Both deterministic and probabilistic phenomena can exist in spacetime

Vesselin Petkov
Minkowski Institute
Montreal, Canada

https://vesselinpetkov.com/13May2025-BAS.html

MINKOWSKI INSTITUTE

Ultimately, the main goal of the talk is to address the fact that

There exists a fundamental continuity at the heart of quantum mechanics — the almost explicit assumption that quantum objects exist continuously in time.

It is frequently asserted that quantum mechanics and relativity are incompatible due to the probabilistic nature of quantum phenomena on the one hand and the deterministic nature of relativity on the other. However, this viewpoint is a consequence of misunderstanding stemming from the primary unresolved question in quantum mechanics: the absence of a spacetime model for the quantum object (quantum mechanics describes not the quantum object itself but rather its states).

As we will see, an analysis of the necessity for discovering an adequate spacetime model of the quantum object reveals that both deterministic and probabilistic phenomena can exist in spacetime.

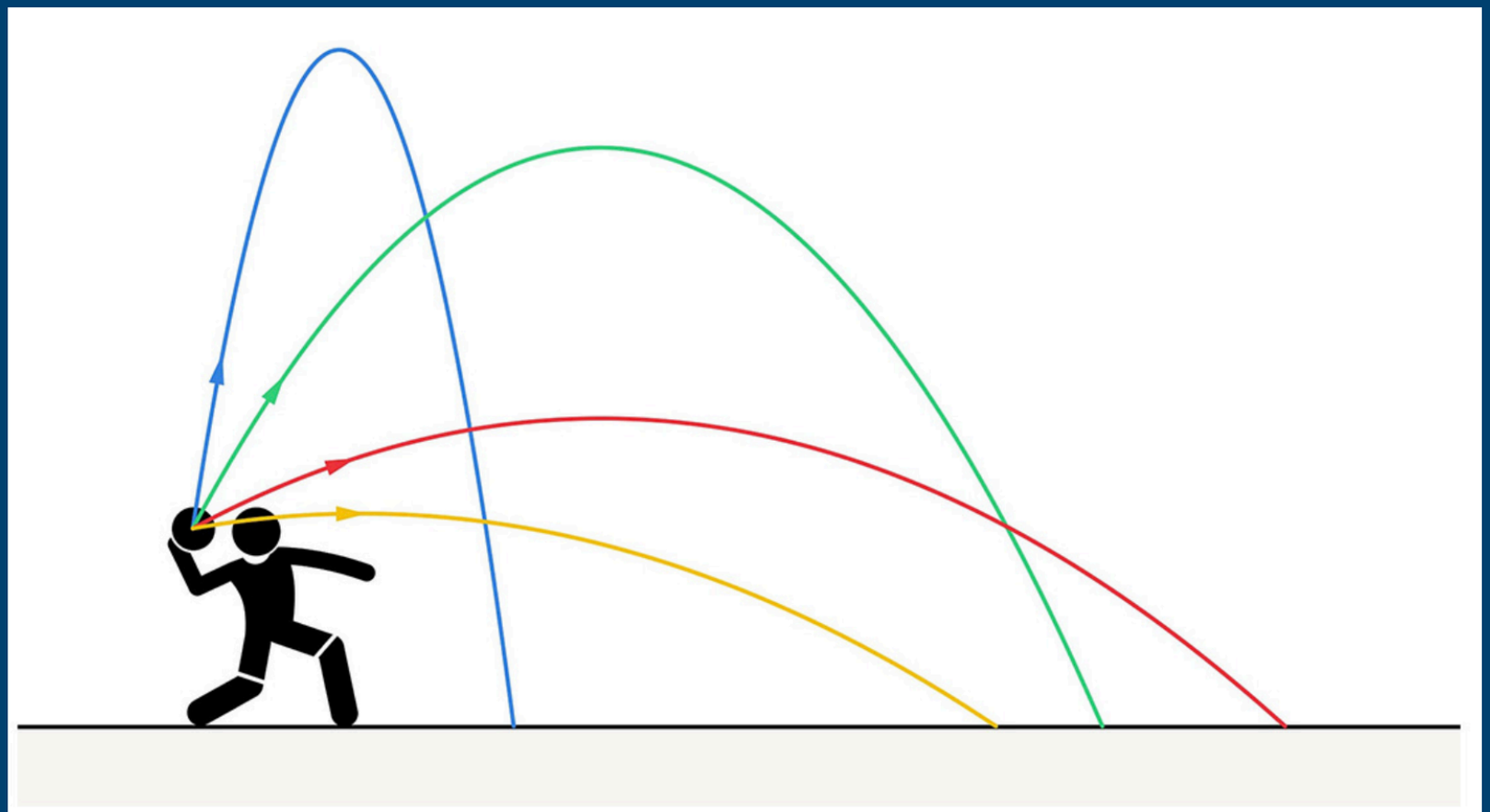
Deterministic phenomena are events or systems where outcomes or future states are entirely predictable and determined by known factors (initial conditions), without any element of randomness or chance. In essence, if you provide the same initial conditions, you will always get the same result.

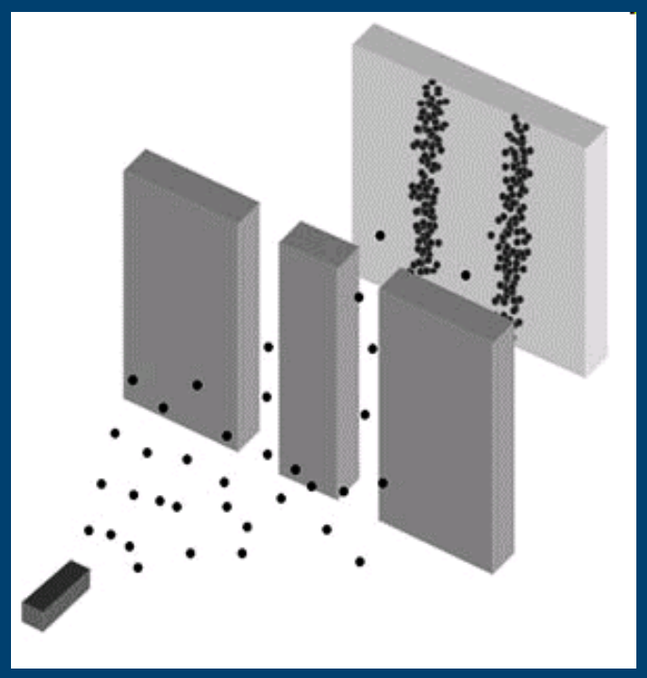
Probabilistic phenomena are events or outcomes whose occurrences are based on probability rather than being certain, i.e., uniquely determined by initial conditions. They are characterized by randomness and uncertainty, where different potential outcomes are assigned different probabilities.

For centuries, before the advent of quantum mechanics, people believed that there existed two fundamental entities in Nature:

- Particles
- Waves - disturbances in different media

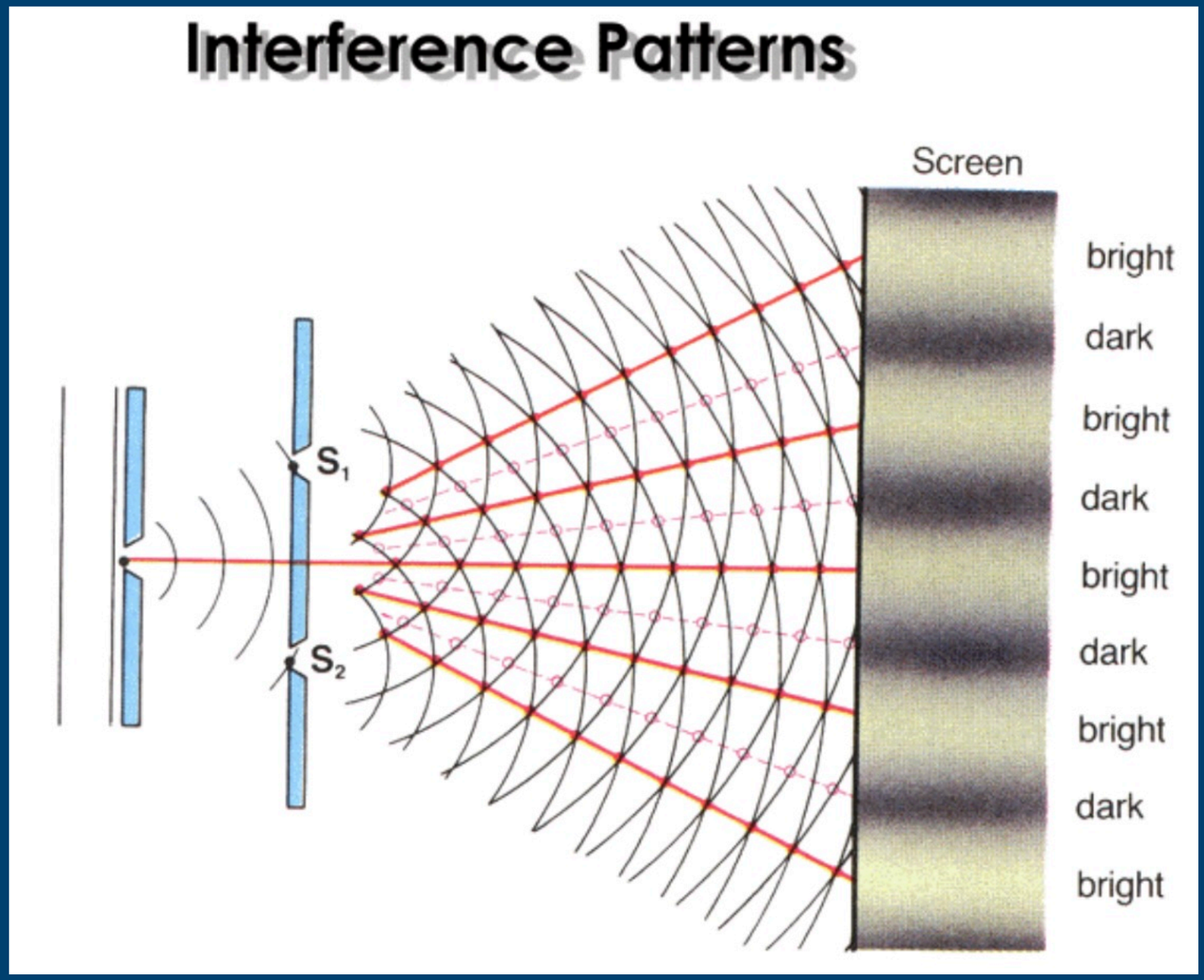
Trajectory





MINKOWSKI INSTITUTE

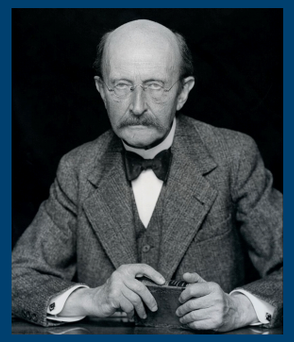
Interference of light is a phenomenon where multiple light waves interact, resulting in either constructive or destructive interference, leading to a redistribution of energy and the formation of an interference pattern. This occurs when waves meet at the same place and their amplitudes either add up (constructive interference) or cancel out (destructive interference), depending on their relative phases.



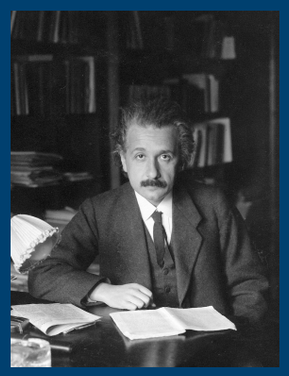
Interference — bright and dark fringes

No trajectory

MINKOWSKI INSTITUTE



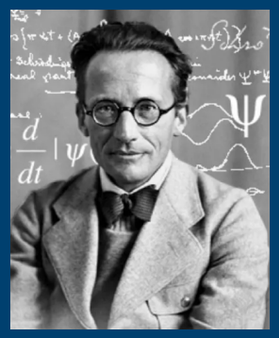
1900 **Max Planck** — light also has particle-like properties (when emitted in quanta)



1905 **Albert Einstein** — light also has particle-like properties (when absorbed in quanta)



1924 **Louis de Broglie** — particles also have wave-like properties (matter waves)



1925 **Erwin Schrödinger** — Schrödinger equation



1926 **Max Born** — matter waves = probability waves

MINKOWSKI INSTITUTE

What is the physical meaning of the probability waves?

To answer this question, first two facts:

- Electrons and photons are always registered as particles.
- When not measured they behave like waves.

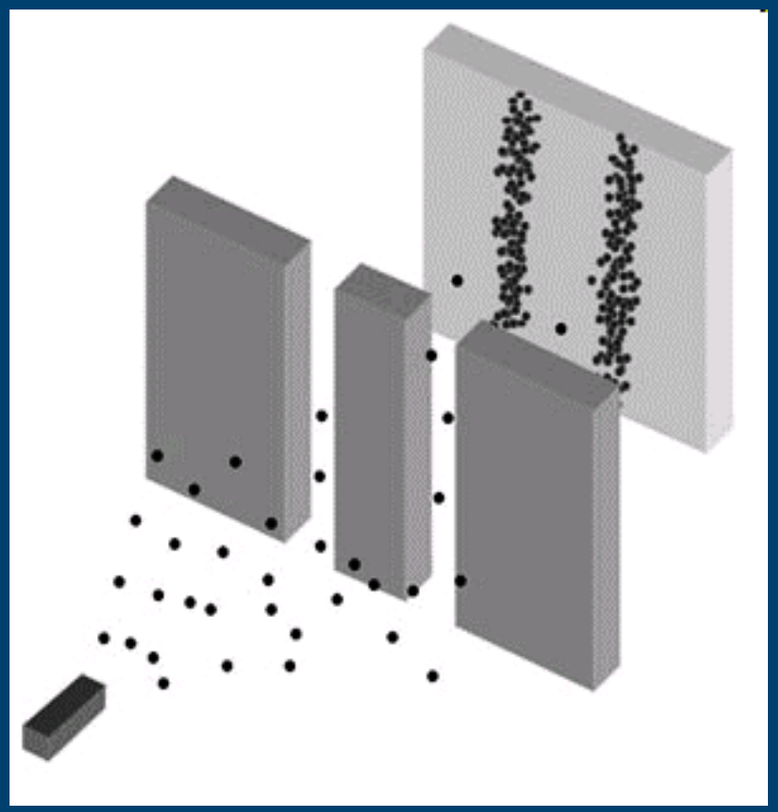
Here are two examples — the double slit interference experiments and the hydrogen atom in s-state — which demonstrate that

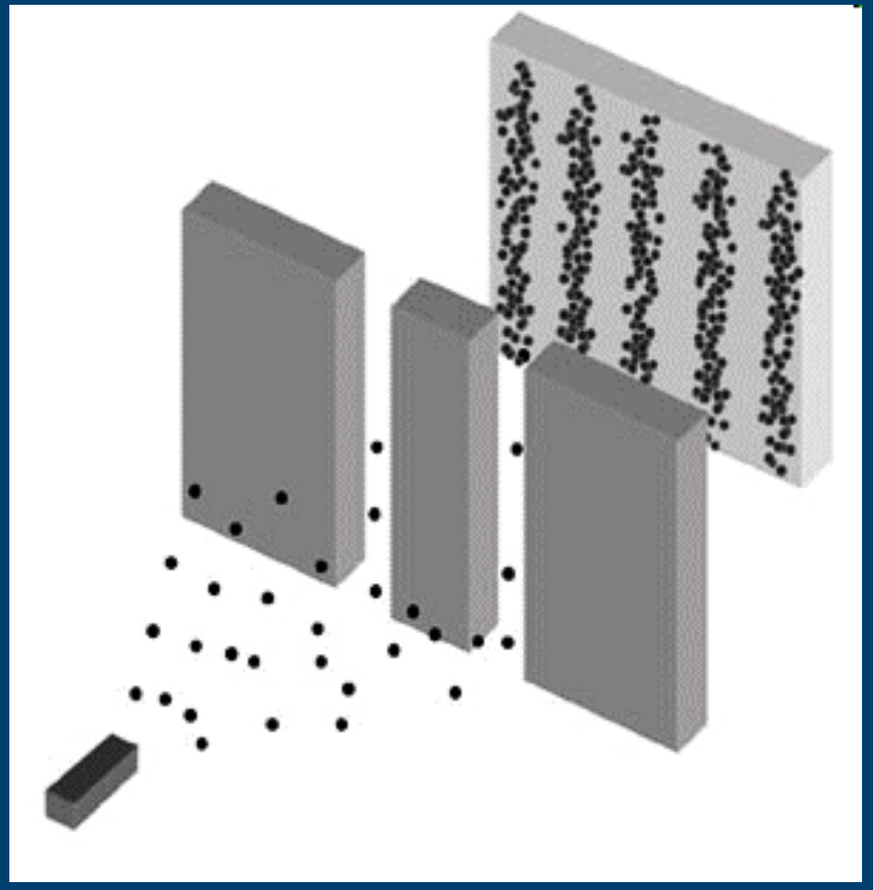
when there is a probability of finding (detecting) an electron, for example, at different location, the electron, before being measured, actually exists at those locations.

MINKOWSKI INSTITUTE

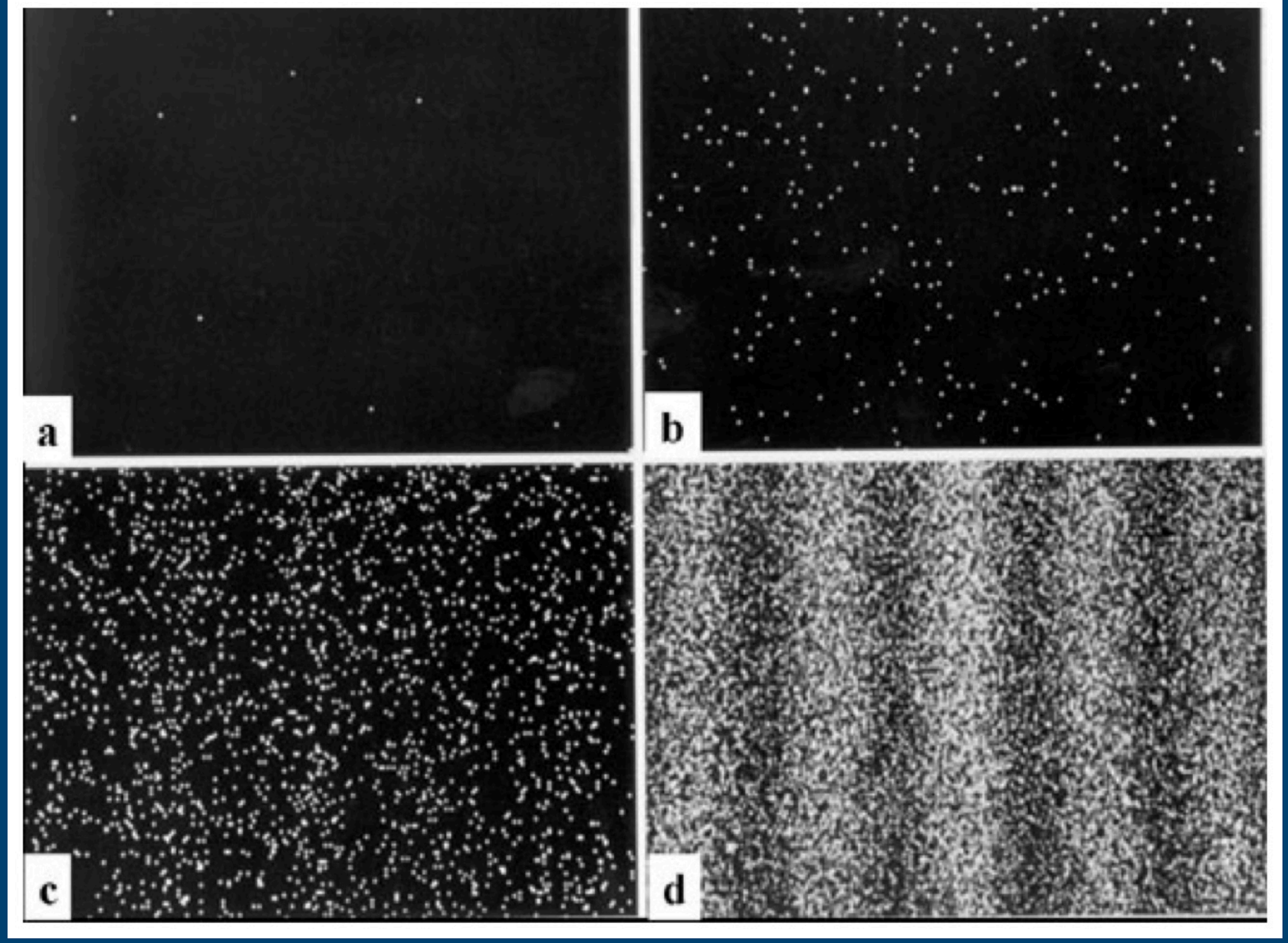
Interference patterns can be observed with single electrons, demonstrating their wave-like nature, even when they are emitted one at a time and cannot interact with each other. This phenomenon is explained by the fact that electrons, like light and other forms of matter, exhibit both particle and wave characteristics, and when they pass through a double slit, they ***interfere with themselves***. In other, more precise, words, ***every electron interferes with itself***, which means that ***every electron passes through both slits***; otherwise

no interference pattern forms.





MINKOWSKI INSTITUTE



https://physicsworld.com/a/the-double-slit-experiment/

Single-electron events build up over a 20 minute exposure to form an interference pattern in this double-slit experiment by Akira Tonomura and co-workers — *American Journal of Physics* 57, 117 (1989), (a) 8 electrons; (b) 270 electrons; (c) 2000 electrons; (d) 60,000.

MINKOWSKI INSTITUTE

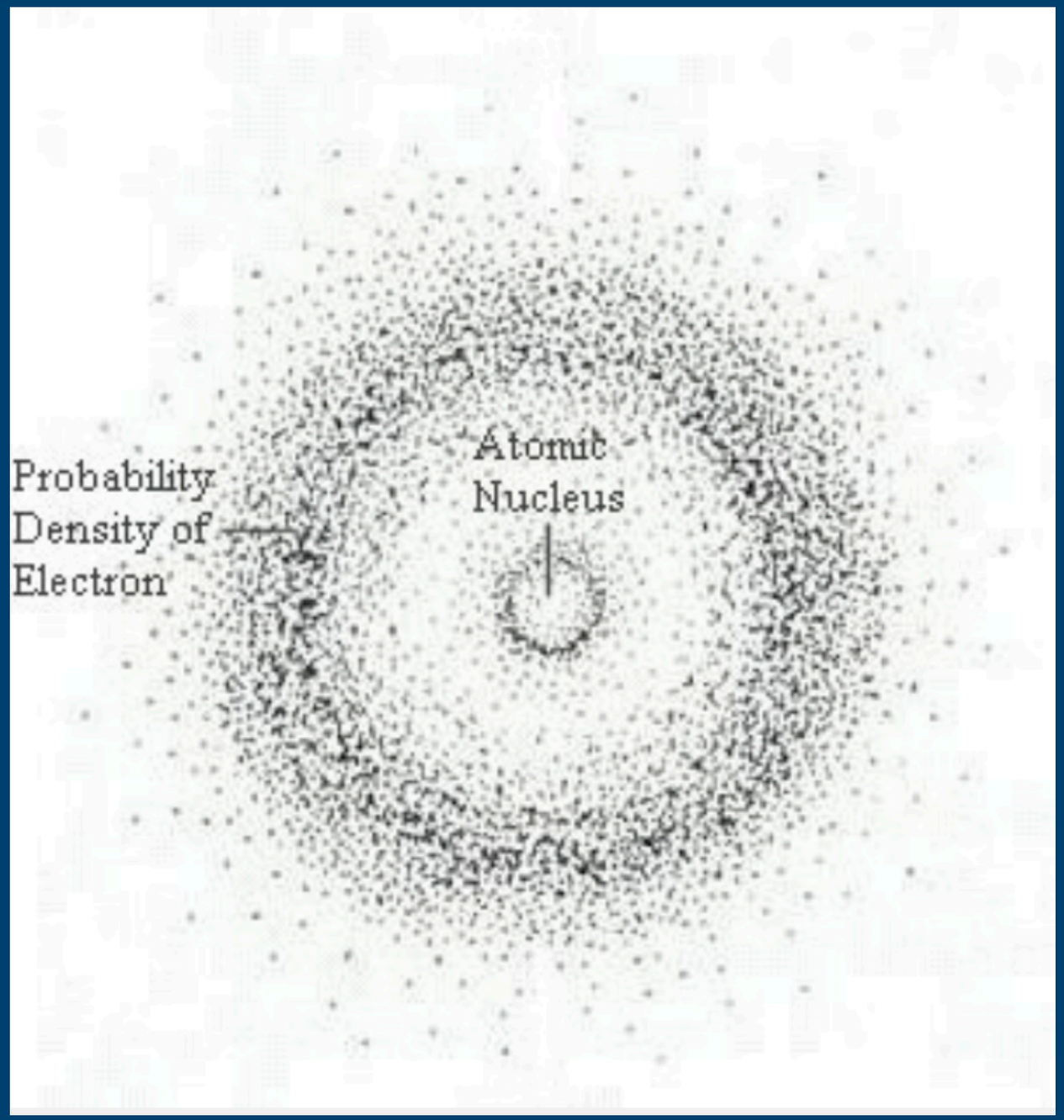
P.A.M. Dirac, *The Principles of Quantum Mechanics* (4ed 1958), p. 9:

"Some time before the discovery of quantum mechanics people realized that the connexion between light waves and photons must be of a statistical character. What they did not clearly realize, however, was that the wave function gives information about the probability of one photon being in a particular place and not the probable number of photons in that place. The importance of the distinction can be made clear in the following way. Suppose we have a beam of light consisting of a large number of photons split up into two components of equal intensity. On the assumption that the intensity of a beam is connected with the probable number of photons in it, we should have half the total number of photons going into each component. If the two components are now made to interfere, we should require a photon in one component to be able to interfere with one in the other. Sometimes these two photons would have to annihilate one another and other times they would have to produce four photons. This would contradict the conservation of energy."

P.A.M. Dirac, *The Principles of Quantum Mechanics* (4ed 1958), p. 9:

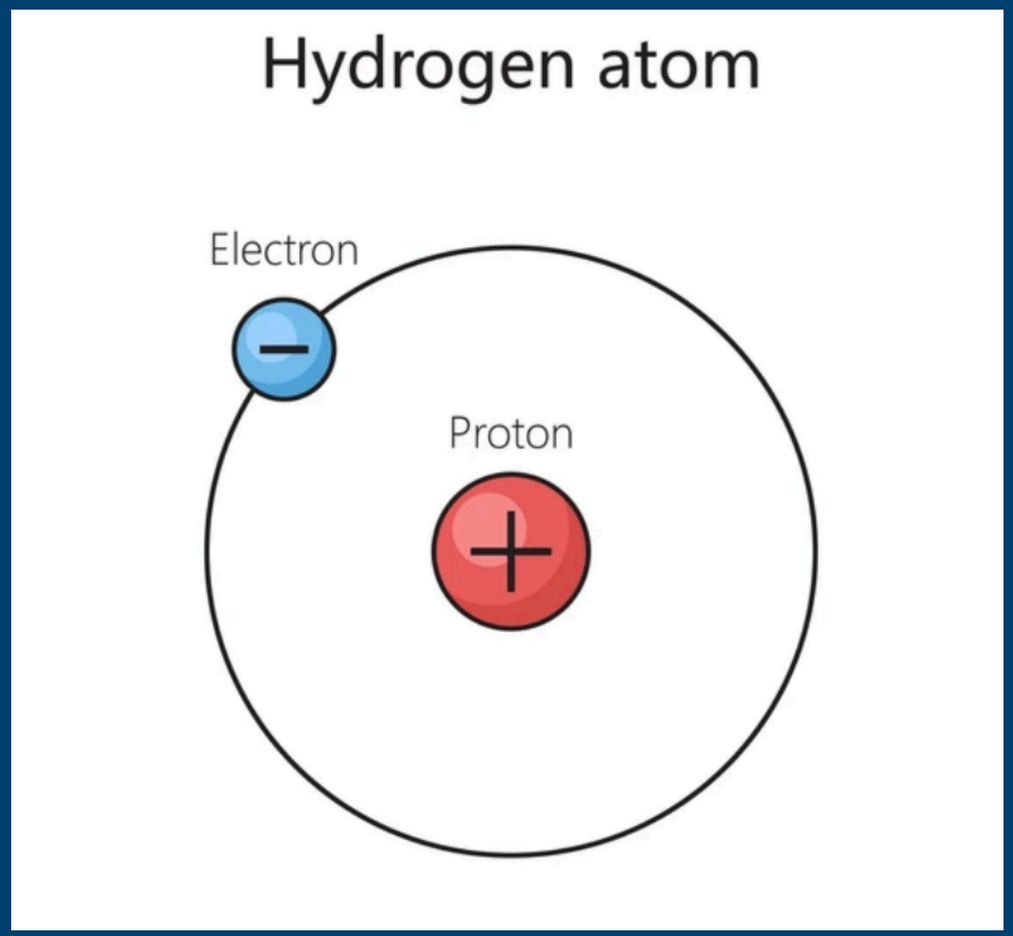
The new theory, which connects the wave function with probabilities for one photon, gets over the difficulty by making each photon go partly into each of the two components. ***Each photon then interferes only with itself.*** Interference between two different photons never occurs."

Quantum mechanics predicts that the electron in its ground (s-) state in the hydrogen atom can be found with a given probability around the nucleus (the proton). If the electron were regarded as a particle, i.e., as localized somewhere above the proton (the nucleus), then the hydrogen atom should possess a dipole moment in its ground state. Both quantum mechanics and experiment show that this is not the case.



MINKOWSKI INSTITUTE

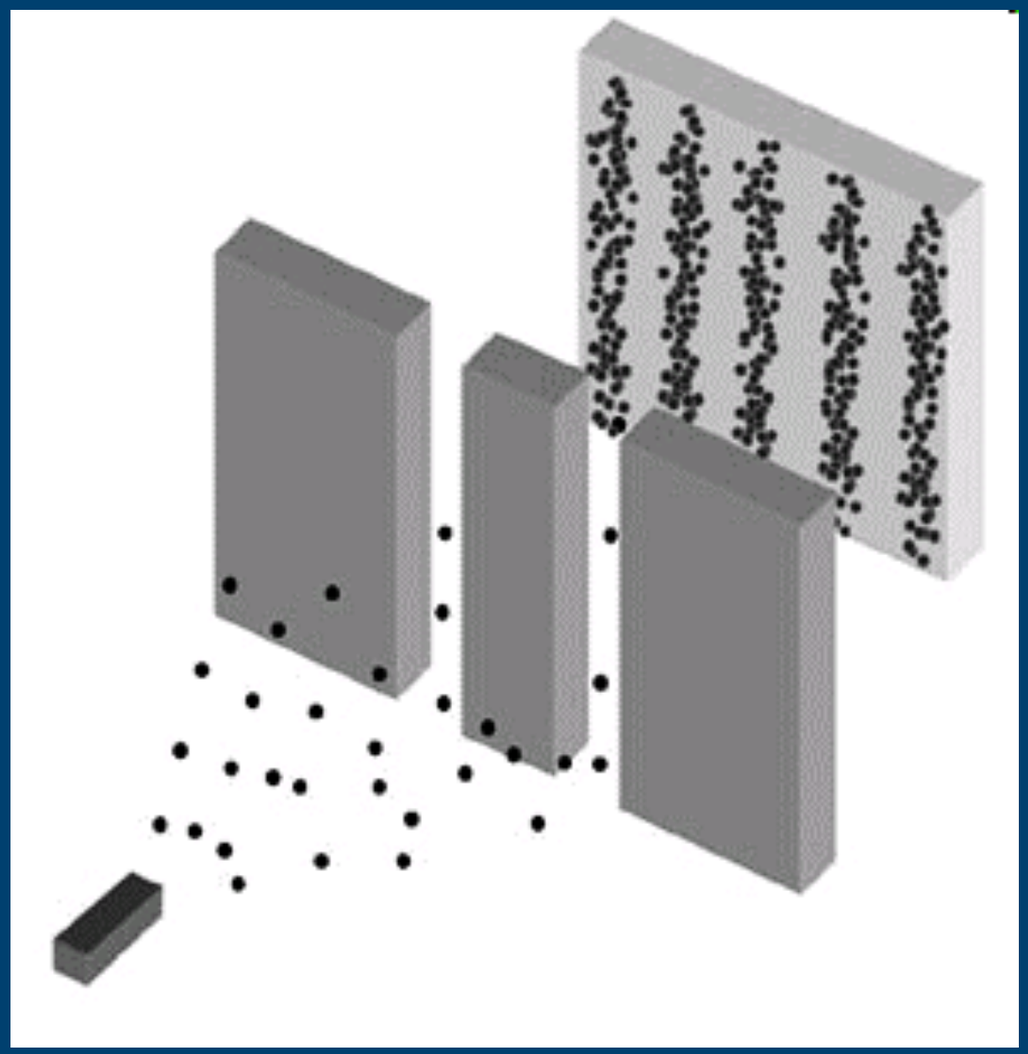
One may picture the electron as so rapidly orbiting the proton that what is experimentally measured is the average value of the dipole moment over the measurement time. And since there is a spherical symmetry in the ground state, all dipole moments cancel out exactly – the average value is zero.

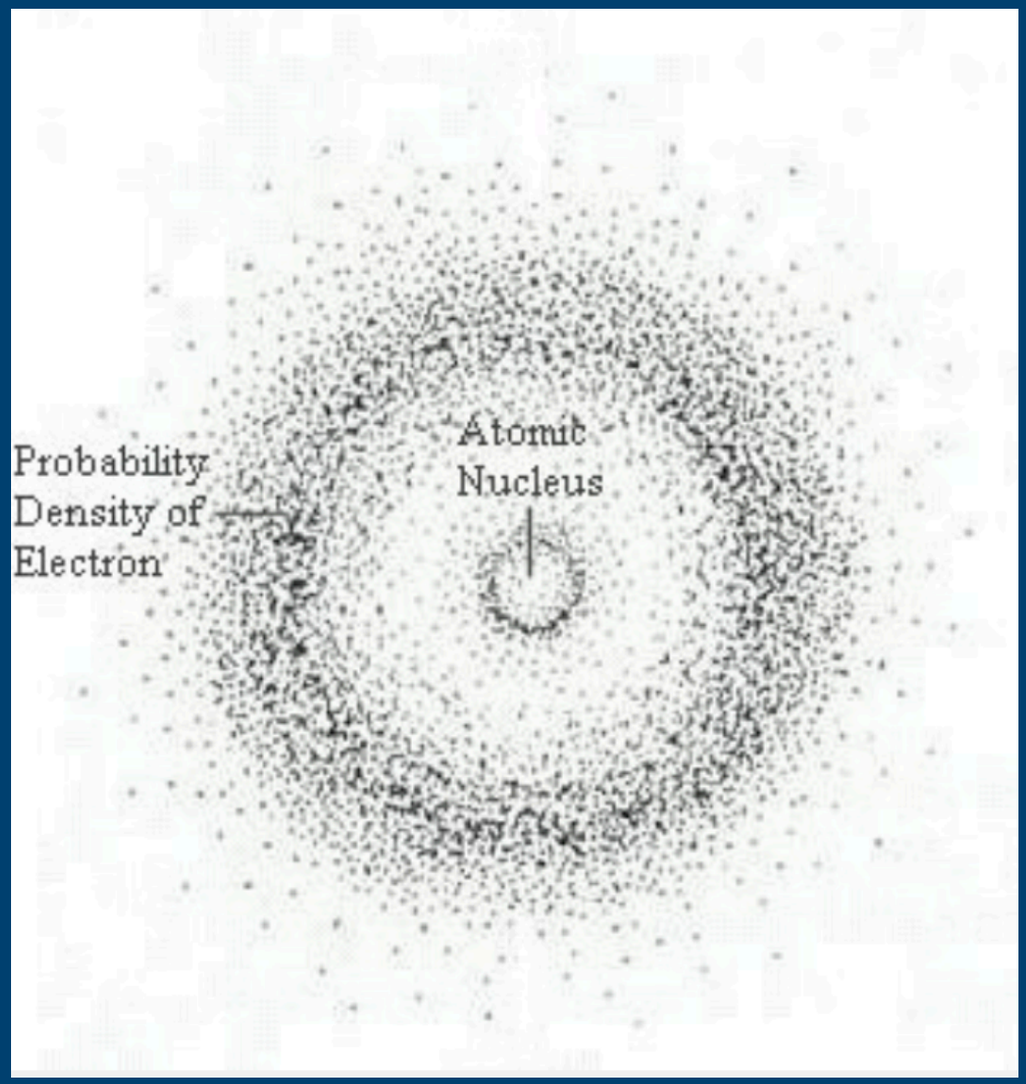


To verify this hypothesis Erwin Madelung calculated the orbital velocity of the electron that would ensure that all dipole moments during the measurement cancel out. It turned out that the electron orbital velocity should be ***several orders of magnitude greater than the velocity of light***.

This shows that the electron charge should be somehow **actually** distributed around the proton. In other words, when not measured, **the electron should exist everywhere where the probability of finding it is different from zero**. Such a requirement resolves the problem about the lack of a dipole moment of the hydrogen atom in s-state.

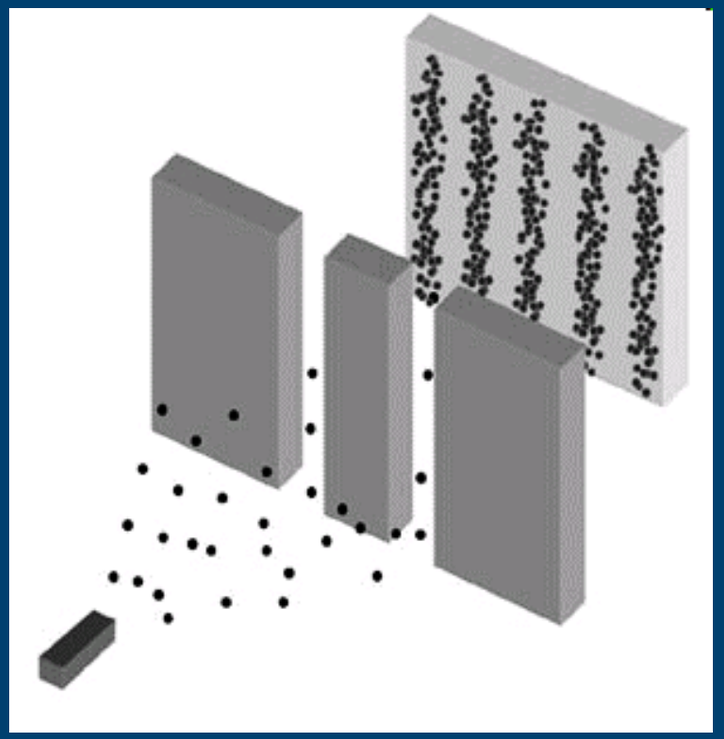
How can electrons and photons be always registered as particle-like (localized) entities but ***each of them pass through both slits*** and, generally, exists everywhere where its wavefunction is non-zero?

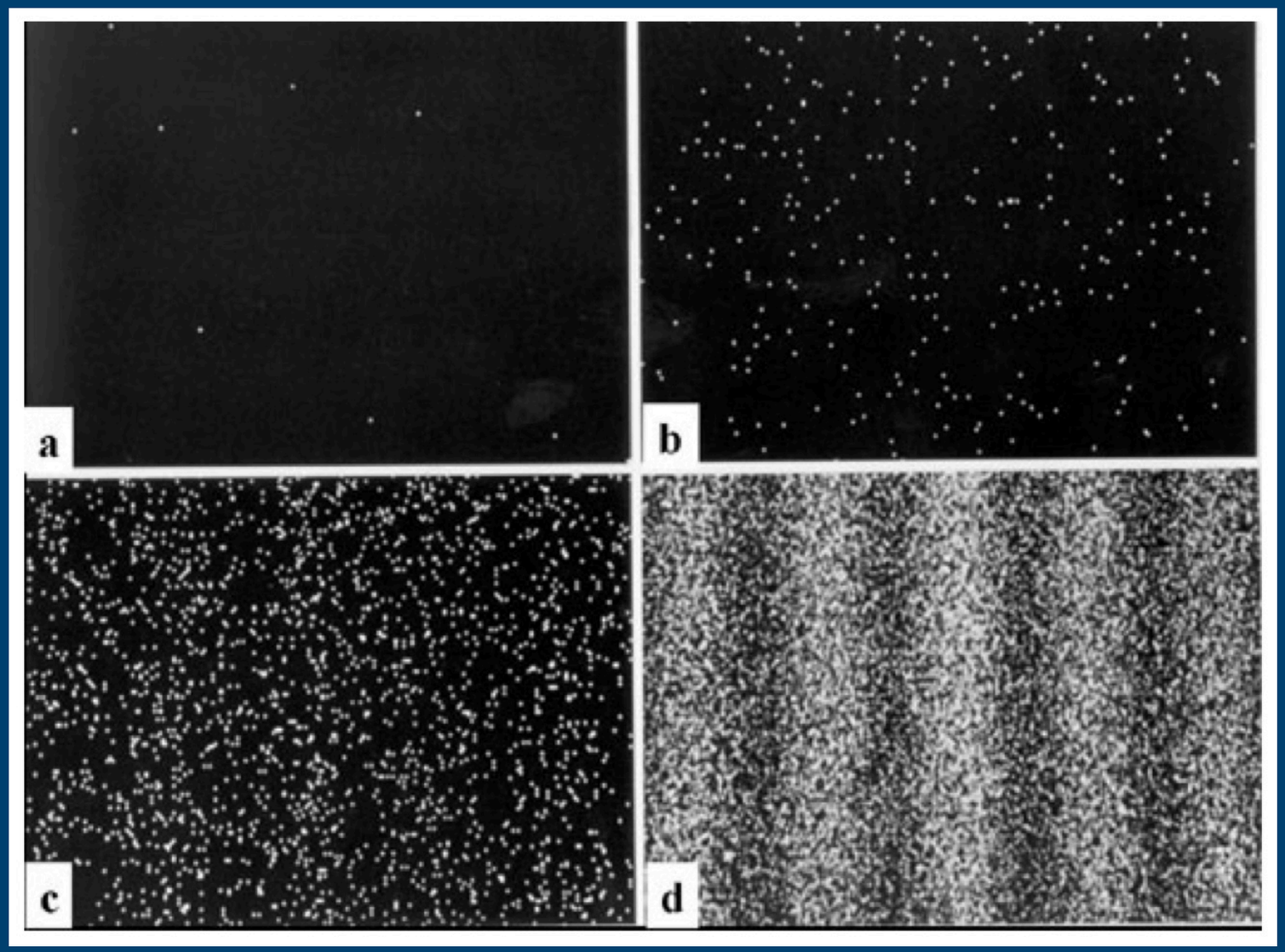




MINKOWSKI INSTITUTE

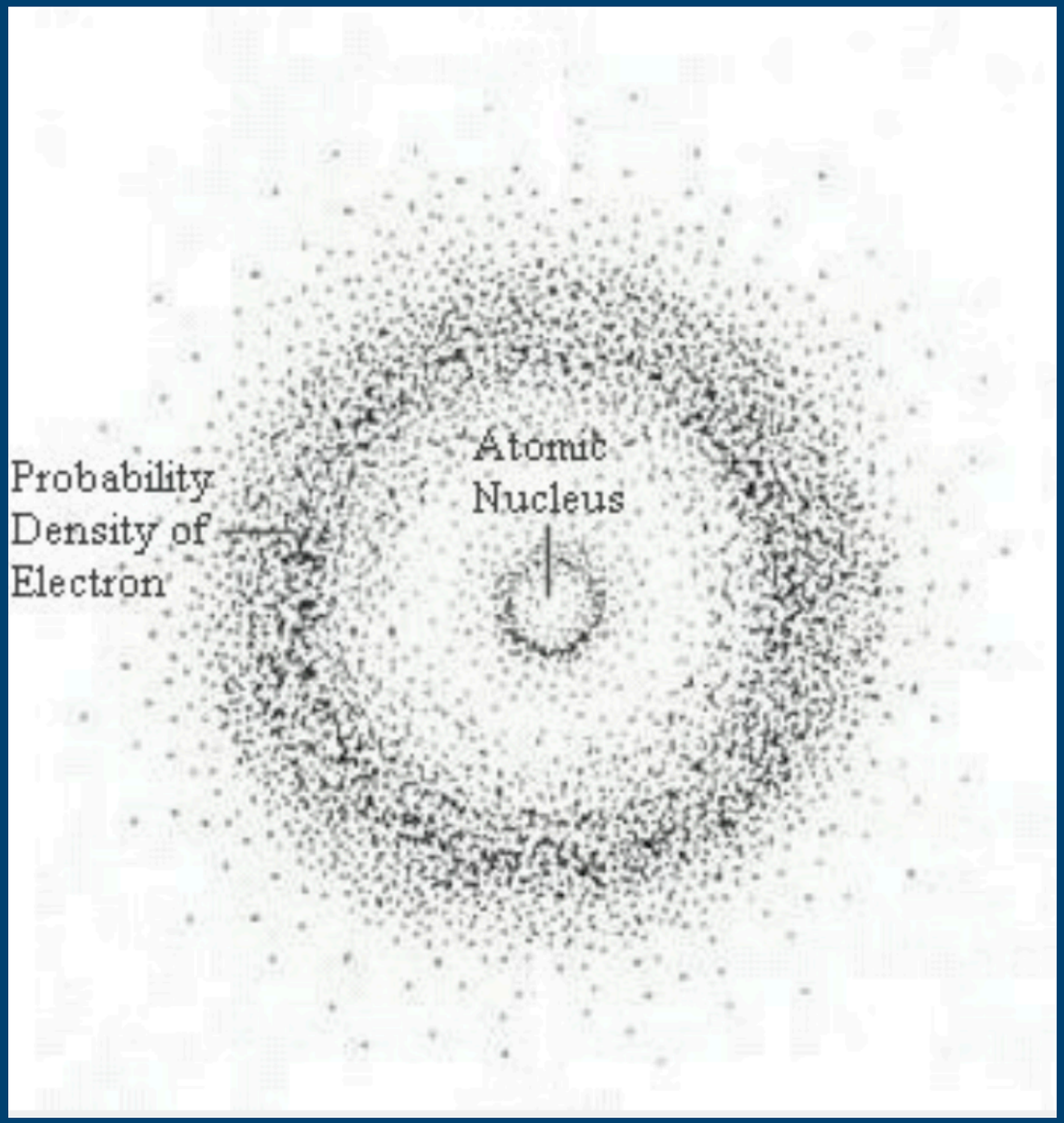
FACT — every single electron goes through both slits; then and only then an interference pattern is formed.





MINKOWSKI INSTITUTE

FACT — in the hydrogen atom (in s-state) the electron **exists everywhere** mostly on a spherical shell around the proton where its wavefunction is non-zero.



MINKOWSKI INSTITUTE

FACT — there is no trajectory of the quantum object.

But such statements are only the first step. The second is to determine what the quantum object itself is.

Secondly and consequently, *there is no trajectory* ~~in the classical sense.~~ If we observe an atom in an interference experiment, we know when and where it was emitted and where and when it was detected, but we cannot say where it was in the meantime.

Classically, we understand the motion of a particle by assuming that, at each moment one can measure the position of a projectile, that the collection of the results consists of a trajectory, and that we can draw a reproducible conclusion independent of the fact that we measure the positions at any moments. We learn these ideas as if they were obvious, but they are wrong. More precisely: in order to penetrate the quantum world, one must get rid of such ideas.

The major open question in quantum mechanics is:
"**What is the quantum object**?"

Again, quantum mechanics does not describe the quantum object itself, but its states. Therefore, we should find a spacetime model of the quantum object.

The lack of such a model hampers our understanding of the quantum world and makes some physicists state that the probabilistic behaviour of quantum objects makes quantum mechanics incompatible with spacetime physics.

However, such statements are obviously incorrect because they are based on the implicit and wrong assumption that the quantum object is a particle.

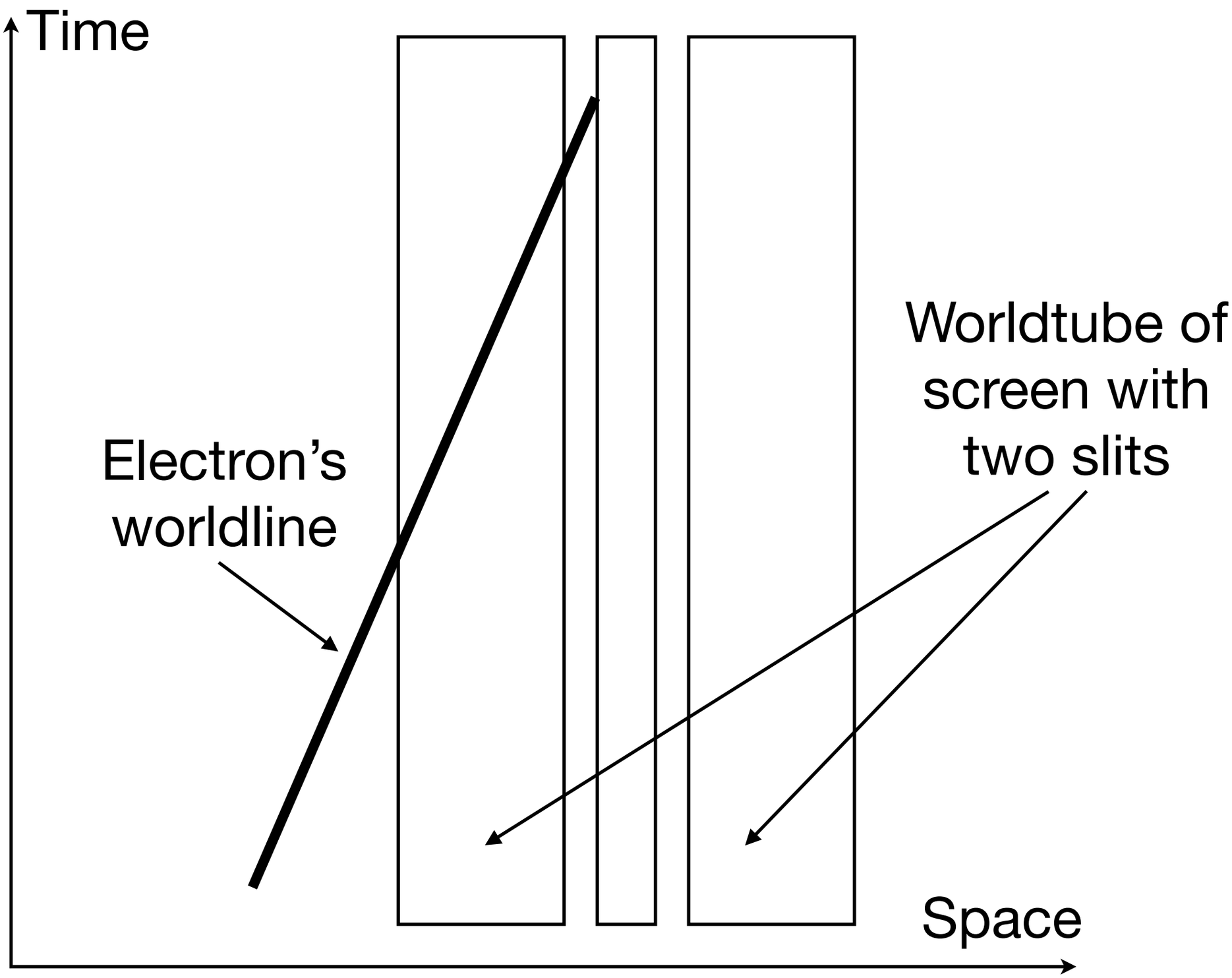
Indeed, **one can talk about probability if and only if the electron is regarded as a particle** — e.g., the statement “there is equal probability for the electron to pass through each slit” implicitly assumes that the electron is a particle.

But we saw that **experiments** demonstrated that probability in quantum mechanics means existence — e.g., equal probability for the electron (implicitly regarded as a particle) to go through both slits means that the entity “electron” does pass through both slits. Therefore, the double-slit experiment demonstrates that the entity “electron” passes through both slits and ***no probability is involved***!

Now the question is: **What an entity the electron is in order to pass through both slits?**

MINKOWSKI INSTITUTE

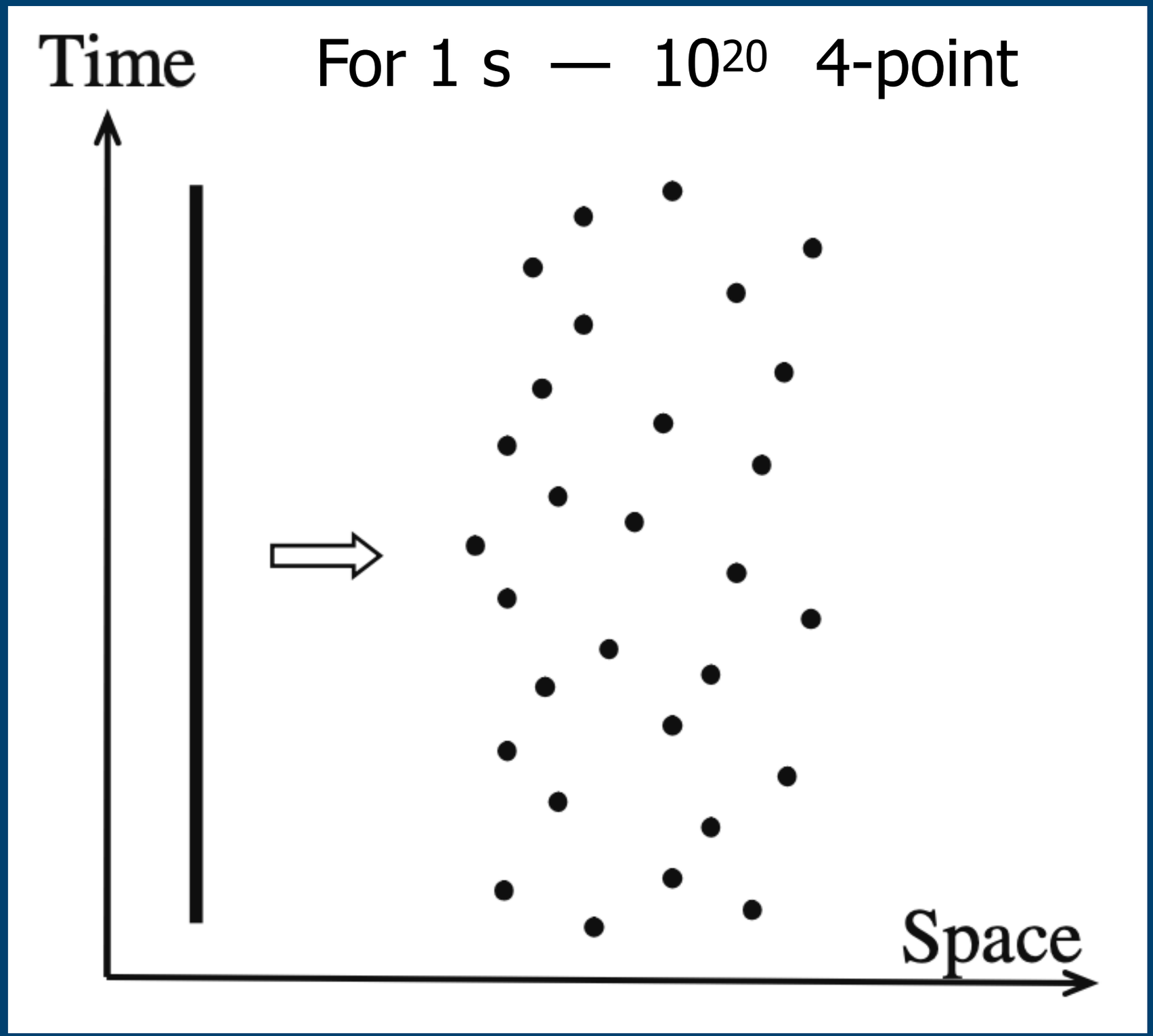
SPACETIME DIAGRAM OF THE DOUBLE-SLIT INTERFERENCE EXPERIMENT



MINKOWSKI INSTITUTE

The apparent contradiction — that a worldline of an electron cannot pass through both slits — is caused by the implicit assumption that electrons (and quantum objects in general) are worldlines in spacetime. But worldlines are not the only thinkable spacetime structures.

If, for the sake of argument, we assume that the quantum object (an electron, for example) is a *different spacetime structure* – atomistic in spacetime (in the spirit of quantum physics) – then the points (the constituents) of the electron's "disintegrated" worldline will be randomly scattered all over the spacetime region where the electron wavefunction is different from zero.



The idea of 4-atomism. An electron is represented, not by its worldline (the solid line), but by the points constituting the worldline

MINKOWSKI INSTITUTE

In the ordinary three-dimensional language this probabilistic spacetime structure, which brings the idea of atomism to its logical completion (discreteness not only in space, but in time as well — four-atomism or atomism in spacetime), manifests itself as appearance and disappearance of the constituents of the electron at the Compton frequency.

The mysterious Compton frequency of the electron given by the expression $f_C = m_e c^2/h \approx 10^{20} s^{-1}$ can be interpreted as the frequency of appearance / disappearance of the electron's constituents.

MINKOWSKI INSTITUTE

It is unfortunate that this novel idea, put forward by the Bulgarian physicist Anastas Anastassov in the early eighties, remained unnoticed despite that it deals with a fundamental continuity at the heart of quantum mechanics — the almost explicit assumption that quantum objects exist continuously in time.

A. H. Anastassov, *The Theory of Relativity and the Quantum of Action (4-Atomism)*, Doctoral Thesis, University of Sofia, 1984; Self-Contained Phase-Space Formulation of Quantum Mechanics as Statistics of Virtual Particles, *Annuaire de l'Universite de Sofia "St. Kliment Ohridski," Faculte de Physique* **81** (1993), pp. 135–163.

https://vesselinpetkov.com/4-atomism.pdf

MINKOWSKI INSTITUTE

ГОДИШНИК НА СОФИЙСКИЯ УНИВЕРСИТЕТ "СВ. КЛИМЕНТ ОХРИДСКИ"

ФИЗИЧЕСКИ ФАКУЛТЕТ

Том 81, 1993

ANNUAIRE DE L'UNIVERSITE DE SOFIA "ST. KLIMENT OHRIDSKI"

FACULTE DE PHYSIQUE

Tome 81, 1993

SELF-CONTAINED PHASE-SPACE FORMULATION OF QUANTUM MECHANICS AS STATISTICS OF VIRTUAL PARTICLES

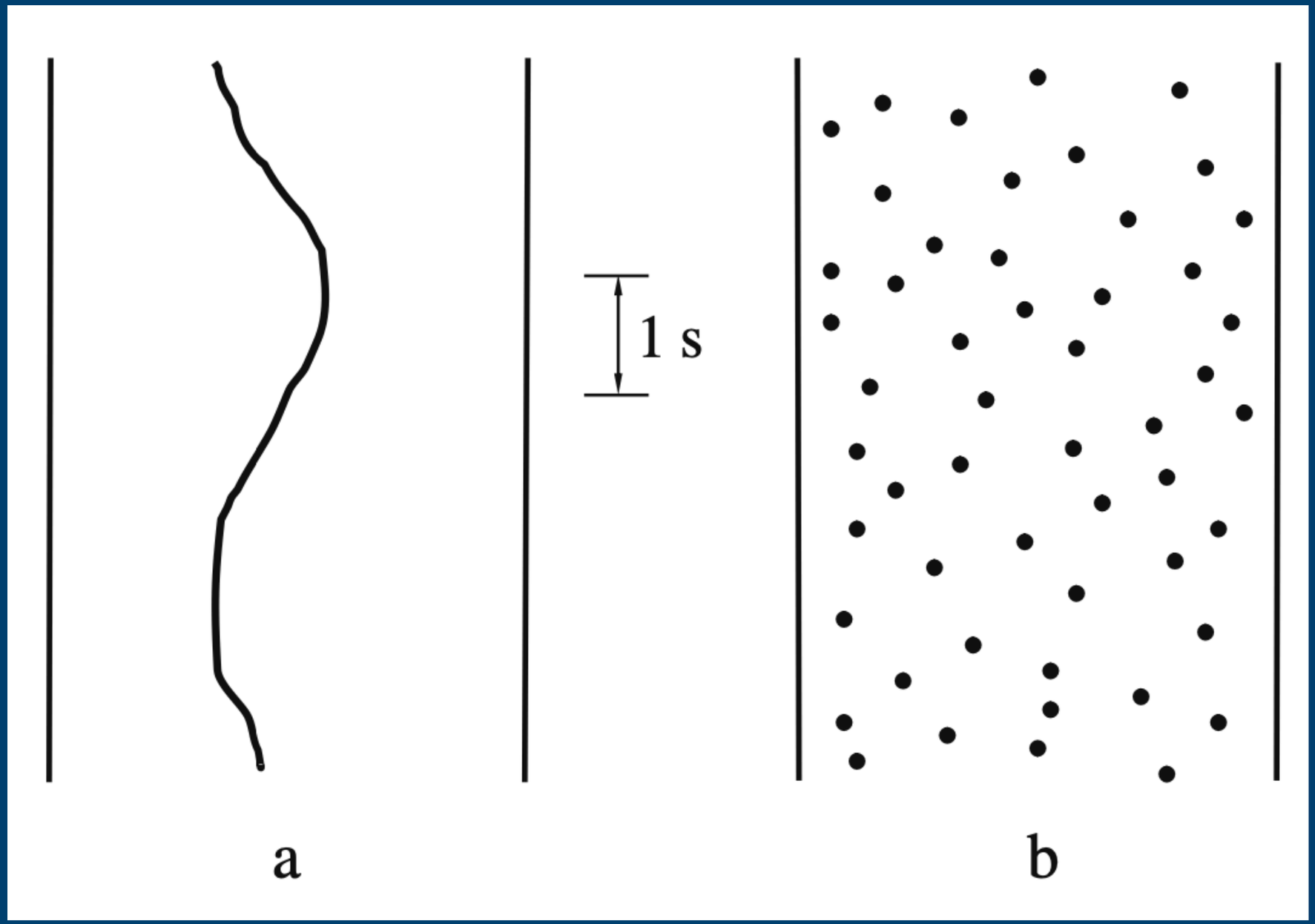
ANASTÅS H. ANASTASSOV

Departament of General Physics

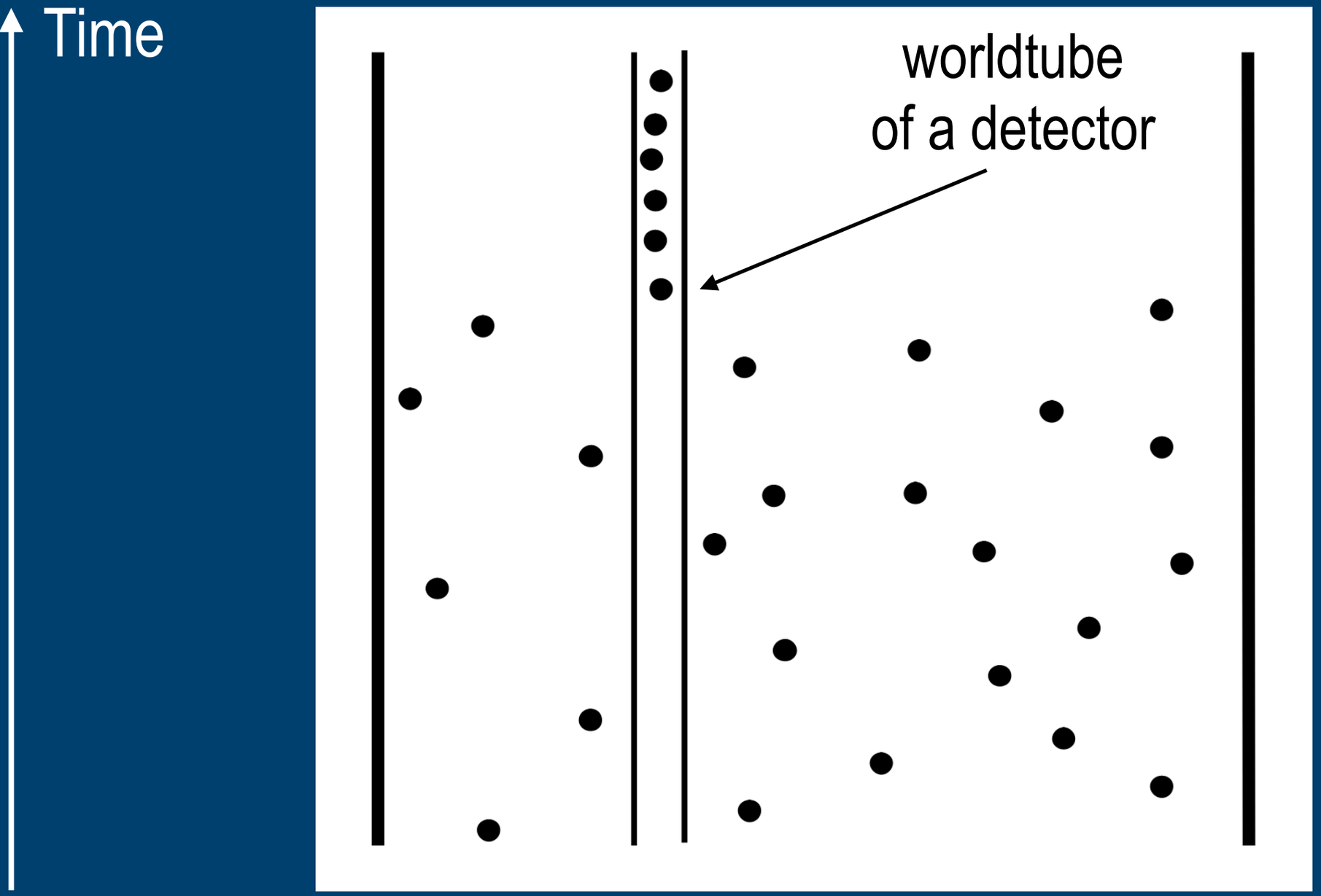
https://vesselinpetkov.com/4-atomism.pdf

MINKOWSKI INSTITUTE

Time



(a) A point-like (classical) electron that exists continuously in time is trapped in a room which is represented by the worldlines of two of its walls. During a given period of time (say, 1 s) such an electron, when not measured, cannot be everywhere in the room, where the probability of finding it is different from zero. (b) During the same period of time an electron which exists discontinuously in time occupies the whole volume of the room.



Before being detected, a single electron in a room occupies the whole volume at its disposal. When the first quanton (constituent) appears in the detector, it is trapped there and all subsequent quantons also start to appear and disappear in the detector. This is not an *ad hoc* hypothesis — real particle detectors work in this way (jump in the boundary conditions).

This spacetime model of the electron — four-atomism — (no matter whether or not it will be confirmed) can explain perfectly the probabilistic features of the electron in spacetime: the behaviour of an electron can be described only in terms of probability, but on the other hand the whole history of the electron in time (the probabilistic distribution of all of its “constituents,” representing the electron at all moments of its history) is forever given in spacetime as a “frozen” (forever-given) probabilistic distribution.

Had Minkowski lived longer he might have been thrilled to describe such a probabilistic spacetime structure by the mystical expression “predetermined probabilistic phenomena.”

H. Minkowski, “Space and Time,” new translation in: H. Minkowski, *Spacetime: Minkowski's Papers on Spacetime Physics*, edited by V. Petkov (Minkowski Institute Press, Montreal 2020)

From the beginning we can determine the ratio of the units of length and time in such a way that the natural limit of velocity becomes $c = 1$. If we introduce $\sqrt{-1}t = s$ instead of t, then the quadratic differential expression

$$d\tau^2 = -dx^2 - dy^2 - dz^2 - ds^2$$

becomes completely symmetric in x, y, z, s and this symmetry is carried over to any law that does not contradict the world postulate. Thus the essence of this postulate can be expressed mathematically very concisely in the mystical formula:

$$3 \cdot 10^5 \ km = \sqrt{-1} \ seconds.$$