Episode 03 - PARTICULARLY WAVY

"Italic": Excerpt pseudoscience speech

[in brackets]: sound effect

OPENING: PSEUDOSCIENCE OF VIBRATIONS ***********************************

[intro - bass]

Leo - When we started researching quantum pseudoscience content, we found a wide range of very confusing ideas, but there were two themes that stood out as the most recurring. The champion of quotations, the theme that appears most often, is the idea that [echo effect] “our thinking builds our reality”. And of course, according to the great disseminators of this idea, you could trust it because it was all based on science. More specifically, quantum theory would be behind this type of idea, providing scientific support.

Gláucia - There is a 2006 film on this topic that was very successful, it is called ‘ The Secret’. Maybe you've already heard of it. This film also became a best-seller book that has been translated into more than 40 languages. Listen to an excerpt from the film here:

[radio static]

> *“Quantum physics really starts to point to this discovery, it says that you cannot have a universe without being mentally in it. That the mind is really forging what is being perceived.”*

[radio static]

Leo - Saying it clearly: this is false, quantum theory does not say that. We will further develop this idea of mind and conscience influencing reality a few episodes later. In fact, what we want to focus on now is the one that came in second place on our podium of the most popular arguments in quantum pseudoscience. The silver medal went to this somewhat vague, somewhat broad idea that [echo effect] "everything has a vibration."

[radio static]

> *"The result was a scientifically validated doctoral thesis that each and every object has energy. The vibratory energy which is known on the scale of consciousness."*

[radio static]

Gláucia - Have you ever met a person, and then… you immediately had a bad feeling? Sometimes we even say that the person has negative energy, a strange vibration. Or the opposite, there is that person who, when they arrive, the environment immediately becomes lighter, it seems that they emit a good vibration. I've felt this too, and I can't explain exactly how it happens. But, one thing is certain. As far as we know, this has absolutely nothing to do with quantum theory.

Leo - In the last episode, we mentioned that objects can emit electromagnetic waves at different frequencies. The frequency is precisely how fast this wave is vibrating. In particular, the human body also emits electromagnetic waves, at infrared frequency. So, in a certain sense, you could say that we really emit a vibration.

Lu - Okay, but that's not the good or bad vibe that we feel from some people, that Gláucia was talking about, right?

Leo - No, it's not. In this more esoteric context, vibration refers more to something like the person's state of mind. In this sense, what we think and what we feel would influence this supposed vibration that we emit.

[radio static]

> *"Hard emotions, like sadness, guilt, humiliation, vibrate on low scales, while feelings of love, happiness, enlightenment, they are vibrating on high scales."*

[radio static]

Gláucia - That's the pseudoscientific point of view. According to it, this vibration would determine, or help to determine, everything that happens to us: our personal achievements, our professional success and even our health. In this context, we could compare the situation in which we are sick or going through a difficult time at work with a radio that is poorly tuned, which keeps wheezing and making that static noise because it is not on the correct frequency.
[poorly tuned radio]

Leo - And, well, there is no evidence that this kind of thing is true, but our main focus here is not to discuss the personal position of those who believe in it. The problem begins when these popular concepts of energy and vibration are mixed with physical concepts and these esoteric ideas start to be disseminated as if they were scientific. And, more specifically, as if they were justified by quantum theory.

[radio static]

> *"There are some techniques that are more, as we say, that is quantum technology. I think it's interesting to talk about the one I've been practicing the most these days, which is quantum floral frequency therapy."*

[radio static]

Lu - This reminds me of the quantum health congress that appeared here in episode 1, in which Marcelo Schappo, who is a physicist and scientific disseminator, told us that he participated in such an event, that there was nothing about science... In fact, in that context that was supposed to be about "health", he heard a lot about vibrating positively. Listen to him here:

> **Marcelo Schappo:** And so folks, that is what permeated the science lectures from start to end. And everything follows the logic of what I'm telling you, that we have to change our mental state, that we have to vibrate positively.

Lu - In other words, talking about vibrations is one of the great crutches to support pseudoscientific ideas. So you can have the vibration of success, the vibration of failure... in the case of this conference that Schappo participated in, one of the great secrets, in quotes, of quantum health, is the so-called "vibration of health".

> **Marcelo Schappo:** So basically that was the congress. And very focused on vibration, the vibration of health, seeking this vibration of health and selling products related to this vibration.

Leo - Indirectly, perhaps this idea is also appealing because it is an individualization of the problem, as if you could ignore all other physical, biological and social factors and improve your health just by changing your individual vibration. It's a simplification, and we generally like to hear that our problems have a simple solution. As a researcher, I can say that quantum theory does not support this idea that there is a health vibration. But then where does this connection between vibration, in whatever sense, and quantum theory come from? [bass] How did quantum theory become famous in certain circles for being the theory of vibrations and frequencies? I am Leonardo Guerini, Professor in the mathematics department at the Federal University of Santa Maria and researcher on the foundations of quantum theory.

Lu - I am Luciane Treulieb, journalist and scientific disseminator at UFSM.

Gláucia - I am Gláucia Murta, a quantum information and cryptography researcher at the University of Dusseldorf, in Germany.
This is the podcast O Q Quântico. In today's first block we talk about the differences between billiard balls and guitar strings. In block two, we tell you a brief history of light. And in the third block, we discuss how these things become even more interesting when quantum comes into play. Come with us as we start Episode 3: Particularly wavy.

[cat]

BLOCK 1: PARTICLES AND WAVES *** ********

Gláucia - At the opening, we heard some pseudoscientific speeches that had words like frequency and vibration. So the first important point that we need to make clear is that, in physics, these things, like frequency, vibration, are concepts related to waves. But another concept that appears side by side, or rather, in opposition to the concept of wave, is the concept of particle. And this is where we begin today's discussion: with one of the great dichotomies of classical physics, which had a tendency to separate everything into waves or particles.

[pause button]
Lu - [radio effect] Just a quick warning: this is our third episode, and we're going to mention ideas that have already appeared in previous episodes. So if you haven't listened to them yet, pause here, listen to these episodes and then come back.
[play button]

> **Pablo Saldanha:** So a wave is something that will propagate through space in time. There are several types of waves. For example, sound is a type of wave. When I speak, the vocal cords vibrate and push air molecules, right? This gives a pressure wave.

Gláucia - This is Pablo Saldanha, physics Professor at the Federal University of Minas Gerais. This voice must be familiar to you because Pablo already appeared in the first two episodes.

> **Pablo Saldanha:** So, I say, for example, my vocal cord is vibrating hundreds of times per second, it's very fast, right? And this disturbance is transmitted to the air, so each molecule pushes the neighboring molecule and this propagates through space, okay? [...] When it reaches my ear, this variation in pressure makes my eardrum vibrate, in short, then my brain can interpret that as a sound.

Gláucia - And he further adds:

> **Pablo Saldanha:** The wave in the water too, if I throw a stone, that stone disturbs the surface of the water, I see those ripples propagating. So wave phenomena are like this, these are things that propagate through space, through time.

Lu - So there's no mystery, right? Waves are exactly what we're used to thinking about, right? Ripples on the lake, sound waves…

Gláucia - Or when you play the guitar: the string itself forms a wave when it vibrates... And these are the most common examples that we see in everyday life. These are mechanical waves, which depend on a medium to propagate. But not all waves are like this.

> **Pablo Saldanha:** That's it, for example, the wave on the water needs water. If you remove the water, there is no wave. The sound wave needs air, if you don't have air the wave won't propagate. [...] But the electromagnetic wave, it propagates even without a medium.

Gláucia -We already talked about electromagnetic waves in the last episode, when we discussed the iron bar that heated up and started to emit light, remember? We also commented that we encounter several examples of electromagnetic waves in our daily lives.

> **Pablo Saldanha:** Light is a type of electromagnetic wave. Radio waves, television, cell phones, they are electromagnetic waves, okay? But then you change the oscillation frequency. The light oscillates very quickly, there are many oscillations, I can't even count them, right? There are barely any detectors that detect this. [...] Whereas a cell phone wave will oscillate very quickly [...] but slower, so that the device can read the information contained in that wave.

Leo - So there are two main types of waves: mechanical waves, which are the wave in the lake, the sound wave and the wave from the guitar string, and the electromagnetic waves, which are light, radio waves, x-rays. Mechanical waves need a physical medium to propagate. Electromagnetic waves, no.

Lu - In this last excerpt, Pablo also spoke about frequency, oscillation frequency, which is the same word that we hear in pseudoscience sentences. Can you explain what this is?

Gláucia - Well, frequency is one of the properties that defines a wave. Imagine that you threw a stone into a still lake. This causes a ripple in the lake. If we look at a specific point, the water stays there, oscillating up and down. Can you visualize it?

Lu - Aham.

Gláucia - So the frequency of the wave is nothing more than the number of oscillations per second: the higher the frequency, the more frenetic the wave, the faster it oscillates and propagates; If the frequency is lower, the wave is calmer, oscillates less and propagates more slowly.

Leo - But not everything is waves. We have already mentioned that there is another class of physical objects, which are particles.

> **Pablo Saldanha:** So for example, I pick up a marble, right? It is a material body, it is extensive. [...] I say, this is a particle.

Leo - In other words, a marble does not behave like a wave, it does not propagate through space. It is a concrete object, which occupies a well-defined position, and that is why we say that it behaves like a particle. In fact, the position and trajectory of an object are two central requirements for us to classify that object as a wave or particle.

> **Pablo Saldanha:** So, a particle, I can always in principle define a trajectory for it. [...] I can even draw what trajectory it had and record that, while a wave is dispersing, it doesn't have a single trajectory, right? Each piece of the wave can go on a different trajectory when the other is propagating.

Gláucia - In other words, the trajectory of a particle is clear, but it doesn't make much sense to talk about the trajectory of a wave. Rafael Chaves, physics Professor at the Federal University of Rio Grande do Norte, who has also appeared here on the podcast, agrees:

> **Rafael Chaves:** And the wave, unlike the particle, is delocalized in space, right? So for example, think of a wave on a string. I ask you, where is the wave? Well, it is in the entire string, it is everywhere, right?

Gláucia - It is in the entire string. Another example, the sound wave that I'm producing now as I speak, it starts from my vocal chords and quickly occupies the entire room. It doesn't go to a specific point, it goes everywhere. The marble always has a specific position, it is not spread out.

Leo - The point is that it is important to understand whether things exhibit wave behavior or corpuscular behavior (corpuscle here is just another word for particle). And to decide between one thing and another, we can look for a specific phenomenon: interference. [blunt]

> **Rafael Chaves:** And in practice, what really differentiates, or the characteristic that I would say is fundamental, is what we call interference. Waves interfere with each other. So if I play one wave against another [...] at some points the amplitude of these waves will decrease. That's what I call destructive interference. And at some points these waves, they will increase.

Leo - So it's as if we can add and subtract waves. In this sense, constructive interference occurs in the parts where one wave reinforces the other, and their intensity increases. This is what happens when we stop at the same distance from two speakers playing the same song, one reinforces the other and our sensation is that the sound becomes louder. While destructive interference occurs when one wave cancels out the other.

Lu - Does one wave simply cancel out the other? What do you mean they disappear?

Leo - Yes. An example of destructive interference and waves canceling each other out occurs in noise canceling headphones. Noise cancellation is exactly that, the phone generates sound waves that cancel out noise external to the phone.

Lu - And interference only happens with waves, right? It won't happen with particles.

Gláucia - Yeah, just with waves. Just as it doesn't make much sense to talk about wave trajectories, in principle it doesn't make sense to talk about particle interference. Look what Rafael tells us:

> **Rafael Chaves:** Corpuscular phenomena do not lead to this interference phenomenon. For example, when I throw two pool balls at each other, I don't create a bigger pool ball. Or the pool balls don't disappear, they continue to maintain their individual characteristics and their specific location in space.

Gláucia - In other words, when two pool balls collide, they do not reinforce or cancel each other out, as waves would do. They act like particles. There is no interference in this case. This is why it is useful to study whether or not a phenomenon exhibits some type of interference. If it does, we already know: it is because this phenomenon is wave-like.

> **Rafael Chaves:** So what characterizes quite precisely whether a phenomenon is wave or corpuscular is the possibility of that phenomenon, of that physical system, giving rise to an interference pattern or not, that is, which would be those regions where the waves add or subtract .

Leo - The reason we are talking so much about wave or corpuscular behavior is because these are two distinct concepts but very well studied in classical physics.

Lu - Can you help me quickly remember what classical physics really is?

Leo - Classical physics is that part of physics that was established before the emergence of quantum and relativity, basically before the twentieth century. So what people at that time firmly believed was that this division between waves and particles organized the world in a categorical way, that is, without any gray area. It was one thing or another.

Gláucia - And if we think about examples from our daily lives, we see that there were good reasons for this division to exist. It is difficult to confuse a marble with a wave, just as it is difficult to confuse a wave on a lake with a particle. They are obviously different things. But there are other physical entities that are not so easy to decipher... especially if we study objects on smaller and smaller scales. And here comes the main character of this whole controversy: the light [glowing sound effect].

[congas]
Leo - We have already presented light as an electromagnetic wave, but in the last episode we also mentioned the photon, which is the fundamental particle of light. So we want to end this block with the following question: after all, is light a wave or a particle?

[cat]

BLOCK 2: BRIEF HISTORY OF LIGHT **

Leo - The nature of light is an old topic of discussion that has given rise to much debate. We already gave some spoilers on this subject in the last episode, when we talked about Einstein's contributions at the beginning of quantum physics, but now we're going to talk a little about how people thought about the light before that. Get ready, we will now bring you a brief history of light.

[classic track]
Gláucia - The first great character in this story is Isaac Newton, English mathematician and physicist who was born in 1643. If Einstein is today the most popular physicist of all, Newton is probably the second great name that comes to mind when you think about physics. That is just talking about fame, ok? We don't want to compare each one's contributions here.

Leo - Yes. But we need to start talking about Newton, because before him, there was no consensus on what the nature of light was. There were several different schools of thought, and each one said something. Then, there was a group that argued that light was formed by particles that emanated from bodies. Another said that light was a kind of modification of the medium between the object and the eye; There was also a third school that thought of light as something that was emitted by our eyes and reached the objects that we see.

Lu - And which one was correct?

Leo - That was the question. And here we need to go back to our episode 1: in science, it's not enough to propose an idea, you need to support it with evidence. The point is that none of these groups offered evidence for their idea of light. In fact, it was even worse, they didn't even have very convincing theoretical arguments for it.

Lu - So what you're saying is that at that moment, these ideas were just different ways of thinking, right? When a person studied these things, they could kind of choose what they believed in, it was practically a matter of taste, of interpretation…?

Leo - That's right, and since none of these groups had evidence to falsify or corroborate these descriptions, they were all equally good, or equally bad. And none of them were very reliable.

Gláucia - So Newton was the first person to create a theory of light that had widespread support among the scientific community of his time. The period we are talking about now is around the year 1700. At that time, an idea that was widespread among physicists and scientists in general was that the universe was made up of tiny particles and that all natural phenomena could be explained through these particles. Based on this, Newton wrote his book entitled "Optics", and in it he presented arguments to defend that light was formed by…[drum roll] particles of matter.

Leo - But again, what was missing was evidence showing this. With this in mind, one of the things Newton's supporters tried to do was to show that when particles of light collided with an object, they exerted a small pressure on it. But they couldn't prove this at all... so although this theory made sense and had the support of the greatest scientific authority of the time, Newton himself, this was still not proven. And without proof, you leave the door open for other theories to be explored.

Gláucia - This idea that light was made of particles was called [echo effect] corpuscular theory of light. As at that time things were divided into particles or waves, those who didn't buy this idea of particles were the people who bet that...light was a wave. The main proponent of this idea was the Dutch physicist and mathematician Christiaan Huygens. There were other people who agreed with him, but they were a minority. The important thing was that the discussion was limited to quarreling, because, as Rafael Chaves says, there was also no great evidence to support a wave theory of light.

> **Rafael Chaves:** The experiments that existed were not capable of detecting any differences between these two theories, the corpuscular and the wave.

[classic track]
Leo - The situation only changed much later, in 1801, when the English scientist Thomas Young carried out a decisive experiment that apparently resolved the issue.

> **Marcelo Terra Cunha:** And this is related, for example, to the double slit.

Leo - Marcelo Terra Cunha, mathematics professor at Unicamp and researcher of the foundations of quantum theory that you heard just now has already explained: the experiment that Young carried out is called the [echo effect] double slit experiment, and is one of the most famous experiments not only among those who study the phenomena of light, but in physics in general.

> **Marcelo Terra Cunha:** The double slit is a fantastic story, right? It starts with Thomas Young, who was trying to understand light, trying to understand how light propagates, and realized that there was this interesting phenomenon of interference, right?

Gláucia - And look at the interference appearing there! Earlier we said that waves interfere with each other, reinforcing or canceling each other out, and that this is a crucial characteristic for differentiating waves from particles. And it was exactly this property of light, the interference, that made Thomas Young's name famous.

Lu - Interference was the thing about adding and subtracting waves, right? So what you're saying is that you can add and subtract... light?

Leo - Yes, in a way this is what the double slit experiment shows.

[pause]
Lu - [radio] Just a warning: from this point on, we will tell you in detail what the double slit experiment is like. But this is a somewhat difficult task, because it has a very visual component. So here's a tip that it might be a little difficult to put together the images in your head, but you can always look for figures of the experiment on our website or on the internet.

[play]

Leo - To give an idea of what the experiment is like, imagine that you make a crack, or a slit, in a piece of aluminum foil and shine a beam of light through that slit. In fact, it can't be just any light, we need it to be a laser, which is that well-organized form of light that Ingrid Barcelos explained to us in the last episode. When we make the laser pass through the crack and reach the wall behind it, what do you imagine we see on that wall, Lu?

Lu - I don't know exactly, I think it would form a light figure on the wall.

Leo - And what shape would this figure of light have?

Lu - The same shape as the slit you made on the paper. Or not?

Leo - Perfect, that's right: we opened a slit in the paper, as if it were a crack, and the part of the laser beam that passes through the paper takes on the same shape as that crack. But for now we only opened one slit, and the name of the experiment is "double slit", right. So what we do next is open a second slit in the foil, or a second crack, very close to the first, and throw a laser beam at them, a beam wide enough to pass through both slits at the same time. And now, what do you think happens?

Lu - I don't know, the same thing? But there will be two light figures on the wall now.

Leo - Well, that's where things get interesting! Because that's not exactly what appears on the wall.

[bass]
Gláucia - And here we arrive at a key point, which may even be a little difficult to imagine: when we look at the light that passed through the two slits and reached the wall that was behind the paper, instead of seeing two figures of light in the shape exactly from each crack, what we find are… several stripes of light, as if there were several cracks. [blunt]

Lu - What? So does more light come out on one side than comes in on the other?

Gláucia - In truth no. But perhaps we get this feeling because when the light shines on the two slits, it is as if each of them generates an independent beam of light, as if there were a flashlight in each slit. Then what happens is that the light that comes from one slit interferes with the light that comes from the other. This interference is both constructive and destructive, so we see that story of adding and subtracting waves happening.

Lu - But do these interferences happen at the same time?

Gláucia - All at the same time, in some places the light from one slit cancels out the light from the other, and in other places they reinforce each other. The result of constructive interference is that light scatters and illuminates locations on the wall that were not directly behind the cracks. That's why despite having only two slits in the paper, we see more than two stripes of light on the wall, we see several... some with a lower intensity and others with a greater intensity of light.

Leo - We call these stripes the [echo effect] interference pattern, and you can see pictures of this on our website. Now, if on the one hand constructive interference makes the light scatter and generates this interference pattern, the result of destructive interference is also unexpected.

Lu - Destructive interference is when they subtract each other, right? So you mean that one light cancels out the other?

Leo - It seems strange, right? But that's it. Because of the destructive interference that occurs, both beams cancel each other out at some points.

> **Marcelo Terra Cunha:** If you closed one of the slits, that region was light, if both were open, that region was dark. And that is surprising.

Leo - This is surprising because with two slits, we allow more light to go through, so we expect a more illuminated figure, right? Even so, in some regions that should be completely lit, we find dark parts because of this cancellation.

Gláucia - Anyway, these strange behaviors that we see in the experiment allow a very clear conclusion: [echo effect] the light interferes. And if something shows interference, it is because that thing has wave behavior.
[classic track]

> **Marcelo Terra Cunha:** Interference was discovered or has been confirmed in this experiment, which essentially ended a big debate about the nature of

light, right? [...] In a way, the double slit experiment decides in favor of Huygens versus Newton, it decides in favor of waves versus particles.

Gláucia - So now we finally have evidence that light is a…[drum roll] wave.

Lu - This means that that big debate you were talking about before has finally been resolved, right?

Gláucia - Uh… not really.

Lu - Putz... :(

Gláucia - And the problem is not in the answer that Thomas Young found, the double slit experiment does everything right. What is problematic is to put the question in the following way: "either light is corpuscular, or it is a wave", as if one thing excluded the other. A long time after the double slit experiment was first carried out, two elements emerged that radically changed physics. The first was quantum theory. And the second was someone called Albert Einstein.

Leo - Although Einstein is famous for his theory of relativity, it was thanks to a contribution to quantum theory that he won his Nobel Prize. As we said in the last episode, when Einstein proposed his theory that light was quantized, he was basically stating that light is made of…[drum roll] particles! Here, Rafael Chaves again.

> **Rafael Chaves:** But then you might wonder, okay, Einstein wasn't the stupid, right? So how come he went against the experiment that conclusively proved that light is a wave? And so that's the story to allow yourself to think outside the box. He said, look, light is a wave, but maybe it also behaves like a particle.

Gláucia - As we saw in episode 2, it was essential to understand that light is made up of fundamental blocks, which are the photons. Only in this way, it was possible to explain the photoelectric effect and a series of other phenomena. And this was corroborated by several other experiments, becoming clear evidence that light, indeed, is made up of particles. And so it also presents corpuscular behavior.

> **Rafael Chaves:** So what was realized is that this categorization between wave and particle is an artificial categorization. So it's true that some physical

systems can behave like a wave, they can behave like a particle, but actually they are neither one thing nor the other. This seems very strange, right?

Lu - Yes, and it is beyond strange... I'm here thinking, how is this possible?

Leo - Exactly. But the question is, why wouldn't this be possible? Maybe it's counterintuitive, but this story about light shows that the universe doesn't care about what people think is strange or not. Note that the strict dichotomy of classical physics of “either a wave or a particle” has lost its meaning and quantum theory has shown that there are physical objects that have characteristics of both one thing and the other.

Lu - A curiosity: you said that physical objects present characteristics of these two things… Why the plural? In addition to light, are there other things that also present this behavior?

Leo - For sure. But before we talk more about that, let's summarize this part of the story. Trying to organize it chronologically we have:

Gláucia - [plim] Until around 1700, there were several different schools of thought, each describing light in its own way.

Leo - [plim] Around that time, 1700, Newton formalized his position defending that light is made up of particles, taking most of the scientific community with him. Huygens disagrees.

Gláucia - [plim] One hundred years later, in 1801, we have a twist, with Thomas Young carrying out the double slit experiment. Because of the interference that is seen, everyone is convinced that light is a wave.

Leo - [plim] But about a hundred years after that, in 1905, we have another twist: Einstein explains the photoelectric effect by saying that light is wavelike, ok, but in addition it is also corpuscular, formed by photons.

[classic track]
Gláucia - And talking about photons is talking about quantization, so here we have already entered the quantum part of the discussion. Our brief history of light ends here, but in block 3 we will continue talking about the double slit experiment...

because when we bring quantum theory into the conversation, things get even weirder.
[cat]

Block 3: QUANTUM REGIME *** **************

Leo - So, we came to the conclusion that light behaves like a wave but is still made up of particles. One really cool thing is that we can see this duality in the double slit experiment itself.

Gláucia - When we described the experiment, we talked about a beam of light passing through the slits. To be more specific, a laser beam. This beam is basically a burst of millions and millions of photons.

Lu - And could you do this experiment by sending just one photon, that is, one particle of light, at a time?

Leo - That's the next big question: what happens in the double slit experiment in the quantum regime, one photon at a time? Before answering, let's play a game to try to understand this experiment better. I want to ask Lu to imagine that she shrank until she was very small, much smaller than an ant. So, Lu, at this size you see that plate, or the aluminum foil, as if it were a large wall and the cracks as if they were two very narrow and long windows in that wall. Behind the cracks you see the wall, okay?

Lu - Ok.

Leo - But imagine that you didn't shrink alone, you brought a bunch of friends who also shrank and with you there are a bunch of tennis balls, also shrunken. What are we going to do? The idea is that you and your friends throw these balls through the cracks. Before, we said that the laser beam was a burst of photons. Now, we're replacing the laser with this burst of balls that you're throwing through the slits. Right?

Lu - Ok, so it's as if my friends and I were emitting a laser, which in this case we're imagining is made up of tennis balls.

Leo - Then you and your friends start throwing the balls towards the paper, towards this giant wall with the two cracks. A bunch of little balls flying in the air at the same time. Some of them hit the wall and come back towards you, but several of them also pass through one slit or another, and hit the wall behind. Can you imagine it?

Lu - For now, yes.

Leo - Okay, so after a while that you are there playing with balls, we can see which figure is formed by the marks that these balls left on the wall. Well, following everything we know about tennis balls, at first we would say that the balls that passed through the left slit left a set of marks behind that slit, and the balls that passed through the right slit left another set of marks behind it, and that's all. But… the double slit experiment shows that, after all, photons are not like tennis balls. As we said in the previous block, the pattern that the photons form on the wall is the interference pattern, with several stripes marked on the wall due to constructive interference.

Lu - So do we have to give up tennis balls?

Gláucia - Wait, that there is still hope. We can make an effort to try to keep the explanation in terms of balls. So far, what we see is that after the tennis balls pass through the cracks, some type of interference occurs, that when we look at the wall, we see several stripes with marks and that there are some places where the balls never hit. Now, what we need to answer is: how could this bunch of balls generate an interference pattern?

Lu - Well, how can there be interference if the slits are parallel and the balls travel straight through them?

Gláucia - Indeed, if the balls followed parallel trajectories, they would never collide. Now, if you and your friends didn't throw the balls exactly straight, but perhaps with some effect or passing through the slits somewhat diagonally, then the ball that came from one slit could end up hitting the ball that came from the other slit. This would cause us to find marks in places that we initially didn't expect to find.

Lu - But then is that it? Would this explain the marks we see?

Leo - That could be a good explanation! The balls colliding in the air explain both constructive interference, light spreading to places that are not immediately behind the cracks, and destructive interference, because the balls collide and end up avoiding certain regions of the wall that we would expect to see marked. For now, this could explain the interference pattern on the wall. But now we can ask that interesting question you mentioned before: what happens if we do the experiment with one photon, or one little ball, at a time?

Gláucia - Under the conditions of this game, it would be analogous to thinking about Lu now alone, throwing only one tennis ball at a time, and marking where it hits the wall when it passes through one of the slits. So she goes there, with all her patience, spends a long time throwing balls. And then little by little, slowly, these marks on the wall will form a pattern. What pattern do you think it forms, Lu?

Lu - Now I have no idea.

Gláucia - Our intuition would say that now that only one ball is in the air at a time, there's no way its trajectory can be affected by another ball, right? So we shouldn't see interference. The surprising thing is that when we do this experiment with photons instead of tennis balls, what we find marked on the wall is… again the interference pattern, with its various stripes.

Lu - Okay, but what changed the ball's route now, if it was alone?

Gláucia - Good question! Finding an interference pattern here is strange because it indicates that even a single photon exhibits wave-like behavior. There are no other photons to influence it, it is alone! It's as if the photon managed to interfere with itself. [blunt]

Leo - We then come to this conclusion that seems very strange. On the one hand, we can check the location where the photons arrive at the wall, and each photon always arrives at a single point, like a tennis ball. So in that sense it acts like a particle. But, after a while, when we see the figure that the photon marks form on the wall, we find an interference pattern, and this is something that only waves do. Here, Pablo Saldanha again:

> **Pablo Saldanha:** My interpretation is the following: if I always detect it at one point, that is not a wave, because a wave spreads. And on the other hand, if I see interference, that's not a particle, because a particle doesn't experience interference. [...] This for me is a paradox that is what we call the wave-particle duality.

Leo - All this discussion about the double slit experiment was to get us to this fundamental concept of quantum theory, the [echo effect] wave-particle duality.

Gláucia - With this story about the double slit, we saw that it is very problematic to talk about quantum using analogies with everyday objects, such as tennis balls; quantum objects, like photons, act stranger.

Lu - But... if it's so problematic to compare a photon with a tennis ball, why did we spend so much time here in the episode making this analogy?

Gláucia - Fair question…For me, this path we have taken is essential for us to really understand where the strangeness of quantum theory appears. We said that to explain the experiments at the end of the 19th century, the idea that light is made up of particles came up. Now, what do these particles look like? Our conversation showed that they are not like tennis balls. So what are they like? We don't have the tools in our daily lives to make direct analogies with quantum phenomena. It's a world apart, that's why it's so difficult to understand what's happening.

Lu - Okay, so that's why you guys talk so much about quantum theory being counterintuitive?

Leo - For this reason, among other things. Bárbara Amaral, who is a Professor and researcher in the physics department at USP, talked to us about this.

> **Barbara Amaral:** And this is the biggest difficulty for us in quantum physics, you will explain classical physics, you can always say, “oh imagine a tennis ball, imagine a cylinder going down an inclined plane”, then you can close your eyes and do that experiment in your head, imagine a tennis ball. This is not possible for us in quantum.

Gláucia - Maybe it doesn't seem like a big deal, but what does it mean when you're studying something and suddenly you say “I understand”? In physics, it often means that you have managed to create a mental image of that content. And in quantum this is an obstacle, as we saw with the failed attempt to use tennis balls, because we find phenomena that do not appear anywhere else.

> **Barbara Amaral:** So when you talk about Newton's laws, you can come up with a simple experiment there, with trivial objects, from our daily lives or do a thought experiment, if you tell the person “imagine that you have a train,

imagine that there is a tennis ball, imagine that you are sliding down a ramp on a skateboard" it is very easy for us to create these mental images. [...] In quantum physics we cannot do one thing or another normally.

Gláucia - Bárbara, in addition to being our interviewee, is our academic sister, mine and Leo's. For those who listen to our bit quânticos, which are the mini-episodes that complement our regular episodes, you already know that Marcelo Terra Cunha, who appeared here earlier, was both my and Leo's doctoral advisor. And Bárbara also did her doctorate with Terra. There's this joke of calling Terra's mentees "Terraqueos", so we can say that Leo, Bárbara and I are three Terraqueos.

Leo - Well, but speaking of Terra, he tells us how this wave-part duality is not something exclusive to light.

Marcelo Terra Cunha: But among the very beautiful things that happened throughout the twentieth century was being able to do a double slit experiment also with things that we would think of as particles if we hadn't learned quantum theory. Nowadays we know quantum theory, we know that the electron is not very different from the photon.

Lu - So the electron also has this weird behavior?

Gláucia - Yes! If we do the double slit experiment sending electrons instead of photons, we see that the electrons also show an interference pattern. In other words, electrons, which we usually think of as particles, also exhibit wave behavior [blunt]. And it does not stop there.

Marcelo Terra Cunha: Electrons were the first step, but then they did it with neutrons, they did it with atoms, they made very large molecules, right? You already have double slit experiments made with molecules with over hundreds of atoms.

Leo - In other words, we increase in size, photons, electrons, atoms, molecules... and all these things, which we were sure to be 100% particles, located in a single point and very different from waves, present this wave behavior that is the interference pattern. This is the kind of thing we are referring to when we say that quantum theory is counterintuitive. Pablo here agrees with me.

> **Pablo Saldanha:** So if you do an experiment like this with a double slit or a double hole, right? With an atom you would expect not to see interference, right? [...] But the experiments show that there is interference. [...] And the formalism describes the propagation of atoms as a wave. So this is very strange.

[congas]

Leo - This is all very strange. But this is exactly why quantum theory is so interesting.

[cat]

CLOSING **

Lu - Phew, after this concentrated dose of experiments, photons, electrons, waves and particles, I got a little lost. Why are we even talking about this?

Gláucia - The beginning of this whole conversation was vibrations, right? But talking about vibrations, in the context of science, is talking about waves. So we talked a little about what characterizes a wave and what characterizes a particle, and the final message of all this is that quantum systems have this dual behavior, which sometimes presents wave characteristics and sometimes particle characteristics. And a consequence of this is that photons, electrons, and even atoms and molecules, in certain specific situations, also present characteristics of waves, like the interference.

Lu - Yeah, one can imagine that this is a full plate for pseudoscience to explore.

Leo - Exactly. When we hear that atoms and molecules can behave like waves... it's strange, because all things, in quotation marks " solid" are made up of atoms and molecules. But we need to remember that this happens in a specific context, in terms of the double slit, of interference.

Gláucia - In the case of atoms and molecules, we need extremely sophisticated experiments to demonstrate this wave behavior. What's more: as we will tell you in the next episodes, everything indicates that outside of these controlled situations, these phenomena do not occur.

Leo - Now, it's very easy for you to take this bombastic statement and use it to the pseudoscientific context, as is done in this excerpt from a pseudoscience channel on YouTube:

[radio static]

> *"One thing that is interesting that science has already proved is the particle-wave duality."*

[radio static]

Leo - So far ok, but…

[radio static]

> *"So imagine this, you give me a smile, or you are being nice to me. You will emit a vibration, my pineal will take this structure and it will become a particle. It will make the organism receive something through this vibration you gave me."*

[radio static]

Gláucia - After this whole episode, we now understand that this person is making reference to the wave-particle duality, but in a distorted way. Firstly, because he assumes that giving a smile to someone means in some way sending a wave to that person. But which wave? Wave of what? Maybe someday science will have something to say about this, but for now there is no scientific relationship between smiling and sending a wave.

Leo - Furthermore, as we saw, saying that an object has wave and particle characteristics is very different from saying that any wave can be transformed into a particle and vice versa. In the speech we heard, it seems something like, poof, it became a particle, poof, it became a wave. No. The behavior of photons and electrons may be very strange, but it has nothing to do with it.

Lu - The same holds for the other speeches that involve vibrations, right?

Leo - Exactly, it's not because on certain specific occasions quantum theory describes atoms as waves, that it makes sense to talk about quantum frequency therapy.

Gláucia - Speaking of which, it is nice that we presented the double slit experiment in some detail, because of sentences like this:

[radio static]

> *“But if we are really energy, is it possible for our thoughts to create our reality? An experiment that shook the scientific world left this question.”*

[radio static]

Gláucia - The narrator goes on to say that this experiment that shook the world is precisely the double slit experiment, as you may have guessed. And from what we said throughout this episode, it has nothing to do with thought creating reality, right?

Leo - Although we can easily exclude these absurd extrapolations, the double slit experiment still leaves open a very simple question: what was the trajectory that the photon (or the electron, or the atom) followed until it reached the wall? Because a wave, like a sound wave, for example, would pass through both slits at the same time… so does this mean that the electron passes through both slits at the same time?

> **Pablo Saldanha:** So, there is a very natural question which is, what happens in that experiment? Does the electron pass through both holes or does it pass through just one hole?

Gláucia - It seems like a simple question, but when we try to verify it in the experiment… things get more and more bizarre. So much so that Pablo confesses:

> **Pablo Saldanha:** I don't know how to answer that question, I don't think anyone does.

Gláucia - We left this question to the end not because it is not important. On the contrary, it is essential for us to continue discussing quantum theory. But how can something as simple as this be so difficult to answer?

> **Pablo Saldanha:** And that causes discomfort, at least I feel uncomfortable. Don’t you, Leo?

[congas]

Leo - I do. Mainly because this forces us to ask an even more complicated question: after all, are these oddities of quantum theory really real or just a story that scientists invented to explain the experiments? In our next episode we discuss philosophical issues, atoms in two places at the same time and one of the most fundamental concepts in quantum theory: we will talk about superposition.

[cat]

CREDITS **

[identity track - drums, then bass and piano]

Leo - In this episode you heard excerpts from interviews with Marcelo Schappo, Pablo Saldanha, Rafael Chaves, Marcelo Terra Cunha and Bárbara Amaral. Many thanks to our interviewees.
In this episode we used excerpts from the YouTube channels Elainne Ourives, TV Unesp and Fatos desconhecidos.

Gláucia - The transcript of the episode and the translation into English are available on our website www.ufsm.br/oqquantico, as well as figures, recommendations and more information about the double slit experiment.
If you liked the episode, you can help us by recommending the podcast to a friend who is interested in the topic. Also follow O Q Quântico on Instagram @oqquantico and be sure to rate the podcast on your favorite podcast platform.

Lu - Q Quantico is presented by me, Luciane Treulieb, Gláucia Murta and Leonardo Guerini.

In addition to the three of us, Samara Wobeto and Vitor Zuccolo complete the team of podcast producers

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Thanks for listening and see you in the next episode!

[transition - cat]