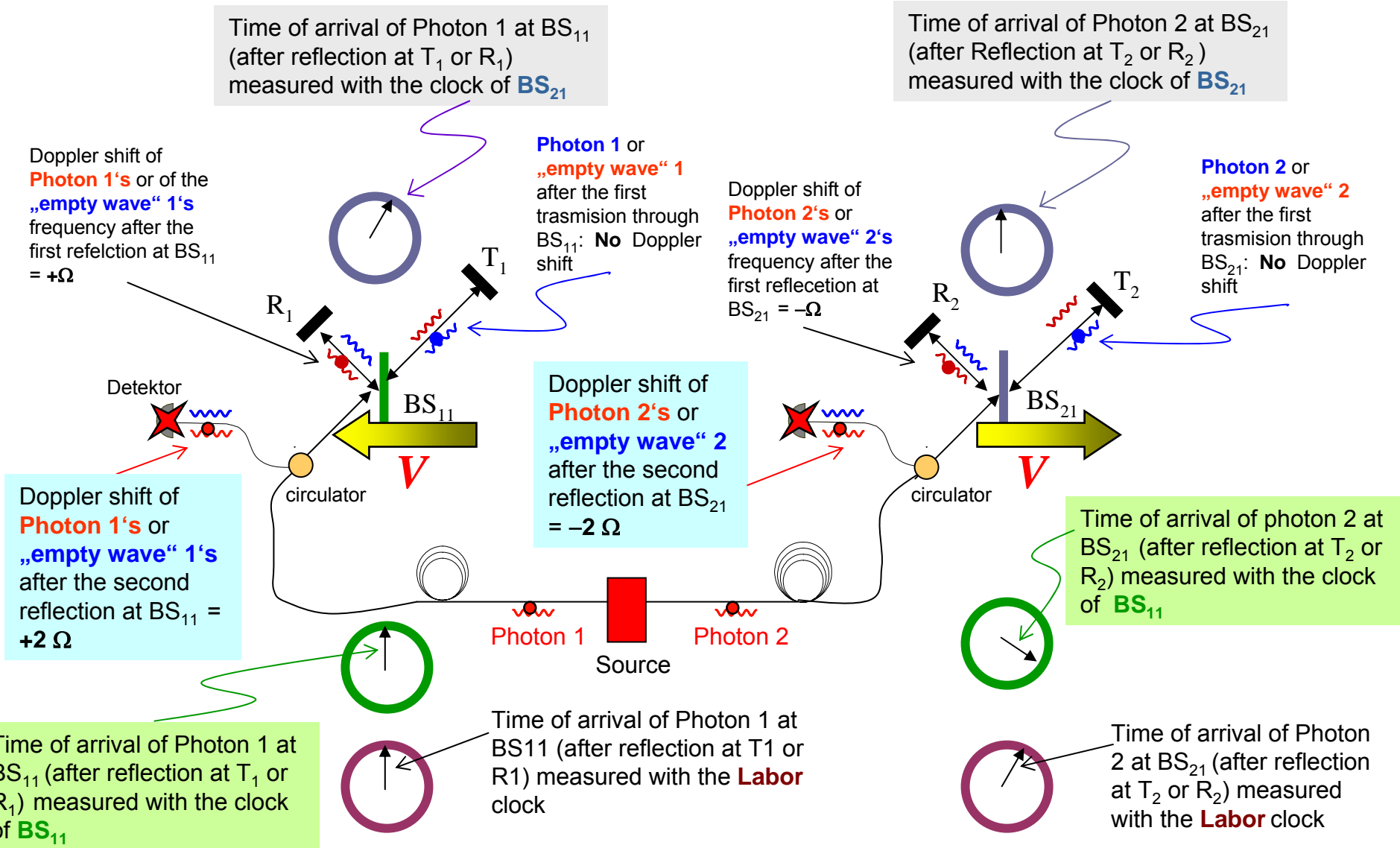
$$|\Delta t| = \tau + \delta t < \frac{V}{c^2} L$$

# In the before-before situation the correlations should disappear



# Before-before Situation

With two beam-splitters in movement it is possible to balance the Doppler shift  $\Omega$  of the light frequency

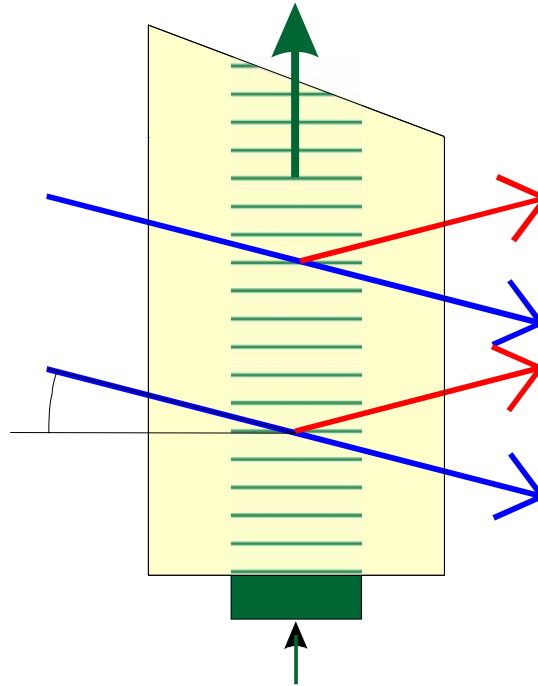


# Sound wave acting as beam-splitter

## Acusto-optic Modulator (AOM)

Velocity of sound=2500 m/s

$\omega_i$ : Frequency of the  
ingoing Photons



The reflected photons exhibit a  
Doppler frequency shift equal  
to the frequency  $\Omega$  of the  
sound wave:

$$\omega_r = \omega_i + \Omega$$

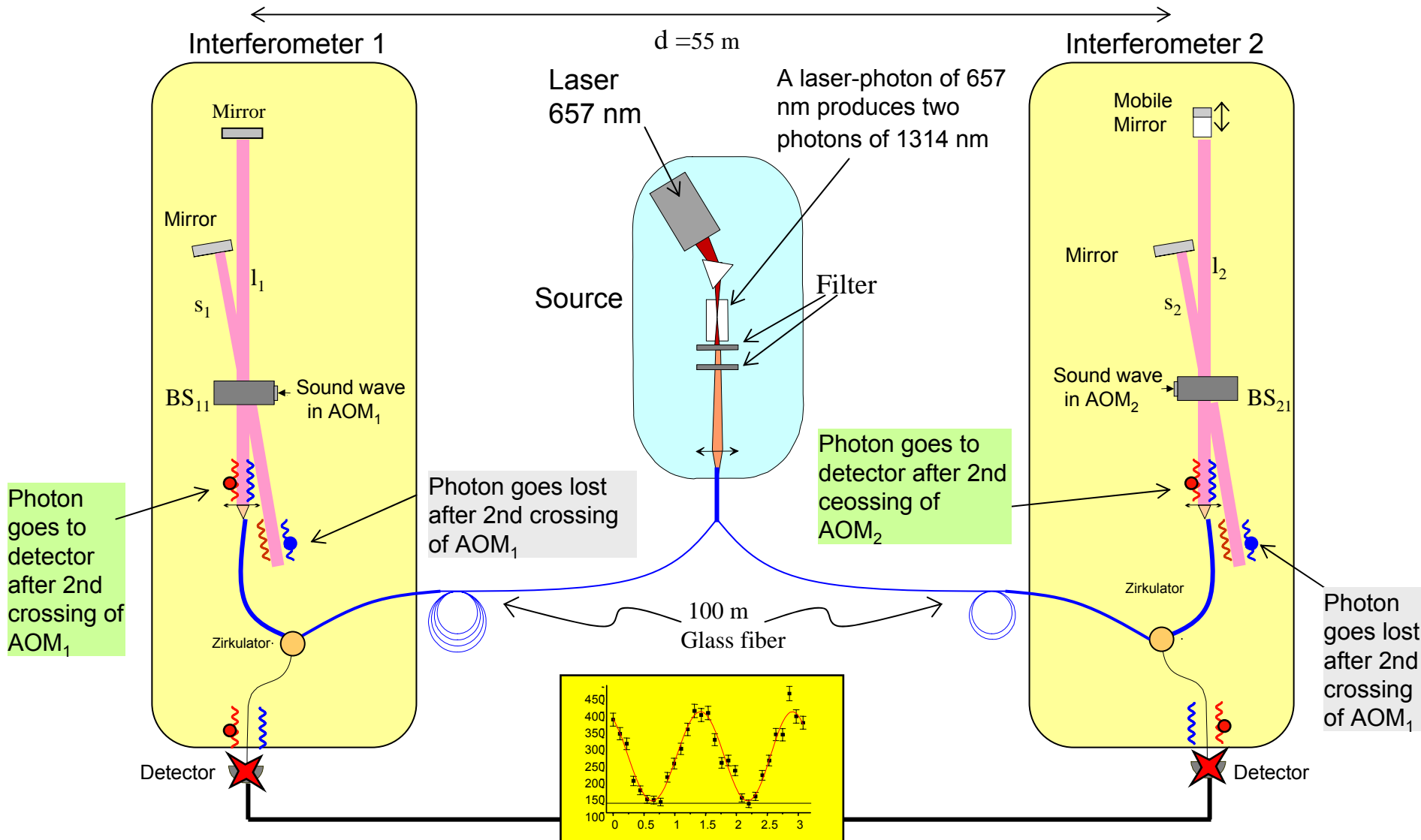
Frequency of the  
transmitted photons

$$\omega_t = \omega_i$$

$\Omega$ : Frequency of  
the sound wave  
(100 MHz)

# The Before-Before Experiment

A. Stefanov, H. Zbinden, N. Gisin and A. Suarez (2001)



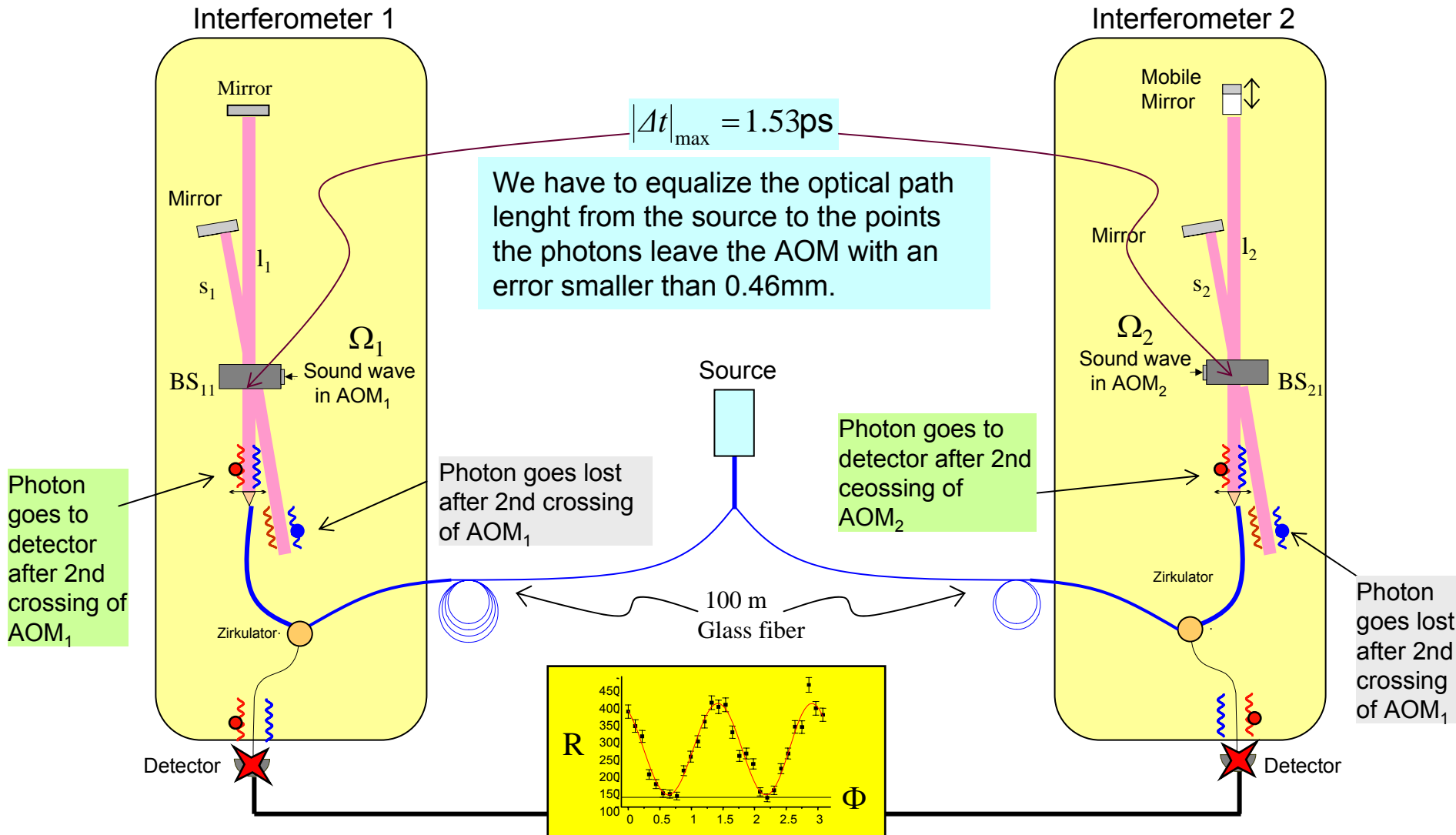
# The Before-Before Experiment

$$\Delta\nu \approx 10\text{MHz}$$

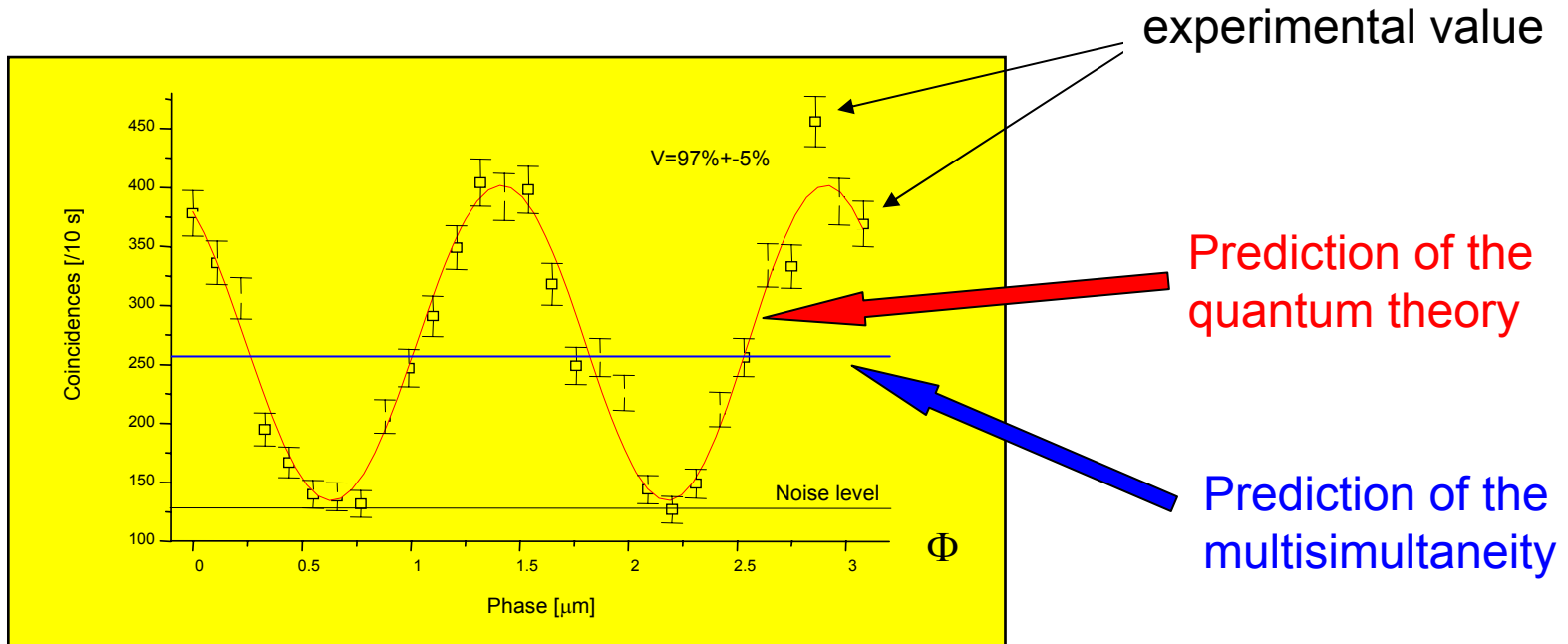
$$\Delta\nu_{ph} \approx 2 \cdot 10^3\text{GHz}$$

$$R = \frac{1}{2}(1 + \cos \Phi)$$

$$\Phi = (\Omega_1 - \Omega_2)t + \omega_1 \frac{l_1 - s_1}{c} + \omega_2 \frac{l_2 - s_2}{c}$$



# Results



**With *before-before* timing the correlations don't disappear !**

The quantum correlations show that there is a dependence between events happening in two separated regions, but this dependence does not correspond to any real time ordering.

There is no real time ordering behind the quantum correlations, one event cannot be considered the cause of the other.

**There is no real time in the quantum world**

Notice however that nothing speaks against maintaining the concept of trajectory.



Correlated events in spacelike separated regions

+ Assumption of the physicist's free will

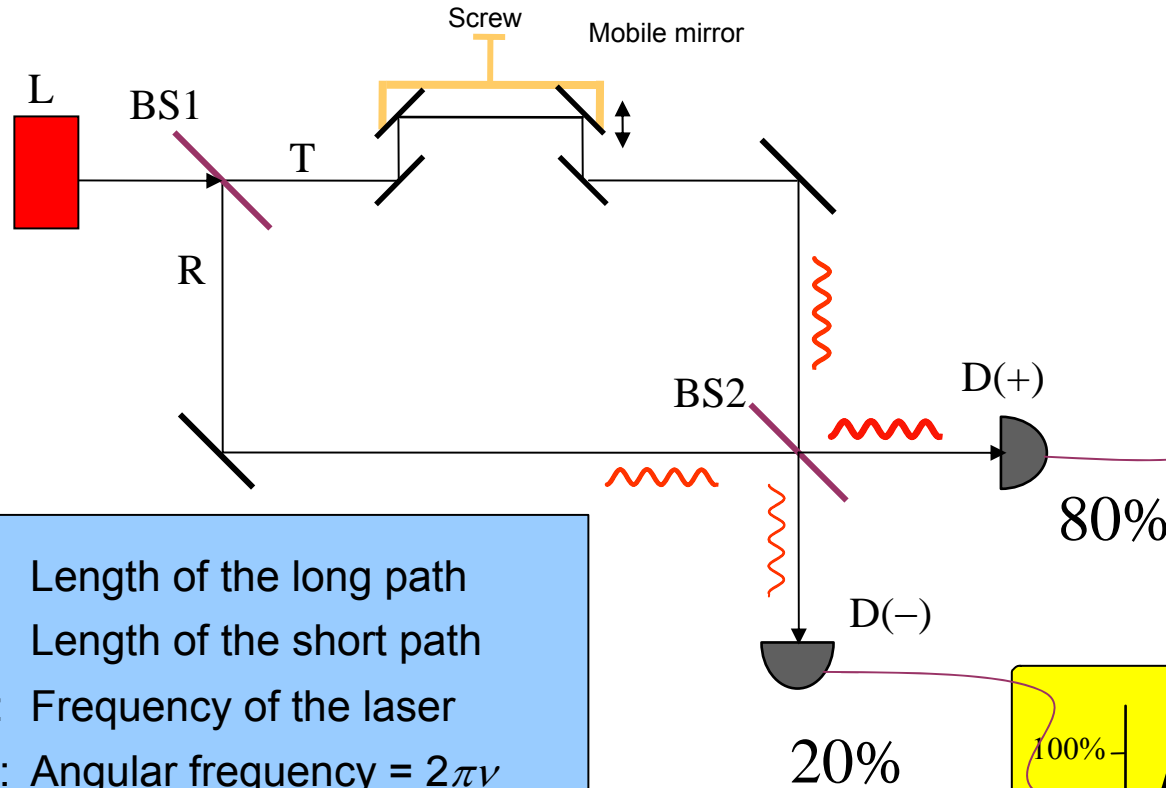
+ Violation of Bell inequalities

+ No signaling

⇒ The events have a common cause  
outside the spacetime

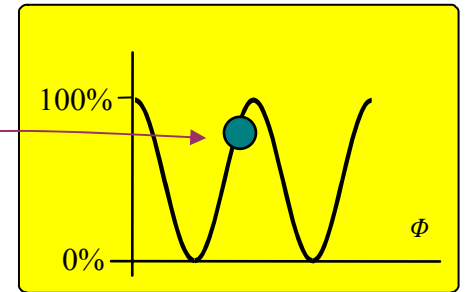
**Either free-will is an illusion,  
or  
the quantum phenomena involve  
information processing outside of space-time and  
without material support**

# Quantum memory without material carrier



Counting rate D(+):

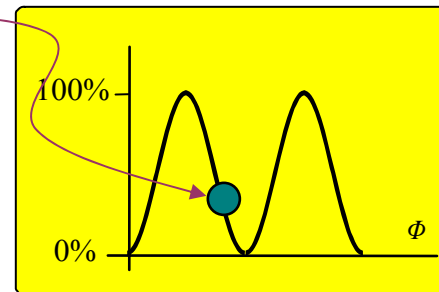
$$\text{Pr}(+) = \frac{1}{2}(1 + \cos \Phi)$$



$l$ : Length of the long path  
 $s$ : Length of the short path  
 $\nu$ : Frequency of the laser  
 $\omega$ : Angular frequency =  $2\pi\nu$   
 $c$ : Velocity of light

$\Phi$ : Phase shift because of the length difference

$$\Phi = \omega \frac{l-s}{c}$$



Counting rate in D(-):

$$\text{Pr}(+) = \frac{1}{2}(1 - \cos \Phi)$$

„Das alles ist ziemlich verrückt. Die spukhafte Fernwirkung – das ist ein Vorgang jenseits von Raum und Zeit, das kann auch ich mir nicht richtig vorstellen.“

Anton Zeilinger,  
Die Weltwoche Nr. 48/2005

„Each single event is an individual act of creation“

Anton Zeilinger

# “Correlations cry out for explanation” (John Bell)

If quantum physics is true, we have to accept that there is no observable temporal cause of the correlations.

## So what?

- There is no agency at all behind the quantum single events: „I am no-thing“.
- Many-worlds interpretation: There is no real choice and no freedom. „All is in advance decided, I don't decide anything“, „I am no-body“.
- „I am someone“, but then there is also “someone” behind the quantum phenomena

# The free will theorem in Quantum Physics

**“if indeed there exist any experimenters with a modicum of free will, then elementary particles must have their own share of this valuable commodity.”**

John Conway and Simon Kochen  
quant-ph/0604079

If human beings make free choices, then free choices happen in the Quantum World too.

**In quantum physics, laws of freedom may be introduced into the causality of the course of nature**

In quantum phenomena randomness  
appears inseparably united  
to creation of information,  
randomness and guidance have the  
same origin, the same cause.

# God plays dice!

Is randomness  
one of the important things  
God created in the beginning?

# Is there time in the Quantum World?

Presentation: Lorenzo De Vittori

Direction: Antoine Suarez

Center for Quantum Philosophy

[www.quantumphil.org](http://www.quantumphil.org)

## The End

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